Session 5: Massive stars and their supernovae as galactic building blocks and engines: Milky Way, nearby galaxies and the early Universe

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The Lives and Death-Throes of Massive Stars
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Massive infrared clusters in the Milky Way

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Abstract. Our position in the Milky Way (MW) is both a blessing and a curse. We are nearby to many star clusters, but the dust that is a product of their very existence obscures them. Also, many massive young clusters are expected to be located near, or across the Galactic Center, where the dust extinction is extreme ($A_V > 15$ mag) and can be better penetrated by infrared photons. This paper reviews the discoveries and the study of new MW massive stars and massive clusters made possible by near infrared observations that are part of the VISTA Variables in the Vía Láctea (VVV) survey. It discusses what the studies of their fundamental parameters have taught us.

Keywords. surveys, stars: distances, stars: evolution, stars: fundamental parameters, stars: Wolf-Rayet, (Galaxy:) open clusters and associations: general

1. Introduction

Our location within our own Galaxy gives us a unique perspective from which we can study star clusters in great detail. It is a great opportunity for making significant progress in our knowledge of stellar formation and stellar evolution. Indeed, it is commonly accepted that the majority of stars with masses $\geqslant 0.50\ M_{\odot}$ form in clustered environments (e.g. Lada & Lada 2003 ; de Wit *et al.* 2005), rather than individually. Consequently, the study of clusters with massive stars is the study of the birth environment of these stars. Also, young clusters can be seen as stellar evolution snap-shots (e.g. Martins *et al.* 2008, Crowther *et al.* 2010, Davies *et al.* 2012, and Liermann *et al.* 2012). When observed in their first few million years of age, the clusters' stellar population can be used to trace the evolution scenario of the most massive stars. The main challenge for reaching a significant statistical sample of clusters is the extinction caused by dust that can be found along the line-of-sight, and/or near the clusters that produced it. This is why new near infrared (NIR) images provided by the VISTA Variable in Vía Láctea (VVV) survey are key for discovering and studying new clusters that are used to reveal the mechanisms involved in the birth and the faith of massive stars.

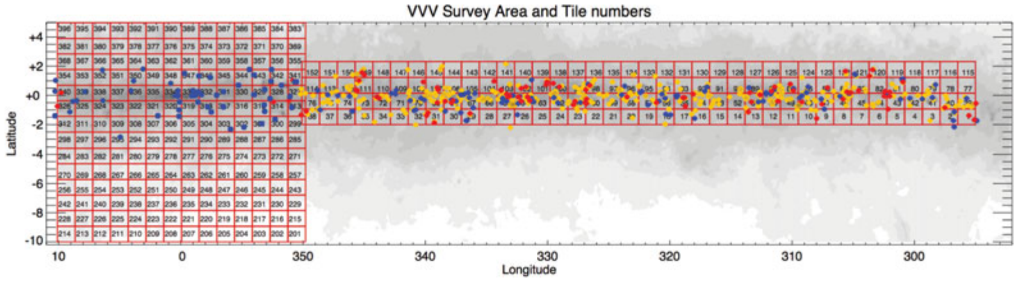

Figure 1. Area covered by the VVV survey. The VISTA tile are 1.5 deg^2 wide and each have a unique ID number. The dots mark the cluster candidates and clusters discovered by (blue) Borissova *et al.* (2011), (2014a), (red) Solin *et al.* (2014) and (yellow) Barbá *et al.* (2015).

2. VISTA Variables in Vía Láctea (VVV) survey

VVV was a key ESO survey that targeted the enigmatic central region of the Galaxy (Minniti *et al.* 2010, Saito *et al.* 2012, Hempel *et al.* 2014), and was carried out from Paranal using the 4-m Visible and Infrared Survey Telescope for Astronomy (VISTA). This successful survey recently completed after having undertaken $\sim$ 2000 hours of exposure through $ZYJHK_S$ filters. Those observations revealed an unprecedented $\sim 10^9$ point sources across 562 deg^2 of sky that spanned the Galaxy's bulge and an adjacent region of the Galactic disk. Our team has constructed color-magnitude diagrams (CMDs) of nearly 1500 bona fide and candidate clusters located in the VVV area, including an impressive new 735 candidates uncovered in the survey that are not included in the Morales *et al.* (2013) catalogue (Borissova *et al.* 2011, 2014a, Solin *et al.* 2014 and Barbá *et al.* 2015, see Fig. 1).

For more information about the survey, please visit `https://vvvsurvey.org/`. For information on how to get your own set of public data, click the link "Data Releases" at the top menu. For J, H, and K_S combined photometric catalogs, one can also search the *Nuevo Observatorio Virtual Argentino* (NOVA) at `http://nova.conicet.gov.ar`.

3. Census of the clusters with massive stars in the MW

Fig. 2 shows the distribution of young (<10 Myrs) clusters and cluster candidates in the MW. The red and blue points are from the Karchenko *et al.* (2013) catalog, which derived fundamental parameters solely based on photometric analysis. Therefore, the uncertainty on these points is unknown and highly variable from point to point. Nevertheless, when used as a bulk, it gives a fair representation of the distribution of the young clusters that are known to date. The red points mark the clusters that were discovered using infrared light. One can appreciate that infrared allows to reach further than the optical light (the blue points). The green points mark the position of the young and massive clusters as derived from the Table 4 of Davies *et al.* (2012). The names of some of the most famous ones are written on the figure. The yellow points mark the clusters with massive stars discovered in the VVV survey. The names of the clusters that are described in more details later in these proceedings are written.

The following is a brief description of some of the most interesting recent findings.

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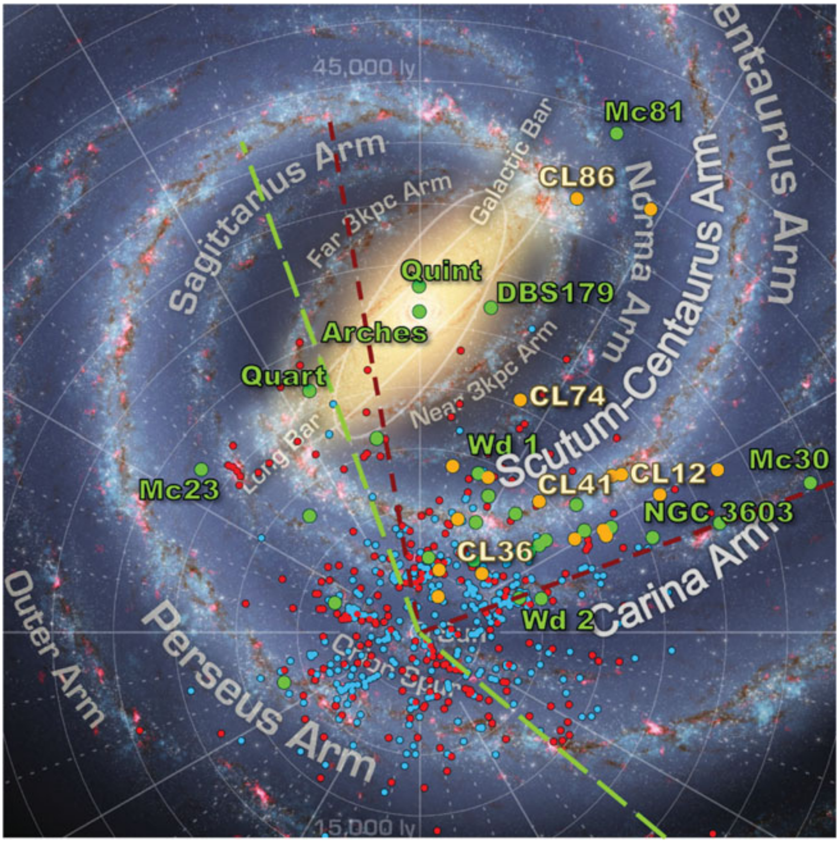

Figure 2. Artist illustration produced by NASA/JPL-CALTECH of the MW seen face-on. The Galactic Bar and different arms are identified. The small blue and red points are young (age < 10 Myrs) clusters and clusters candidates that were discovered in the optical and in the NIR light, respectively. There distances were determined by Karchenko *et al.* (2013). The big green points mark the census of known massive clusters. The big yellow points mark the clusters with massive stars that were discovered using the VVV survey images. The red dashed line indicates the area covered by the VVV survey. The green dashed lines show the wider area that will be covered by the newly allocated survey VVVX (`https://vvvsurvey.org/`).

4. The VVV clusters

4.1. *VVV CL086, an OB star cluster at the fat end of the Galactic Bar*

The position of VVV CL086 places this clusters containing numerous OB stars at the far end of the Galactic Bar (Ramírez Alegría *et al.* 2014). This cluster is the second one found in that region, after Mercer 81 (Davies *et al.* 2012).

4.2. *VVV CL012, a cluster with massive young stellar objects*

Using the host clusters of massive young stellar objects (YSO), we can determine their age, distance and reddening. Also, since VVV provides us with multi-epoch of K_S observations of the whole field over many years, we can extract the light curve of the massive YSOs (see Fig. 3). As demonstrated by Caratti o Garatti *et al.* (2016; and references therein), massive YSO show the same type of outburst as the one seen in YSO of other masses. The monitoring of the changes in brightness of YSO helps defining what is the priviledged mechanism for massive stars formation. Fig. 3 shows an example from

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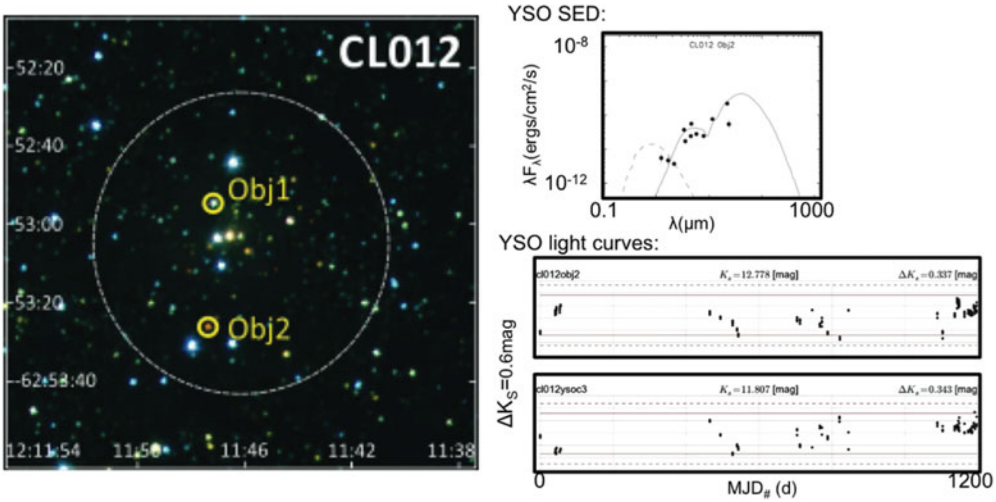

Figure 3. *Left*: False color JHK_S image from VVV. The stars marked in yellow were observed in spectroscopy. *Right*: The top shows the SED obtained from VVV, Spitzer and Apex observations. The bottom panels show the K_S light curves extracted from VVV for the two stars marked in yellow in the image at the left.

Borissova *et al.* (2016) with VVV CL012, where two massive YSOs are monitored. Also, an SED fit is made possible by combining VVV, Spitzer and APEX data.

4.3. *VVV CL074, having access to the whole massive star population*

VVV CL074, at a distance of 6 ± 1 kpc contains at least three Wolf-Rayet (WR) stars and a handful of OB stars (Chené *et al.* 2013). In addition to the VVV photometry, we collected the spectra of 11 stars. All the observed O stars are supergiants. We used the radiative transfer code CMFGEN (Hillier & Miller 1998) to determine their stellar and wind parameters. It allowed us to place the best observed stars into the HR diagram shown in Fig. 4. This first result gives an approximate age of 7 Myrs and could indicate that $\sim$40 $M_\odot$ O supergiant stars are linked to the evolved WN8 stars (Hervé *et al.* 2015). This result requires the spectra of more stars for final confirmation. Very interestingly, the O dwarfs are about 2 magnitudes fainter, which means that in a reasonable amount of time on an 8m telescope, we can characterize by using NIR spectroscopy the complete massive stellar population of the cluster. We currently have secured observing time on the VLT to achieve this in the 17A semester.

4.4. *VVV CL036, highlighting binary evolution*

VVV CL036 has a fairly peculiar massive star population (see Fig. 5). In the same cluster, we find a WN, a blue supergiant (BSG) and a red supergiant (RSG) star (Chené *et al.* 2013). These three stars cannot be coeval, if one considers only single star evolution. The only way to explain such a population is by involving a multiple system evolution for, at least, the WN star that was rejuvenated through matter exchange during binary interaction. The study of more stars in the cluster would pin down a more accurate age, defining a clearer scenario of the cluster's history. Note that the WN stars shows a WR nebula (Borissova *et al.* 2014b), which is not detectable in the optical due to the extreme reddening ($A_V \sim 24$ mag).

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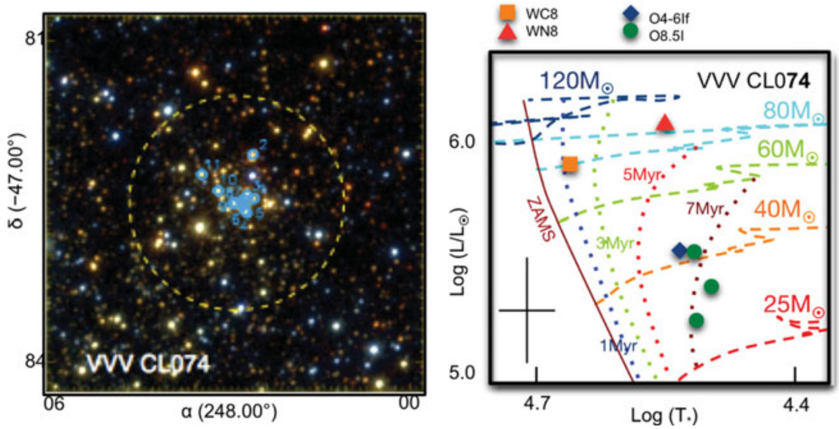

Figure 4. *Left*: False color JHK_S image from VVV. The stars marked in blue were observed in spectroscopy. *Right*: HR diagram with the brightest observed stars. The evolution tracks are from Ekström *et al.* (2012). The error bars are plotted on the bottom-left corner.

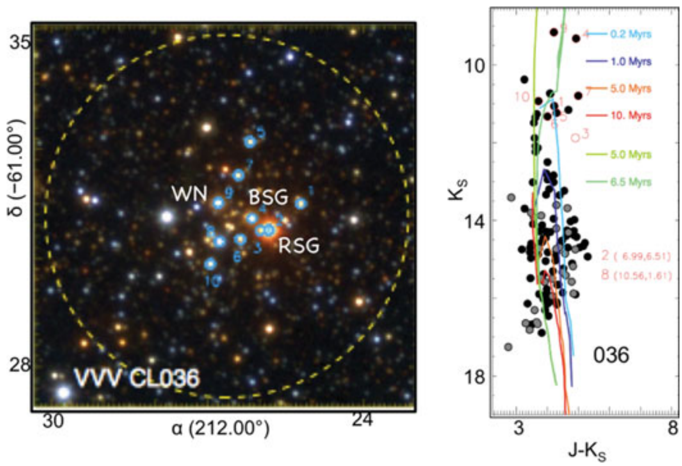

Figure 5. *Left*: False color JHK_S image from VVV. The stars marked in blue were observed in spectroscopy. *Right*: K_S vs $J - K_S$ diagram. The isochrones are from Ekström *et al.* (2012). The values for the RSG star (star#2) are off boundaries, and are written on the diagram. The WN and the BSG stars are stars #9 and #4, respectively.

4.5. *VVV CL041, a new very massive star candidate*

Very massive stars (VMS) are defined as stars with masses higher than 100 $M_\odot$. VVV CL041 contains a newly discovered VMS candidate, WR 62-2 (Chené *et al.* 2015). That star, a WN8-9h type star equivalent to what is observed in the Arches cluster (Martins *et al.* 2008), is one of the most luminous stars known to date. Applying the same spectral analysis as described for VVV CL074, we obtained a HR diagram for the 5 brightest stellar members of the cluster. The cluster's age is around 2 Myrs, and WR 62-2 might have a mass higher then 120 $M_\odot$. Of course, if it is in a binary system, then the total mass would be shared by the two components.

4.6. *Summary of the best studied VVV clusters with massive stars*

One can refer to Sebastian Ramírez Alegría's paper in these proceedings about the massive clusters in VVV. Here, we present a summary of the fundamental parameters for

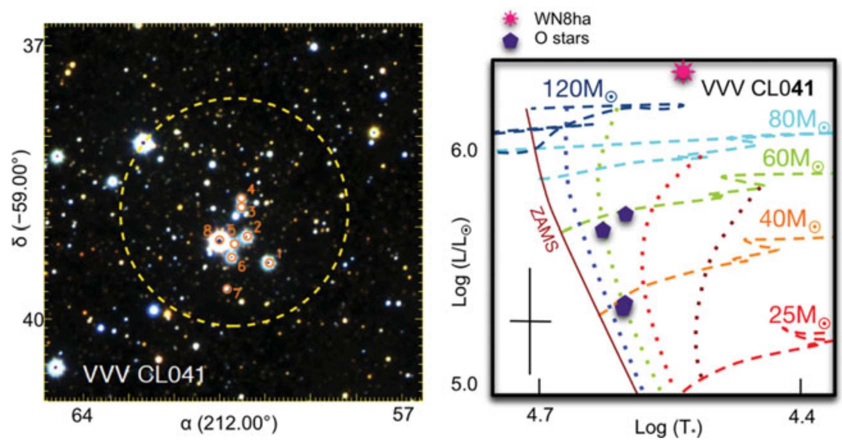

Figure 6. Same as Fig. 4, for VVV CL041.

the current census of VVV clusters with massive stars, compiling results from Borissova *et al.* (2016), Chené *et al.* (2013), (2015), Ramírez Alegría *et al.* (2014), (2016).

Table 1. Parameters of VVV clusters with massive stars

VVV	A_V (mag)	d (kpc)	Age (Myrs)	RA	DEC
CL009	5.4 ± 0.1	5 ± 1	4-6	179.0125	-63.3117
CL010	12.6 ± 0.3	8 ± 2	2-5	182.9458	-61.7733
CL011	9.4 ± 0.1	5 ± 2	3-7	183.1708	-62.7094
CL012	11.8 ± 0.3	7 ± 1	8-12	185.0583	-62.8850
CL013	11.4 ± 0.3	4 ± 2	1-5	187.1542	-62.9733
CL027	5.0 ± 0.2	6 ± 2	6-8	203.1000	-62.7275
CL028	3.7 ± 0.3	6 ± 1	20	205.0958	-61.7333
CL036	24 ± 3	2 ± 1	5-7	212.2666	-61.2661
CL041	8.0 ± 0.2	4 ± 1	1-3	221.6083	-59.3881
CL059	17.7 ± 0.3	12 ± 2	<20	241.4666	-50.7967
CL062	6.3 ± 0.3	1 ± 2	10	243.0333	-51.9689
CL073	19.3 ± 0.3	4 ± 3	<7	247.6000	-48.2167
CL074	23.4 ± 0.1	6 ± 1	4-6	248.0250	-47.8253
CL086	12.8 ± 0.1	11 ± 5	1-5	252.0625	-45.4350
CL088	15.7 ± 0.3	3 ± 2	6-8	253.1416	-44.6019
CL089	15.0 ± 0.3	2 ± 2	8-10	253.4458	-43.2675
CL099	15.2 ± 0.2	4 ± 1	4-6	258.6083	-38.1661

5. Mention of other groups work based on VVV data

There are currently more than 30 publications written based on VVV data by authors that are not member of the VVV science team. This includes massive stars related studies such as the X-ray observations of massive stars in VVV CL077 (Bodaghee *et al.* 2015), the monitoring Cepheid stars in open clusters (Chen *et al.* 2015), and the thorough study of the Dragonfish nebula de la Fuente *et al.* (2016). The later uses HST for the inner, crowded areas, and VVV for the surrounding clusters.

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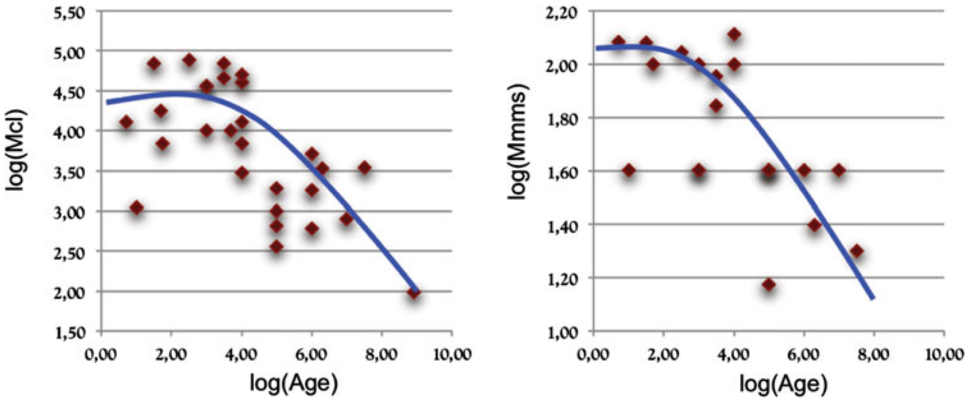

Figure 7. Mass of the cluster (Mcl) and mass of the most massive star cluster member (Mmms) as a function of age (in logarithmic scale). The blue lines show the general trends in the two cases.

6. Playing with the clusters fundamental parameters

Having access to previous studies, together with fresh results on newly discovered clusters gives a preliminary list of more than 40 clusters with massive stars. We can play the game of comparing some fundamental parameters together. We searched for correlations between the physical radius, the age, the total mass of the cluster, the mass of the most massive star in the cluster, the number of WR stars and the extinction using a Kendall's τ rank analysis. We could find only 3 real significant (anti-)correlations:

- the total mass of the cluster vs. the mass of the most massive star,
- the age vs. the mass of the most massive star,
- the age vs. the total mass of the cluster.

The first one echoes the result from Weidner *et al.* (2010), but with a much poorer statistic. The two last ones are plotted in Fig. 7. The second one may show an effect of stellar evolution, since passed an age of 4 Myrs, the mass of the most massive star decreases. It is indeed expected that the most massive members of the clusters end their life after ony a few Myrs. The last one could be showing the effect of cluster evolution, since after 3 Myrs, the total mass of the cluster seems to decrease. It is indeed suggested that clusters loose mass at early times, due to gravitational interaction or massive mass loss in the form of gas expelled during the supernova explosion of the most massive stars, or both (Portegies Zwart *et al.* 2010).

Of course, the statistics of these results are quite poor. Yet, there could be an indication that adding more clusters would clarify some phase of stellar and cluster evolution. And potentially, outliers would provide us with opportunities to unveil other star formation channels or yet unexpected cluster evolution destiny.

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