Census of Milky Way Star Clusters from Infrared Surveys

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Abstract Recent near- and mid-infrared wide-field sky surveys are reviewed, and their applicability for Milky Way star cluster studies are discussed. The on-going VISTA Variables in Via Lactea survey is described. Finally, the first results from a simulation addressing the completeness of cluster searches are presented.

1 Infrared Surveys Relevant for Milky Way Star Cluster Studies

Cluster studies are hampered by extinction – clusters concentrate in the plane of the Galaxy, and the optical surveys have been able to provide us with reasonably complete cluster census only for the nearest 1–2 kpc (see Fig. 15 in [25]). Until a decade ago it was impossible to carry out a wide-field infrared (IR) surveys that would "see" through the dust (i.e., $\mathrm{A}_{K_S} = 0.112 \times \mathrm{A}_V$; [30]) because of technological limitations. However, the recent advances of the IR detectors made it possible to carry out homogeneous observations of wide areas of the sky, comparable with the state of the art wide-field optical surveys, and the new space missions such as *Spitzer*, opened to us the mid-IR wavelength range. For the first time the Milky Way cluster studies could rely on excellent quality preexisting data to find and characterize clusters. Table 1 describes the near- and mid-IR surveys with depth and sky coverage that make them suitable for these purposes.

The strategies of these surveys can be summarized as follows:

- 2MASS – simultaneous JHK_S observations [32]
- DENIS – semi-simultaneous $I_{Gunn}JK_S$ [11]

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Table 1 Near- and mid-infrared surveys, relevant for Milky Way cluster studies

Survey	Area deg^2	Bands / 5σ-limit	Cluster searches	Status and data products
2MASS	All sky	J/16.5 mag H/15.8 mag K_S/15.1 mag	Hundreds of new clusters: Dutra and Bica [8, 9], Ivanov et al. [17], Bica et al. [1], Borissova et al. [7], Dutra et al. [10], Froebrich et al. [12, 13]	Completed (1997–2001); last DR Mar 2003;∼471 million PSC + 2 arcsec resolution JHK_S atlas
DENIS	16700	Gunn I/18.5 mag J/16.5 mag K_S/14.0 mag	Two new clusters (Reylé and Robin [29])	Completed (1995–2001); as of DR3 from Sept 2005:∼355 million PSC + IJK_S atlas
UKIDSS GPS	1800 – JHK 300 – H_2	J/19.8 mag H/19.0 mag K/18.1 mag H_2/...	∼170 new clusters (Lucas et al., in prep.)	In progress (2006–2013), as of DR6 (Oct 2009): ∼604 million PSC + ∼1 arcsec resolution JHK atlas
VVV	300 – bulge 220 – disk	Z/21.5 mag Y/20.7 mag J/20.2 mag H/19.3 mag K/19.3 mag (disk)	Search in progress	Raw paw-prints public via the ESO Data Archive; first v. 1.0 tiles+catalogs recently available to the team via CASU
GLIMPSE I+II+3D + 360	220+60+ 134+290 =∼700	[3.6]/0.2 mJy [4.5]/0.2 mJy [5.8]/0.6 mJy [8.0]/4.0 mJy	59 new clusters (Mercer et al. [22])	In progress (2003–2012); ∼100 million PSC (up to GLIMPSE 3D) + ≤2 arcsec resolution atlas

- UKIDSS GPS – semi-simultaneous JHK imaging, and two more K-band re-visits for proper motion and variability purposes [20]
- VVV – two visits during which semi-simultaneous YZ and JHK_S images are taken, and multiple (50–80) K_S re-visits separated by up to 5 yrs (see Sect. 2 for details) [27]
- GLIMPSE – simultaneous [3.6] and [5.8], and simultaneous [4.5] and [8.0] imaging; two visits, separated by 20 s to 3 h [7]

The relative depth of the various surveys and a sensitivity versus area plot are shown in Fig. 1. The sky footprints are shown in Figs. 2 and 3. While the depth and the spatial resolution of the 2MASS allowed detailed study only of the closest star clusters, the new generation of near-IR surveys (UKIDSS and VVV) lets us to characterize the clusters, at least to some extent. For example, VVV revealed the pre-main sequence population of some young clusters that would have been invisible in 2MASS. Of course, studies of most clusters require spectroscopy which is typically the most reliable method for measuring their distances, and all parameters

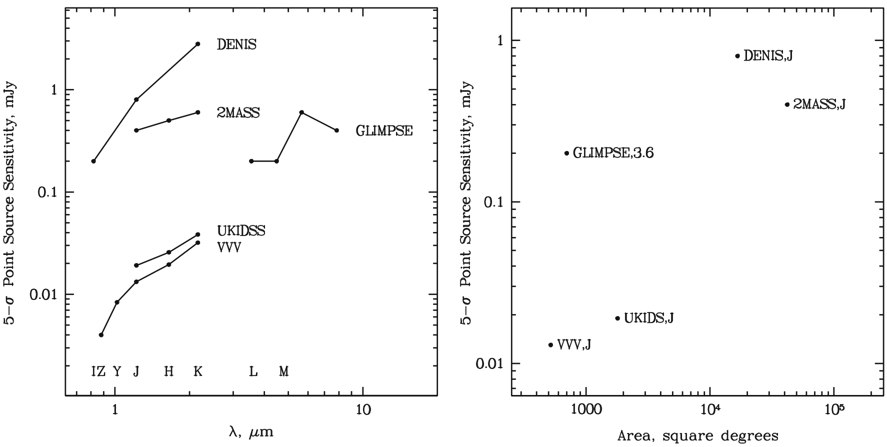

Fig. 1 Relative depth of the various surveys (*left*), and sensitivity versus area plot (*right*)

that scale with distance, including their mass, total luminosity, and even the age – for the clusters with no main sequence turn off point.

2 VISTA Variables in Via Lactea Survey

The *VISTA Variables in Via Lactea* (VVV) Survey was designed to probe the time axis – producing a large-scale 3-dimensional map of the Milky Way with the RR Lyr and Cepheid variables. The survey has two sub-components: the bulge ($-10<l<10$ deg, $-10<b<5$ deg) and the disk ($-65<l<-10$ deg, $-2<b<2$ deg), observed with nearly identical strategies, but with mildly different integration times and depths. The total footprint spans 520 deg^2 (green on Fig. 3), and the final point source catalog is expected to contain 10^9 sources, including 10^6 variable stars of different types. Proper motion measurements with $\geq$5 yr baseline will also be obtained.

The VVV has a broad range of corollary science goals related to clusters: distances to some of them, based on their variable star members, and most importantly – providing a broad new census of clusters including, in particular, young ones containing obscured pre-main sequence stars. The VVV team has broad experience in cluster identification and characterization [2–6, 14–18, 23–25], and we will search for clusters on the deepest ever K_S-band sub-arc-second image of the Galaxy that will be created stacking together all multi-epoch VVV observations.

The yearly strategy of VVV involves a complicated timing schedule for randomized sampling of light curves, and for proper motion studies:

- 1 year : quasi-simultaneously $ZYJHK_S$ and 6 separate epochs in K_S of the entire survey area

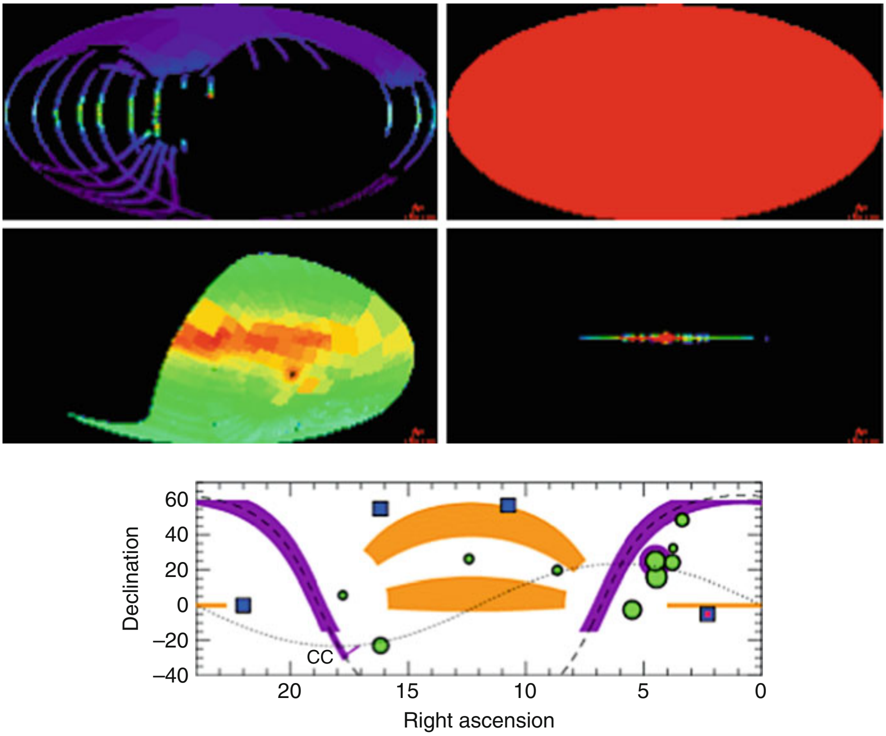

Fig. 2 Sky footprints of various surveys: *top left* – SDSS (large optical CCD survey, shown here for comparison), *top right* – 2MASS, *middle left* – DENIS, *middle right* – GLIMPSE, without the recent extensions are (all four maps are in Galactic coordinates), and *bottom* – UKIDSS (in Equatorial coordinates; GPS is shown in *violet*, GCS in *green*, LAS in *yellow*, DXS in *blue*, and USD in *red*). The top for plots are courtesy of the VizieR database, the bottom is courtesy of the UKIDSS team (*http://www.ukidss.org*)

- 2 years : 6 separate epochs in K_S of the entire survey area
- 3 years : 80 separate epochs in K_S of the bulge – main bulge variability campaign
- 4 years : 70 separate epochs in K_S of the disk – main disk variability campaign
- 5 years : 20 epochs in K_S of the bulge and 9 of the disk; subset of pointings will be observed more frequently; provides the large baseline for the proper motion studies

The survey is on-going. Observations started in the first half of 2010, and high level data products are being generated as of mid-2010, but they are still undergoing quality control and verification, and have not yet been released to the general users. For example, the entire data set from the first half a year of observations has been re-reduced three times, to improve the data quality.

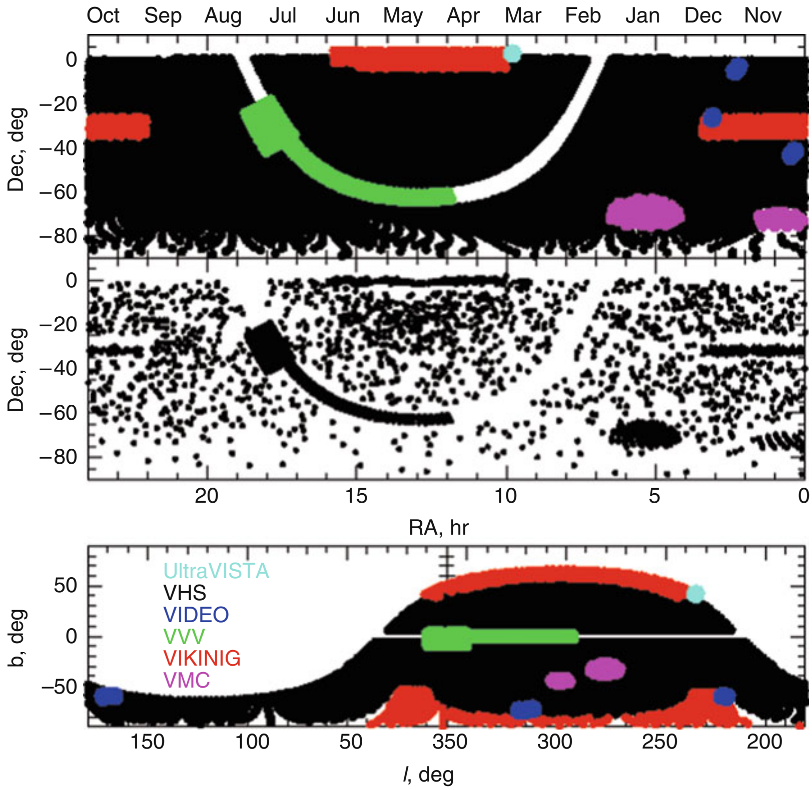

Fig. 3 Sky footprints of the original VISTA surveys. The *top* and the *bottom panels* show all telescope pointings necessary to cover the areas of the surveys, in Equatorial and Galactic coordinates. The middle panel shows the subset of the pointings excepted to be observed during the first year of VISTA operation

3 Incompleteness of the Milky Way Cluster Census from the 2MASS

Finding and characterizing new clusters can be an exciting challenge, but the discovery of yet a few more objects, as interesting and important as they may be, does not help to address the question of the total population's size – dust obscuration makes the Milky Way cluster census incomplete for distances larger than a few kpc. GLIMPSE demonstrated that even mid-IR surveys have difficulties in detecting distant clusters because the [3.6] band is still noticeably affected by extinction ($A_L = 0.058 \times A_V$; [30]), and the longer wavelengths are more sensitive to extended dust emission than to stars.

To address the issue of completeness we began a project [19] to simulate the cluster population of the Galaxy, to merge it with a real point-source catalog, and to run a cluster search using various algorithms. It became clear form the beginning,

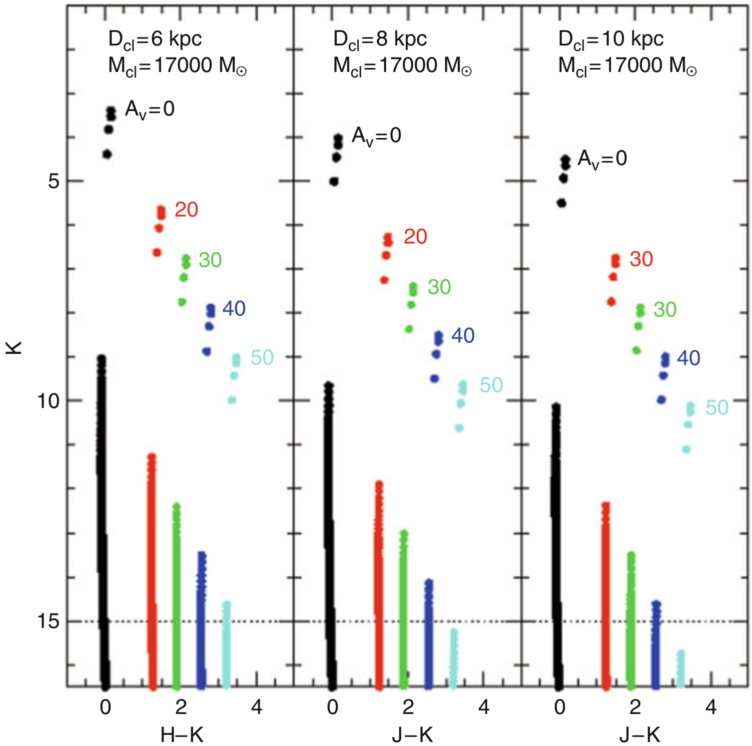

Fig. 4 Color-magnitude diagrams for a cluster with total mass M_{cl}=17,000 $M_\odot$) and age of 10 Myr for various distances and optical extinctions A_V, generated from the Padova isochrones [21]. The *horizontal dotted line* shows the approximate 2MASS completness limit in the most crowded regions of the Galaxy

that we can hope to derive incompleteness corrections for distances beyond a few kpc for the most massive clusters only. Therefore, for now we will consider only supermassive clusters (M_{cl} =17,000 $M_\odot$) with age of 10 Myr. The young age makes the member stars intrinsically brighter, and somewhat alleviates the question of the infant mortality. Synthetic color-magnitude diagrams for such clusters at different distances and values of A_V are shown in Fig. 4 to illustrate the depth necessary for detecting their member stars.

We assumed that the clusters follow a spatial distribution close to that of the stars in the Milky Way disk, and generated 10^5 clusters in na exponential disk-like distribution (Fig. 5) with scale length $R_0^{cl} = 1.8$ kpc and scale height $Z_0^{cl} =$ 55 pc. The obscuring dust also has exponential distribution, with $R_0^{dust} = 3$ kpc and $Z_0^{dust} = 200$ pc. These values were adopted from the Besançon Milky Way model [31]. The spatial distribution of the stars within the clusters was taken directly from MASSCLEAN (Massive Cluster Evolution and Analysis Package; [28]).

Let us consider a “pencil” beam (3×3 deg) at $l = +60$ deg $b = 0$ deg (red dots in Fig. 5). It contains 286 of all generated clusters. It is clear from the synthetic

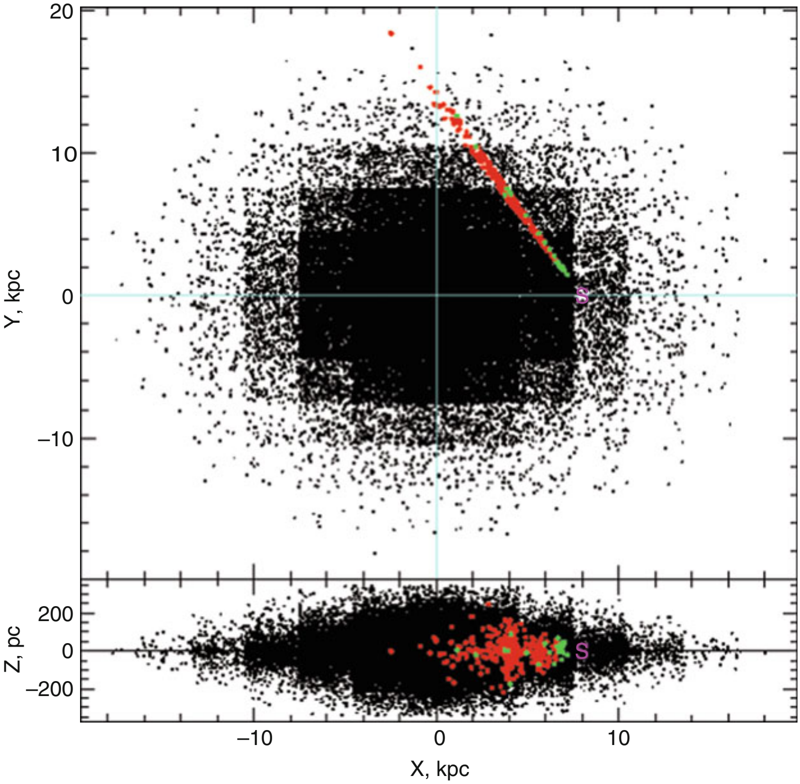

Fig. 5 Cluster simulation [19]. The *green dots* are potentially detectable clusters, the *red dots* are undetectable clusters. The Sun's position is marked with the letter "S"

color-magnitude diagram (Fig. 4) that four stars at the red supergiant stage dominate the cluster. We exclude from the sample the clusters for which more than one of these four member star is rendered undetectable by the proximity to bright foreground stars (taken from the real 2MASS point-source catalog [32]) because the stars on the main sequence are too faint to be detected in the glare of the bright cluster members, and therefore, the cluster can only be detected by the red supergiants. This "cleaning" left us with only 24 clusters, or ∼8%, that remain potentially detectable as groups of three or more stars with similar colors and magnitudes. Note that 17 of these clusters are "local", i.e. reside within 5 kpc from the Sun.

The potential detectability does not guarantee that a cluster will be detected because of the fore- and background star density variation, and the clumpy structure of the dust. Therefore, the ∼8% is an optimistic upper limit for the 2MASS cluster search in that direction. In reality, the detection rate even for supermassive red supergiant phase clusters (that are the easiest to detect) in this direction will be lower. Note that the better spatial resolution and depth of VVV with respect to the 2MASS will increase somewhat the detection rate.

4 Summary

The modern near- and mid-infrared surveys provide observational bases for detailed cluster census and characterization but the completeness rate of the cluster searches even for the deepest surveys is likely to remain low.

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