Mining the VVV: star formation and embedded clusters

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ABSTRACT

Aims. We aim to locate previously unknown stellar clusters using the VISTA variables in the Vía Láctea Survey (VVV) catalogue data.

Methods. The method fits a mixture model of Gaussian densities and background noise and uses the expectation maximization algorithm to pre-filtered near-infrared survey stellar catalogue data; it was developed by the authors for the UKIDSS Galactic Plane Survey (GPS).

Results. The search located 88 previously unknown candidates, most of which are embedded stellar cluster candidates, and 39 previously unknown sites of star formation in the 562 deg² covered by VVV in the Galactic bulge and the southern disk.

Key words. open clusters and associations: general – methods: statistical – catalogs – surveys – infrared: stars

1. Introduction

The ESO public survey VISTA variables in the Vía Láctea (VVV; [Saito et al. 2012](#)) maps 562 deg² in the Galactic bulge and the southern disk in the *ZYJHK_s* filters ([Minniti et al. 2010](#)). The VVV survey was designed to complement among others the UKIDSS Galactic Plane Survey (GPS; [Lucas et al. 2008](#)) which maps $|b| < 5^\circ$ in Galactic latitude in the northern plane.

In [Solin et al. \(2012; hereafter Paper I\)](#) we presented an application of Gaussian mixture modelling, optimised with the expectation maximization (EM) algorithm ([Dempster et al. 1977](#)) to automatically locate stellar clusters in the UKIDSS GPS ([Lucas et al. 2008](#)). This study applies the same method to the VVV survey first data release (DR1). The background and motivation for this work and the data mining approach to the cluster search is described in Paper I.

The search algorithm and filtering of the catalogue artefacts have been presented in detail in Paper I. The data is described in this paper in Sect. 2 and the search method and results in Sects. 3 and 4. In Sect. 5 the results, supplementary information on the cluster candidates and selected individual cluster candidates are discussed. Conclusions are drawn in Sect. 6.

2. The data

The VVV survey began in May 2010 and is expected to run for a total of about five years. The DR1 catalogues contain 2.96×10^8 stellar sources detected in at least one of the five photometric bands (*ZYJHK_s*). There are no overall limiting magnitudes as they depend strongly on crowding in the inner Galactic regions. The VVV survey is carried out by the VIRCAM (VISTA InfraRed CAMera; [Dalton et al. 2006](#)) on the VISTA (Visible and Infrared Survey Telescope for Astronomy) at the ESO

Paranal observatory. The VISTA Data Flow System pipeline processing and science archive are described in [Irwin et al. \(2004\)](#) and [Hambly et al. \(2008\)](#). We have used data from the first data release, which is described in detail in [Saito et al. \(2012\)](#). The catalogue data is used for the automated search, and the image data for visual inspection of the cluster candidate areas given by the detection algorithm. Stars brighter than $K = 10^m$ from the 2MASS survey are used to locate potential false positive clusters created by these bright stars (see Appendix B).

3. Search method

The search method and algorithm are described in detail in Sect. 3 in Paper I. In the following we present a short summary and outline the differences between these two studies.

The catalogue parameter `mergedClass` classifies as stars or galaxies every object in the WFCAM Science Archive (WSA) ([Hambly et al. 2008](#)) catalogue data table `gpsSource` used in Paper I and in the VISTA Science Archive (VSA) ([Cross et al. 2012](#)) catalogue data table `vvvSource` used in this study. These catalogues tend to classify objects seen superposed on variable surface brightness as galaxies. This can be used in the search for stellar clusters either embedded in or near molecular/dust clouds, and in the search for locations of star formation. The clusters and newly formed single stars that are associated with dust clouds create variable surface brightness which broadens the stellar point spread function or creates false, extended sources. “Galaxy” in the archive parlance is more precisely described as “non-stellar” or “extended” object.

A fraction of the catalogue sources are due to data artefacts. In Paper I a few different types of artefacts in the UKIDSS survey data were addressed. In this study only false `mergedClass = +1` classifications caused by diffraction patterns around bright stars

are addressed. The other types addressed in Paper I are either not numerous or not at all present in the VVV survey data. Comparison between UKIDSS and VVV survey data and the artefacts in them is done in Appendices B and C.

The catalogue data table `vvvSource` contains 113 attributes for each detected object. These parameters strongly resemble those of the UKIDSS GPS. In addition to the `mergedClass` parameter, in Paper I we also tested the usefulness of other parameters in our clustering effort, but ultimately both studies make use only of this stellar/non-stellar classifier.

As in UKIDSS the VVV classification of sources fainter than 17^m in H and K_s as stellar/non-stellar objects is highly unreliable. These sources were filtered out from the data because they create strong erratic background noise.

In addition to the K magnitude used in Paper I, here we also use the H magnitude because in VVV DR1 the H magnitude is given for many tiles where the K_s magnitude is missing. Many candidates were found in areas where only the H magnitude is given. In order not to lose true positives we also do not reject any sources based on the quality error bit flags for each source detection (VSA 2011). Cluster candidate 12 lies in a region where the parameters `hppErrBits` and `ksppErrBits` have often a high value. `HpErrBits` and `ksppErrBits` mostly fall below the value 17 and only a negligible part of the parameters `hErrBits` and `ksErrBits` are other than zero.

The VVV DR1 catalogue data table `vvvSource` contains 260.2×10^6 sources measured in the H or K_s filter with magnitude brighter than 17^m . These sources are divided according to the `mergedClass` parameter so that a negligible fraction are probable galaxies or noise, 6% probable stars, 64% stars, and 30% galaxies. We decided to use sources with H or K_s magnitudes brighter than 17^m and `mergedClass` = +1 for the detection algorithm. These amount to 76.8×10^6 sources (~19% out of all sources measured in the H or K_s filter in VVV DR1). Except for step 3 below, the magnitudes listed in the VVV catalogue are in no way used in the automated search.

The automated search proceeds using following steps which are similar to those in Paper I where the model and its parameters are presented in detail. When K_s band data is not available H band data is used in the search.

1. The pre-filtered catalogue data is divided into smaller overlapping spatial bins $4'$ by $4'$ in size; this was chosen as a suitable size for the bin based on experiments with the cluster candidates in the UKIDSS GPS list by Lucas. Apart from bins at the dataset edges, each bin overlaps one half of its neighbouring bins.
2. False `mergedClass` = +1 classifications around bright stars are removed as explained in Appendix A.1 in Paper I.
3. In order to track clusters with bright members the detection algorithm is run five times: once with all (filtered) input data and then using 80, 60, 40, and 20% of these sources arranged in descending order of the H or K_s magnitude.
4. The spatial coordinates are rescaled to the interval $[0, 1]$ to make all bins equally important but still allowing them to have differing means and variances. This step is relevant only for bins at the dataset edges and which are smaller than $4'$ by $4'$.
5. In order to initialise the model parameters the data bin is divided into 16 subgrids to find the area with the highest spatial density. The initial value of the cluster mean μ is the centre point of the subgrid with the highest density. The covariance matrix of the data points assigned to the subgrid with the highest density give the initial values for the cluster covariance Σ . The weights τ have as initial values the same value: $\tau_0 = \tau_1 = 0.5$.
6. Each data bin is represented by a mixture model of a background component and one Gaussian cluster component as explained in Paper I.
7. For each data bin a candidate cluster, i.e. an ellipse with the centre point at the mean μ and half-axes determined by the covariance Σ , is returned by the EM algorithm.
8. The candidates are rearranged in descending order of the Bayesian information criterion (BIC; Schwarz 1978).
9. Cluster candidates closer than one arcmin to each other are merged.
10. The following cluster candidates are removed from the list: Dutra & Bica (2000; hereafter [DB2000]); Dutra et al. (2003; [DBS2003]); Bica et al. (2003a; [BDB2003]); Bica et al. (2003b; [BDS2003]) (200 covered by VVV); Mercer et al. (2005; [MCM2005b]) (67 covered by VVV); Froebrich et al. (2007) (17 covered by VVV); Lucas (17 out of the 331 cluster candidates from UKIDSS GPS DR4 are covered also by VVV); and Borissova et al. (2011) (96 cluster candidates from VVV).

The source screening was done in exactly the same manner as in Paper I (Sect. 3.3 there) with the exception that the BIC threshold was lowered to 0 (BIC can also have a negative value) in order not to lose true positives that only give a weak signal to our system. As in Paper I, only a small fraction (~2%) of the candidates given by the automated search are true cluster candidates.

We note that the centre point for the cluster given by the automated search is not always exactly at the cluster centre. Often during the source screening the coordinates for the candidates need to be slightly adjusted.

4. Results

The search located 88 cluster candidates and 39 star formation location candidates which, to our knowledge, were previously unknown. The cluster candidates are listed in Table 1 and the candidate locations of star formation in Table 2. In addition, in Table 3 we list 26 faint nebulae whose nature cannot be clearly defined. The division of the candidates into these three groups is subjective and is based on the optical appearance of the candidates and also on their SIMBAD associations:

- A cluster candidate has more than a few stars.
- A location for a star formation candidate has bright nebular emission, but only one or a few stars. SIMBAD associations that are star formation indicators are also considered as evidence.
- Faint nebula candidates are similar to location for star formation candidates but are considered too weak in terms of the criteria mentioned. These sources are often in the direction of infrared dark clouds (IRDC) where a large number of other indications of star formation (IRAS, MSX, (sub)mm sources, masers, and HII regions) are present. No stellar cluster can be resolved, but the surface brightness (red nebulous compact objects or only those with faint red surface brightness) created by putative star formation triggers the classification of the VVV `mergedClass` parameter and thus the cluster search algorithm.

The columns in the tables list (1) a running number; (2) source identification; (3 and 4) Galactic coordinates; (5 and 6) J2000.0 equatorial coordinates; (7) description of selected SIMBAD

Table 1. List of cluster candidates.

No.	ID	l [°]	b [°]	α (J2000) [h m s]	δ (J2000) [° ' "]	Associated sources ^S	References
1	G009.617+0.197	009.617	+0.197	18 06 14	-20 31 44	IRAS, MSX, HII, smm, mm, Mas, IRDC, bub	1, 2, 3, 6, 7
2	G009.927-0.746	009.927	-0.746	18 10 24	-20 42 54	smm, mm, IRDC, bub	3, 7
3	G294.988-0.539	294.988	-0.539	11 42 10	-62 20 13	...	...
4	G295.103-1.677	295.103	-1.677	11 40 27	-63 27 54	IRAS	10
5	G295.557-1.378	295.557	-1.378	11 45 04	-63 17 46	IRAS, MSX, 2MASX	8
6	G297.533-0.823	297.533	-0.823	12 03 17	-63 11 20	IRDC	7
7	G300.947+0.911	300.947	+0.911	12 34 35	-61 53 46	IRAS, IRDC	7
8	G302.021+0.253	302.021	+0.253	12 43 31	-62 36 18	IRAS, MSX, IRDC	7
9	G302.032-0.061	302.032	-0.061	12 43 32	-62 55 08	IRAS, MSX, HII, mm, Mas, IRDC	3, 7
10	G302.151-0.948	302.151	-0.948	12 44 22	-63 48 32	IRAS, MSX	8
11	G302.390+0.280	302.390	+0.280	12 46 44	-62 35 13	IRAS, IRDC	7
12	G302.487-0.032	302.487	-0.032	12 47 32	-62 54 00	IRAS, IRDC	7
13	G303.405+1.789	303.405	+1.789	12 55 21	-61 04 44	...	...
14	G303.641+1.338	303.641	+1.338	12 57 23	-61 31 34	RNe	...
15	G304.559+0.329	304.559	+0.329	13 05 32	-62 29 53	IRAS, IRDC	7
16	G305.201+0.208	305.201	+0.208	13 11 10	-62 34 37	MSX, HII, mm, Mas, IRDC	3, 6, 7
17	G305.350+0.194	305.350	+0.194	13 12 28	-62 34 44	IRAS, HII, mm, Mas, IRDC, bub	3, 5, 6, 7
18	G305.484+0.224	305.484	+0.224	13 13 36	-62 32 17	MSX, IRDC	7
19	G305.634+1.648	305.634	+1.648	13 13 50	-61 06 22	IRAS	...
20	G305.800-0.250	305.800	-0.250	13 16 44	-62 58 52	IRAS, MSX, HII, mm, Mas, of?, IRDC	3, 4, 7
21	G307.100+0.527	307.100	+0.527	13 27 08	-62 03 22	IRAS, 2MASX	...
22	G307.560-0.587	307.560	-0.587	13 32 31	-63 05 20	IRAS, HII, mm, IRDC	7
23	G307.973-1.595	307.973	-1.595	13 37 42	-64 00 47	IRAS	...
24	G309.221-0.463	309.221	-0.463	13 46 38	-62 39 32	2MASX, IRDC	7
25	G309.909+0.325	309.909	+0.325	13 50 54	-61 44 20	of?, IRDC	4, 7
26	G310.146+0.758	310.146	+0.758	13 52 00	-61 15 47	IRAS, MSX, 2MASX, Mas, of?, IRDC	4, 7
27	G311.177-0.400	311.177	-0.400	14 02 53	-62 07 23	IRAS, IRDC	7
28	G311.426+0.597	311.426	+0.597	14 02 36	-61 05 46	IRAS, HII, 2MASX, IRDC	7
29	G311.639+0.301	311.639	+0.301	14 04 59	-61 19 16	MSX, HII, Mas, IRDC	6, 7, 8
30	G312.597+0.047	312.597	+0.047	14 13 14	-61 16 48	IRAS, MSX, HII, mm, Mas, IRDC	7
31	G313.317-0.463	313.317	-0.463	14 20 18	-61 31 48	IRAS, IRDC	7, 10
32	G313.457+0.194	313.457	+0.194	14 19 35	-60 51 50	MSX, HII, Mas, IRDC	7, 8
33	G313.576-1.154	313.576	-1.154	14 24 23	-62 05 20	IRAS	...
34	G318.051+0.087	318.051	+0.087	14 53 43	-59 08 49	IRAS, MSX, HII, Mas, of?, IRDC	4, 6, 7
35	G318.723-0.752	318.723	-0.752	15 01 27	-59 34 37	IRAS, IRDC	7
36	G318.774-0.151	318.774	-0.151	14 59 34	-59 01 26	IRAS, MSX, HII, mm, IRDC	7
37	G318.915-0.164	318.915	-0.164	15 00 35	-58 58 08	HII, mm, 2MASX, Mas, IRDC	3, 7
38	G321.032-0.484	321.032	-0.484	15 15 53	-58 11 10	MSX, HII, Mas, IRDC	7
39	G323.460-0.079	323.460	-0.079	15 29 20	-56 31 23	IRAS, MSX, HII, mm, Mas, IRDC	7, 8
40	G326.477+0.697	326.477	+0.697	15 43 19	-54 07 26	IRAS, MSX, mm, Mas, of?, IRDC	4, 6, 7, 8, 9
41	G326.783-0.241	326.783	-0.241	15 48 56	-54 40 34	IRAS, Mas, of?	4, 6
42	G326.789-0.553	326.789	-0.553	15 50 19	-54 54 58	IRAS, IRDC, bub	5, 7
43	G326.794+0.381	326.794	+0.381	15 46 21	-54 10 48	IRAS, MSX, of?, IRDC	4, 7
44	G326.878-0.514	326.878	-0.514	15 50 38	-54 49 48	...	...
45	G327.735-0.393	327.735	-0.393	15 54 40	-54 11 38	mm, of?, IRDC	4, 7
46	G327.809-0.632	327.809	-0.632	15 56 07	-54 19 48	IRAS, mm, Mas, IRDC	6, 7, 9
47	G328.958+0.567	328.958	+0.567	15 56 51	-52 40 23	IRAS, MSX, HII, IRDC	7
48	G329.477+0.842	329.477	+0.842	15 58 17	-52 07 41	IRAS, MSX, IRDC	7, 8
49	G330.020+0.917	330.020	+0.917	16 00 38	-51 43 01	IRDC	7
50	G330.033+0.752	330.033	+0.752	16 01 24	-51 50 02	...	...
51	G331.419-0.354	331.419	-0.354	16 12 50	-51 43 26	HII, IRDC	7

Notes. ^(S) Source classification from SIMBAD: IRDC stands for infrared dark cloud, of? for outflow candidate, bub for bubble, Mas for maser, (s)mm for (sub-)millimetre source, 2MASX for 2MASS extended source, RNe for reflection nebula, and DNe for dark nebula.

Notes on individual sources: cluster candidate 2 is 3.1' from cluster candidate 315 in the UKIDSS GPS list by Lucas; cluster candidate 16 is 3.7' from [DBS2003] 131; cluster candidate 17 is 2.9' from cluster VVV CL022; cluster candidate 38 and location of star formation candidate 17 are 1.8' apart; cluster candidate 51 is 2.1' from cluster VVV CL063; cluster candidate 52 and faint nebula 18 are 2.8' apart; cluster candidate 56 is 4.5' from cluster VVV CL064; cluster candidates 56 and 57 are 3.7' apart; cluster candidates 61 and 62 are 2.1' apart; cluster candidate 75 and faint nebula 21 are 2.4' apart; cluster candidates 76 and 77 are 1.3' apart; and cluster candidate 80 and faint nebula 22 are 3.8' apart. Cluster candidates 7, 21, 25, 34, 36, 40, 43, 70, and 88 are included in the list of new embedded clusters by [Morales et al. \(2013\)](#) which appeared in arXiv at the time of submission of this paper.

References. (1) [Hofner & Churchwell \(1996\)](#); (2) [Thompson et al. \(2006\)](#); (3) [Hill et al. \(2005\)](#); (4) [Cyganowski et al. \(2008\)](#); (5) [Churchwell et al. \(2006\)](#); (6) [Harju et al. \(1998\)](#); (7) [Peretto & Fuller \(2009\)](#); (8) [Mottram et al. \(2007\)](#); (9) [Culverhouse et al. \(2011\)](#); (10) [Fontani et al. \(2005\)](#).

Table 1. continued.

No.	ID	l [°]	b [°]	α (J2000) [h m s]	δ (J2000) [° ' "]	Associated sources ^s	References
52	G331.603−0.108	331.603	−0.108	16 12 37	−51 25 08	IRAS, Mas, IRDC	7
53	G331.709+0.603	331.709	+0.603	16 10 01	−50 49 34	MSX, mm, of?	4, 9
54	G332.062+0.508	332.062	+0.508	16 12 04	−50 39 18	IRAS, IRDC, bub	5, 7, 10
55	G332.095−0.421	332.095	−0.421	16 16 17	−51 18 22	MSX,mm,Mas,IRDC	7
56	G332.294−0.096	332.294	−0.096	16 15 46	−50 56 02	IRAS,MSX, HII, mm, Mas, of?, IRDC	4, 7
57	G332.352−0.116	332.352	−0.116	16 16 07	−50 54 29	Mas, of?, IRDC	4, 7
58	G333.029−0.065	333.029	−0.065	16 18 57	−50 24 00	MSX, 2MASX, Mas, IRDC	7
59	G333.163−0.100	333.163	−0.100	16 19 42	−50 19 52	MSX, HII, mm, Mas, of?, IRDC	4, 7, 8
60	G333.315+0.106	333.315	+0.106	16 19 29	−50 04 41	MSX, Mas, of?	4
61	G333.725+0.371	333.725	+0.371	16 20 08	−49 36 04	IRAS, HII, mm, IRDC	7
62	G333.760+0.364	333.760	+0.364	16 20 19	−49 34 55	MSX, IRDC	7
63	G334.332+0.965	334.332	+0.965	16 20 13	−48 45 07	IRAS, HII	...
64	G336.290−1.250	336.290	−1.250	16 38 10	−48 51 47	RNe	...
65	G337.691−0.346	337.691	−0.346	16 39 43	−47 12 58	IRAS, IRDC, bub	5, 7
66	G337.784−0.508	337.784	−0.508	16 40 48	−47 15 14	IRDC	7
67	G338.324−0.408	338.324	−0.408	16 42 27	−46 46 55	of?, IRDC	4, 7
68	G338.851+0.409	338.851	+0.409	16 40 55	−45 50 49	IRAS, IRDC	7
69	G338.919+0.548	338.919	+0.548	16 40 34	−45 42 14	MSX, Mas, of?, IRDC	4, 7, 8
70	G338.926−0.501	338.926	−0.501	16 45 09	−46 23 17	IRAS, IRDC	7
71	G339.191−1.854	339.191	−1.854	16 52 12	−47 03 22	...	...
72	G339.682−1.206	339.682	−1.206	16 51 06	−46 15 54	IRAS, MSX, HII, mm, Mas	8, 9
73	G339.801−1.391	339.801	−1.391	16 52 22	−46 17 28	IRAS	...
74	G340.071+0.927	340.071	+0.927	16 43 16	−44 35 17	IRAS, MSX, IRDC	7, 8
75	G343.724−0.183	343.724	−0.183	17 00 48	−42 28 26	MSX, mm, of?, IRDC	4, 7
76	G343.834−0.106	343.834	−0.106	17 00 51	−42 20 20	HII, IRDC, bub	7
77	G343.855−0.099	343.855	−0.099	17 00 53	−42 19 08	IRAS, HII, IRDC, bub	7, 10
78	G344.874+1.435	344.874	+1.435	16 57 49	−40 34 08	MSX	8
79	G345.119+1.589	345.119	+1.589	16 57 59	−40 16 52	IRAS, Mas	...
80	G345.327+1.020	345.327	+1.020	17 01 00	−40 28 12	IRAS, IRDC	7
81	G345.489+0.316	345.489	+0.316	17 04 28	−40 46 19	IRAS, HII, mm, Mas, IRDC	7, 9
82	G345.590+0.374	345.590	+0.374	17 04 33	−40 39 22	IRDC	7
83	G349.643−1.092	349.643	−1.092	17 23 00	−38 13 48	IRAS, MSX, mm	8
84	G350.011−1.340	350.011	−1.340	17 25 06	−38 03 58	IRAS, mm, Mas	9
85	G350.707+1.026	350.707	+1.026	17 17 20	−36 08 46	bub	9
86	G351.043−0.335	351.043	−0.335	17 23 50	−36 38 49	IRAS, HII, mm, bub	9
87	G352.314−0.442	352.314	−0.442	17 27 48	−35 39 14	IRAS, mm	...
88	G352.488+0.797	352.488	+0.797	17 23 15	−34 48 58	IRAS, MSX, DNe	9

Fig. 1. Galactic distribution of the 88 cluster candidates (filled circles) in Table 1, the 39 star formation location candidates (open circles) in Table 2, and the 26 faint nebulae (crosses) in Table 3. The grey area marks the VVV DR1 coverage in the H or K_s filter.

sources within 2' of the direction of the candidate; and (8) references to selected publications in Table 4.

The distribution of the candidates is shown superposed on the VVV area in Fig. 1. The grey area marks the VVV DR1 coverage in the H or K_s filter. Some areas in the VVV mapping do not contain observations in either filter. These locations are shown blank in Fig. 1. The cluster candidates

(Table 1) are marked with filled circles, the star formation location candidates (Table 2) as open circles, and the faint nebulae (Table 3) as crosses. Most candidates are in the Galactic plane outside the bulge area. Because in the bulge the contamination from the field stars, despite filtering sources fainter than 17 mag, is overwhelming and our method is not able to trap the clusters.

Table 2. List of location of star formation candidates that cannot be verified as clusters.

No.	ID	l [°]	b [°]	α (J2000) [h m s]	δ (J2000) [° ' "]	Associated sources ^S	References
1	G298.903+0.358	298.903	+0.358	12 16 44	−62 14 31	of?, IRDC	4, 7
2	G300.401+0.546	300.401	+0.546	12 29 42	−62 13 08	IRAS, 2MASX	...
3	G300.720+1.200	300.720	+1.200	12 32 50	−61 35 31	IRAS, MSX	8
4	G301.814+0.781	301.814	+0.781	12 41 53	−62 04 12	IRAS	...
5	G303.117−0.971	303.117	−0.971	12 53 07	−63 50 31	IRAS, HII, 2MASX	...
6	G303.346+1.821	303.346	+1.821	12 54 51	−61 02 53	IRAS	...
7	G308.734−0.508	308.734	−0.508	13 42 33	−62 48 11	IRAS	...
8	G309.014+0.208	309.014	+0.208	13 43 42	−62 02 42	IRAS	...
9	G309.999+0.504	309.999	+0.504	13 51 18	−61 32 38	of?, IRDC	4, 7
10	G311.179−0.072	311.179	−0.072	14 02 08	−61 48 22	MSX	8
11	G313.710−0.189	313.710	−0.189	14 22 36	−61 08 17	IRAS, Mas, of?	4
12	G313.763−0.859	313.763	−0.859	14 24 59	−61 44 53	IRAS, MSX, HII, Mas, of?, IRDC	4, 7
13	G313.787−0.251	313.787	−0.251	14 23 23	−61 10 12	MSX, IRDC	7
14	G316.588−0.809	316.588	−0.809	14 46 24	−60 35 46	IRAS, MSX, IRDC	7, 8, 10
15	G319.088+0.460	319.088	+0.460	14 59 29	−58 20 13	IRAS, 2MASX, IRDC	7
16	G320.738−1.700	320.738	−1.700	15 18 55	−59 22 26	DNe	...
17	G321.051−0.507	321.051	−0.507	15 16 05	−58 11 46	MSX, HII, Mas, IRDC	6, 7, 9
18	G326.145+1.071	326.145	+1.071	15 39 58	−54 01 30	IRAS	...
19	G326.270−0.486	326.270	−0.486	15 47 11	−55 11 10	IRAS, of?, IRDC	4, 7
20	G327.118+0.506	327.118	+0.506	15 47 34	−53 52 55	IRAS, MSX, HII, Mas, of?	4, 6
21	G327.131−0.264	327.131	−0.264	15 50 54	−54 28 34	IRAS, Mas, bub	5, 10
22	G327.403+0.445	327.403	+0.445	15 49 19	−53 45 11	IRAS, MSX, HII, mm, Mas, of?, IRDC	4, 6, 7, 9
23	G336.426+1.733	336.426	+1.733	16 40 55	−49 04 55	...	...
24	G336.740−1.300	336.740	−1.300	16 40 13	−48 33 36	...	...
25	G339.887−1.263	339.887	−1.263	16 52 06	−46 08 35	IRAS, MSX, HII, Mas	6
26	G342.958−0.318	342.958	−0.318	16 58 48	−43 09 32	IRAS, IRDC	7
27	G344.904−1.357	344.904	−1.357	17 09 44	−42 14 38	IRAS	...
28	G344.989−0.268	344.989	−0.268	17 05 20	−41 31 23	HII, mm, IRDC	7
29	G345.145−0.217	345.145	−0.217	17 05 37	−41 22 05	IRDC	7
30	G345.853+1.416	345.853	+1.416	17 01 04	−39 48 43	...	...
31	G345.955+0.612	345.955	+0.612	17 04 43	−40 13 16	IRAS, IRDC	7
32	G346.281+0.586	346.281	+0.586	17 05 51	−39 58 41	of?, IRDC, RNe	4, 7
33	G349.145−0.976	349.145	−0.976	17 21 05	−38 34 26	IRAS, of?, IRDC	4, 7
34	G349.187+0.344	349.187	+0.344	17 15 42	−37 46 48	...	...
35	G351.556+0.205	351.556	+0.205	17 23 04	−35 55 08	mm, bub	...
36	G352.630−1.067	352.630	−1.067	17 31 14	−35 44 10	IRAS, MSX, HII, mm, Mas	9
37	G355.031+1.323	355.031	+1.323	17 28 00	−32 24 54	...	...
38	G355.937+0.207	355.937	+0.207	17 34 46	−32 16 08	mm	...
39	G358.385−0.484	358.385	−0.484	17 43 38	−30 33 58	IRAS, MSX, HII, mm, Mas	...

Notes. Notes and references are as in Table 1. Location of star formation candidates 9, 12, 28, and 39 are included in the list of new embedded clusters by Morales et al. (2013) which appeared in arXiv at the time of submission of this paper.

Images in the JHK_s bands of the new cluster candidate areas (sized 4' by 4') are available in electronic form¹. Most of the images show clear signs of reflected light in particular in the K_s band, thus indicating embedded clusters or sites of star formation. Example 2' by 2' K_s -band images of candidates are shown in Figs. 2 and 3. Cluster candidate 85 (Fig. 2 on the left) has so far been identified as a bubble. Cluster candidate 87 (Fig. 2 on the right) has around its location an IRAS source and a millimetre source. Cluster candidate 21 (Fig. 3) has so far been identified as an IRAS source and an extended 2MASS extended source (2MASX). It is also included in the list of new embedded clusters by Morales et al. (2013) which appeared in arXiv at the time of submission of this paper. The cluster area is shown in Fig. 3 on the left as a VVV image and on the right as a 2MASS image. No cluster can be seen in the 2MASS image. Additional example images of cluster candidates including their colour–colour and colour–magnitude diagrams are shown in Appendix A.

Besides the sources in Tables 1–3, the search algorithm found a number of sources that are not clusters and sources that cannot be clearly classified using presently available data. Some of these may be of general interest. The sources IRAS 17340-3757 and IRAS 13428-6232 are two post-AGB stars. Possible zone of avoidance galaxies are 2MASS J16353747-4459364, 2MASS J16361578-4448452, 2MASS J18054356-4130103, and 2MASS J18164114-3816136. Object 2MASS J13065758-6212037 is a bright compact source in the middle of a small dark cloud. The sources are listed in Table 5. Colour images of these sources are shown in Figs. 5 and 6.

5. Discussion

As in Paper I, SIMBAD was used to search for sources within 2' to the candidates in Tables 1–3 and 5 with the following results (the number of sources are given in parenthesis): IRAS point source (89), MSX source (54), (sub)millimetre source (38), maser (42), outflow candidate (31), and HII region (41).

¹ <http://www.helsinki.fi/~osolin/clusters>

Table 3. List of faint nebulae with unknown nature.

No.	ID	l [°]	b [°]	α (J2000) [h m s]	δ (J2000) [° ' "]	Associated sources ^S	References
1	G295.176−0.574	295.176	−0.574	11 43 39	−62 25 16	HII, IRDC	7
2	G295.733+0.386	295.733	+0.386	11 50 17	−61 37 41	...	...
3	G297.253−0.754	297.253	−0.754	12 00 58	−63 04 05	IRAS, 2MASX, IRDC	7
4	G297.658−0.975	297.658	−0.975	12 04 07	−63 21 40	IRAS, HII, Mas, bub	5
5	G299.325−0.308	299.325	−0.308	12 19 37	−62 57 25	IRDC, RNe	7
6	G301.720+1.121	301.720	+1.121	12 41 12	−61 43 37	MSX, mm, 2MASX	8
7	G310.076−0.228	310.076	−0.228	13 53 23	−62 14 13	of?, IRDC	4, 7
8	G310.375−0.298	310.375	−0.298	13 56 01	−62 13 59	IRAS, MSX, of?, IRDC, DNe	4, 7
9	G310.866+0.473	310.866	+0.473	13 58 24	−61 21 47	IRDC	7
10	G312.742−0.716	312.742	−0.716	14 16 26	−61 57 29	IRAS, IRDC	7
11	G314.274+0.096	314.274	+0.096	14 26 08	−60 40 23	MSX, HII, Mas, IRDC	7
12	G317.463−0.398	317.463	−0.398	14 51 18	−59 50 42	of?, IRDC	4, 7
13	G326.466−0.381	326.466	−0.381	15 47 49	−54 58 55	IRAS, MSX, HII, mm, IRDC	7, 8
14	G326.647+0.749	326.647	+0.749	15 44 01	−53 58 44	of?, IRDC	4, 7
15	G326.884−0.104	326.884	−0.104	15 48 53	−54 30 22	IRDC	7
16	G326.933+0.783	326.933	+0.783	15 45 25	−53 46 41	IRAS, IRDC	7
17	G328.336−0.528	328.336	−0.528	15 58 24	−53 54 40	IRDC	7
18	G331.561−0.128	331.561	−0.128	16 12 30	−51 27 43	MSX, HII, mm, Mas, IRDC	7, 8
19	G331.623+0.523	331.623	+0.523	16 09 58	−50 56 35	IRAS, MSX, mm, of?, IRDC	4, 7, 9, 10
20	G339.724−1.120	339.724	−1.120	16 50 52	−46 10 41	IRAS, IRDC	7
21	G343.722−0.224	343.722	−0.224	17 00 59	−42 30 00	IRAS, HII, IRDC	7
22	G345.379+1.056	345.379	+1.056	17 01 02	−40 24 25	IRDC, bub	5, 7
23	G345.713+0.815	345.713	+0.815	17 03 06	−40 17 24	IRAS, MSX, mm, of?, IRDC	4, 7, 9
24	G347.617+0.152	347.617	+0.152	17 11 48	−39 09 54	Mas, IRDC	7
25	G350.692−0.492	350.692	−0.492	17 23 30	−37 01 34	IRAS, MSX, mm, Mas, IRDC, bub	7, 9
26	G351.922+0.642	351.922	+0.642	17 22 19	−35 22 12	IRAS, bub	...

Notes. Faint nebula 24 is 3.3' from cluster [DBS2003] 179. Faint nebulae 1, 5, 11, and 12 are included in the list of new embedded clusters by [Morales et al. \(2013\)](#) which appeared in arXiv at the time of submission of this paper. Notes and references are as in Table 1.

Table 4. List of publications referenced in Tables 1–3.

No.	BibCode	Authors	Description
1	1996A&AS...120..283H	Hofner & Churchwell	Water maser emission of UC HII regions
2	2006A&A...453.1003T	Thompson et al.	SCUBA mm survey of IRAS and UC HII regions
3	2005MNRAS...363..405H	Hill et al.	mm observations of SFRs
4	2008AJ....136.2391C	Cyganowski et al.	MYSO outflow candidates
5	2006ApJ...649..759C	Churchwell et al.	Bubble candidates from GLIMPSE
6	1998A&AS...132..211H	Harju et al.	SiO emission of masers
7	2009A&A...505..405P	Peretto & Fuller	GLIMPSE IRDCs: initial conditions of stellar protocluster formation
8	2007A&A...476.1019M	Mottram et al.	Mid-infrared observations of candidate massive YSOs
9	2011ApJS...195....8C	Culverhouse et al.	A Compact Source Catalog from the QUaD Galactic Plane Survey
10	2005A&A...432..921F	Fontani et al.	Search for massive protostellar candidates

Table 5. Sources that are not clusters, but are of general interest.

No.	ID	l [°]	b [°]	α (J2000) [h m s]	δ (J2000) [° ' "]	Associated sources ^S	References
1	G304.741+0.617	304.741	+0.617	13 06 58	−62 12 00	IRDC	7
2	G309.159−0.593	309.159	−0.593	13 46 21	−62 47 56	IRAS, MSX, 2MASX	...
3	G338.866+1.669	338.866	+1.669	16 35 37	−44 59 38	...	...
4	G339.075+1.708	339.075	+1.708	16 36 16	−44 48 47	...	...
5	G351.085−9.794	351.085	−9.794	18 05 44	−41 30 11	...	...
6	G351.412−3.339	351.412	−3.339	17 37 29	−37 59 20	...	...
7	G354.979−10.189	354.979	−10.189	18 16 41	−38 16 16	...	...

Notes. Notes and references are as in Table 1.

Ninety-eight candidates are seen in the direction of an IRDC which are compact, cold, dense, and massive dark clouds seen in absorption against the high Galactic mid-IR surface brightness. Many IRDCs have no indication of active star formation (e.g. [Pillai et al. 2006](#)). It has been suggested that these clouds are the

cold precursors to high mass star clusters (e.g. [Rathborne et al. 2006](#)). The rest of the IRDCs are associated with typical signs of star formation, e.g. masers, IR, and (sub)mm sources. In this paper some IRDCs are visually classified as star forming regions or faint nebulae.

Fig. 2. Typical VVV K_s -band images of cluster candidates. *Left panel:* cluster candidate 85. *Right panel:* cluster candidate 87. Image size is $2'$ by $2'$ and image orientation north up and east left.

Fig. 3. *Left panel:* VVV K_s -band image. *Right panel:* 2MASS image of cluster candidate 21. Image size is $2'$ by $2'$ and image orientation north up and east left.

Even though the search was made using only VVV stellar data the search located IRDC clouds that were not associated with clustered stars but with the faint nebulae in Table 3. We argue that this surface brightness is not due to dark clouds reflecting the ambient Galactic radiation field but due to embedded star formation. The high dust extinction hides the stars and only a small fraction of the diffuse radiation produced by the star formation process is able to escape. The optical extinction of IRDCs is high even in mid-IR. Because of multiple scattering no scattered Galactic near-IR radiation field is expected (cf. Lehtinen & Mattila 1996; Juvela et al. 2008) and the surface brightness must have a local source; for example objects 21 and 23 in Table 3 are small angular size localised spots seen

in the H and K_s bands. Reflected light from the general ambient Galactic interstellar radiation field would instead cause a broadly distributed surface brightness at the boundaries of the densest region.

As in Paper I, only IRAS point sources with fluxes typical of embedded sources in star forming clouds (a good quality flux rising from 12 microns to 60 or 100 microns) were included, and cirrus-like IRAS point sources were excluded. In most cases more than one of these indicators were seen in the direction of the candidates. Only one cluster candidate (71), one star formation region candidate (23), and two objects (3 and 7) in Table 5 had no entry within $2'$ in the SIMBAD data base.

Fig. 4. Cluster candidate 71. On the left a false colour image produced from VVV J , H , and K_s -band images. Image size is $8'$ by $8'$. Image orientation is north up and east left. In the middle and on the right a colour-colour diagram and a colour-magnitude diagram drawn with 2MASS data within a $8'$ by $8'$ box around the cluster candidate. The red points are within a $0.6'$ by $0.6'$ box around the candidate.

Fig. 5. False colour images produced from VVV J , H , and K_s -band images. Image size is $2'$ by $2'$ in the upper row and $4'$ by $4'$ in the lower image. Image orientation is north up and east left. In the upper row two post-AGB stars: IRAS 13428-6232 and IRAS 17340-3757. Below 2MASS J13065758-6212037 is a bright compact source in the middle of a small dark cloud.

Fig. 6. False colour images of possible zone of avoidance galaxies produced from VVV J , H , and K_s -band images. Image size is $2'$ by $2'$. Image orientation is north up and east left. The sources are (clockwise from upper-left corner) at the locations ($l = 351.085^\circ$, $b = -9.794^\circ$), ($l = 338.866^\circ$, $b = 1.669^\circ$), ($l = 339.075^\circ$, $b = 1.708^\circ$), and ($l = 354.979^\circ$, $b = -10.189^\circ$).

5.1. Notes on individual sources

Cluster candidate 8 has been proposed as a young stellar object candidate (Ramos-Larios et al. 2012). This candidate is also included in a study of embedded structures within IRDCs and other cold, massive molecular clouds (Ragan et al. 2012). Cluster candidates 16, 17, 18, and 20 and cluster [DBS2003] 131 are in the G305 star-forming complex. Cluster candidates 34 and 40 are included in a study of circumstellar environments of MYSOs (Wheelwright et al. 2012). Cluster candidate 50 is dense, but the cluster stars are not reddened.

Cluster candidates 59, 65, and 69 are in the massive star formation complexes studied in Rahman & Murray (2010). Cluster candidate 71 has no associated SIMBAD sources within $5'$. This is a dense clustering of stars. No VVV K_s magnitudes are available for this field in DR1, but the colour–colour diagram using 2MASS data indicates homogeneous visual reddening of ~ 10 mag on the assumption that the cluster stars are early type stars (see Fig. 4). Cluster candidate 81 is $35''$ from cluster [MCM2005b] 88 but seems to be an individual compact cluster. Faint nebula 8 is included in a study of embedded structures within IRDCs and other cold, massive molecular clouds (Ragan et al. 2012).

Faint signs of cluster candidates 17, 43, and 87 can also be seen in 2MASS images, but they have not been listed as clusters in SIMBAD.

Many candidates are located near each other and/or near already known clusters as noted in the comments to Tables 1–3.

6. Conclusions

We have applied the method developed in Paper I for the UKIDSS GPS to the VVV survey. The search using the UKIDSS GPS resulted in 137 previously unknown cluster candidates and 30 previously unknown sites of star formation. The corresponding figures for the VVV are 88 and 39 with an additional 26 faint nebulae of unknown nature. There are many similarities in the results obtained from these two surveys. For both cases only a small percentage of the cluster candidates produced by the automated search turn out not to be data artefacts or false positives. References 1–7 to selected publications in Table 4 are also listed in the equivalent table in Paper I. Specifically, many of the VVV candidate SIMBAD associations are IRDCs. This is not surprising as these clouds are assumed to be the forming sites of massive clusters. Like the UKIDSS cluster candidates in Paper I, the VVV candidates do not form a homogeneous cluster sample, but they vary in both size and stellar number density. In addition to clustered stars (Table 1), the search algorithm is triggered by locations of star formation with only one or only a few stars (Table 2), or even faint dark cloud surface brightness spots (see Table 3). The number of star formation indicators seen in the direction of the candidates, and structures of surface brightness and single stars in both the UKIDSS and VVV images give confidence that most of the candidates are real entities. Like in the UKIDSS search, most VVV cluster candidates and location of star formation candidates are highly concentrated on the Galactic plane. Most of the VVV candidates are in the disk area and only a few in the bulge where our method is not able to handle the contamination from the field stars.

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References

- Bica, E., Dutra, C. M., & Barbuy, B. 2003a, A&A, 397, 177 (BDB2003j)
- Bica, E., Dutra, C. M., Soares, J., & Barbuy, B. 2003b, A&A, 404, 223 (BDS2003j)
- Borissova, J., Bonatto, C., Kurtev, R., et al. 2011, A&A, 532, A131
- Churchwell, E., Povich, M. S., Allen, D., et al. 2006, ApJ, 649, 759
- Cross, N. J. G., Collins, R. S., Mann, R. G., et al. 2012, A&A, 548, A119
- Culverhouse, T., Ade, P., Bock, J., et al. 2011, ApJS, 195, 8
- Cyganowski, C. J., Whitney, B. A., Holden, E., et al. 2008, AJ, 136, 2391
- Dalton, G. B., Caldwell, M., Ward, A. K., et al. 2006, in SPIE Conf. Ser., 6269
- Dempster, A. P., Laird, M. M., & Rubin, D. B. 1977, J. R. Stat. Soc. Ser. B, 39, 1
- Dutra, C. M., & Bica, E. 2000, A&A, 359, L9 (DB2000j)
- Dutra, C. M., Bica, E., Soares, J., & Barbuy, B. 2003, A&A, 400, 533 (DBS2003j)
- Fontani, F., Beltrán, M. T., Brand, J., et al. 2005, A&A, 432, 921
- Froebrich, D., Scholz, A., & Raftery, C. L. 2007, MNRAS, 374, 399
- Hambly, N. C., Collins, R. S., Cross, N. J. G., et al. 2008, MNRAS, 384, 637
- Harju, J., Lehtinen, K., Booth, R. S., & Zinchenko, I. 1998, A&AS, 132, 211
- Hill, T., Burton, M. G., Minier, V., et al. 2005, MNRAS, 363, 405
- Hofner, P., & Churchwell, E. 1996, A&AS, 120, 283
- Irwin, M. J., Lewis, J., Hodgkin, S., et al. 2004, in SPIE Conf. Ser. 5493, eds. P. J. Quinn, & A. Bridger, 411
- Juvela, M., Pelkonen, V.-M., Padoan, P., & Mattila, K. 2008, A&A, 480, 445
- Lehtinen, K., & Mattila, K. 1996, A&A, 309, 570
- Lucas, P. W., Hoare, M. G., Longmore, A., et al. 2008, MNRAS, 391, 136
- Mercer, E. P., Clemens, D. P., Meade, M. R., et al. 2005, ApJ, 635, 560
- Minniti, D., Lucas, P. W., Emerson, J. P., et al. 2010, New Astron., 15, 433
- Morales, E. F. E., Wyrowski, F., Schuller, F., & Menten, K. M. 2013, ApJ, 560, A76
- Mottram, J. C., Hoare, M. G., Lumsden, S. L., et al. 2007, A&A, 476, 1019
- Peretto, N., & Fuller, G. A. 2009, A&A, 505, 405
- Pillai, T., Wyrowski, F., Carey, S. J., & Menten, K. M. 2006, A&A, 450, 569
- Ragan, S., Henning, T., Krause, O., et al. 2012, A&A, 547, A49
- Rahman, M., & Murray, N. 2010, ApJ, 719, 1104
- Ramos-Larios, G., Guerrero, M. A., Suárez, O., Miranda, L. F., & Gómez, J. F. 2012, A&A, 545, A20
- Rathborne, J. M., Jackson, J. M., & Simon, R. 2006, ApJ, 641, 389
- Saito, R. K., Hempel, M., Minniti, D., et al. 2012, A&A, 537, A107
- Schwarz, G. 1978, Ann. Statist., 6, 461
- Solin, O., Ukkonen, E., & Haikala, L. 2012, A&A, 542, A3 (Paper I)
- Stead, J. J., & Hoare, M. G. 2009, MNRAS, 400, 731
- Thompson, M. A., Hatchell, J., Walsh, A. J., MacDonald, G. H., & Millar, T. J. 2006, A&A, 453, 1003
- VSA. 2011, Quality Error Bit Flags, presented at <http://horus.roe.ac.uk/vsa/ppErrBits.html>
- Wheelwright, H. E., de Wit, W. J., Oudmaijer, R. D., et al. 2012, A&A, 540, A89

Appendix A: Examples of cluster candidates

Example cluster candidates are shown in Figs. A.1 and A.2. The different panels in the figures are as follows. On the left 1' by 1' VVV greyscale K_s -band and false colour images of the cluster area. The images are produced using the J , H , and K_s fits files obtained from the VSA. In the K_s band, image sources (both stellar and non-stellar) in the cluster direction brighter than 17^m in K_s are marked with red crosses. All the sources within a 4' by 4' box around the cluster candidate are plotted in the $(H - K, J - H)$ colour–colour and $(H - K, K)$ colour–magnitude plots. The red filled circles mark the same sources as the red crosses in the greyscale image. As in Paper I, the automated search uses by default the *AperMag3* magnitudes ($2.0''$ aperture diameter). For the colour–colour and colour–magnitude plots we also experimented with the *AperMag1* ($1.0''$ aperture diameter) and *AperMag4* ($2.8''$ aperture diameter) extended source magnitudes. The arrow indicates an optical extinction of 5 mag. In the colour–colour plot blue dots mark sources brighter than 17^m and green dots sources fainter than 17^m in K_s . The approximate unreddened main sequence is plotted with a continuous line and approximate main sequence reddening lines are shown with dashed lines. The numbers on the reddening lines show the optical extinction when the star originates from the early or late main sequence. The value of 1.6 for the reddening slope is the mean of all the reddening tracks in Stead & Hoare (2009).

Both example cluster candidates are in crowded fields. As in Paper I, in an effort to get better precision than with *AperMag3* magnitudes ($2.0''$ aperture diameter) we also experimented with the *AperMag1* ($1.0''$ aperture diameter) and *AperMag4* ($2.8''$ aperture diameter) magnitudes. However, the colour plots only show a small variation depending on the magnitudes used.

For both cases all three colour–colour plots indicate infrared excess and all three colour–magnitude plots suggest that the cluster members are of early type.

Appendix B: VVV and GPS catalogue artefacts

Only catalogue artefacts created around bright stars coincide in the GPS and VVV surveys because of the different optics of the

Fig. A.1. Cluster candidate 11. The $1'$ by $1'$ false colour image of the cluster candidate is shown below the greyscale image. Image orientation is north up and east left. All the sources within a $4'$ by $4'$ box around the cluster candidate are plotted in the $(H - K, J - H)$ colour–colour and $(H - K, K)$ colour–magnitude plots. In the colour–colour plot blue dots are sources brighter than 17^m and green dots fainter than 17^m in K_s . The colour–colour and colour–magnitude diagrams, from left to right, are plotted using the *AperMag3*, *AperMag1*, and the *AperMag4* magnitudes, respectively. The red crosses in the $1'$ by $1'$ greyscale image and the red filled circles in the colour plots are sources (both stellar and non-stellar) in the cluster direction brighter than 17^m in K_s .

Fig. A.2. As Fig. A.1 for cluster candidate 5.

UKIRT/WFCAM and VISTA/VIRCAM. The typical artefacts in the GPS survey are the bow-tie, beam, array edge flare, and persistence images (see Sect. A.1 in Paper I). Many of these artefacts either do not exist in the VVV survey or their number is greatly reduced in comparison with the GPS survey. Most importantly, the automatic search algorithm used in this work does not produce as many false positive clusters due to artefacts in the VVV survey catalogue as in the UKIDSS GPS catalogue.

Particularly in the second catalogue the persistence images and array edge flares produce a large number of strong false positive clusters.

B.1. False positive clusters caused by bright stars

The most common catalogue artefact found in this work is that caused by bright stars. The extended halo around the bright stars

Fig. B.1. A false positive cluster caused by the bright $K = 4^m8$ star 2MASS J17565546-2511015. In the *upper row* are the images and plots from UKIDSS and in the *lower row* from VVV. In the *right column* are the zoomed in images of the areas around the bright central star. The red points in the catalogue plots and red crosses in the images are sources brighter than 17^m in K and classified as non-stellar. In the catalogue plots all other catalogue sources are plotted in black. Image orientation is north up and east left. Image size is $4'$ by $4'$ in the *middle column* and $1'$ by $1'$ in the *right column*.

Fig. B.2. A false positive cluster caused by the bright $K = 5^m3$ star 2MASS J18275636-3343355. In the *upper row* are the images and plots from UKIDSS and in the *lower row* from VVV. Image orientation is north up and east left. Image size is $4'$ by $2.7'$. Plot markers (dots and crosses) are as in Fig. B.1.

Fig. B.3. Artefacts caused by the $K = 3^m.2$ star 2MASS J17571476-2408354 and the $K = 4^m.1$ star 2MASS J17571117-2408210. In the *upper row* are the images and plots from UKIDSS and in the *lower row* from VVV. In the UKIDSS image is a persistence image at ($l = 5.420^\circ$, $b = 0.232^\circ$). Image orientation is north up and east left. Image size is $2.5'$ by $2.5'$. Plot markers (dots and crosses) are as in Fig. B.1.

and diffraction spikes cause varying surface brightness which either broadens the image of real stars or produces spatially extended false sources, both of which are classified as non-stellar sources. An example of a false positive cluster caused by a bright star is shown in Fig. B.1. This field is included in the GPS and the VVV surveys. The upper three images, from left to right, in Fig. B.1 show the catalogue plot, catalogue K_s image, and zoom on the bright star in the K_s image, respectively. The field size is $4'$ by $4'$ in the left and centre panels, and $1'$ by $1'$ in the right panel. The objects classified as extended are indicated with a red cross. The corresponding VVV images are shown in the three lower images. The number of visible strong diffraction spikes is lower in the GPS image (eight) than in the VVV image, where they are weaker. The bright star produces more non-stellar classifications in the VVV catalogue than in the GPS catalogue. In the VVV catalogue all of the sources within this area are brighter than 17^m in K but only 85% in the UKIDSS catalogue. Bright stars produce false positive clusters in both the GPS and VVV catalogues. For both catalogues the remedy is to discard non-stellar sources very near 2MASS stars brighter than $K = 10^m$ in K . The brighter the star, the greater the distance to which it produces false classifications (see Appendix A.1 in Paper I).

In Fig. B.2 the bright star produces many more non-stellar classifications in the VVV catalogue than in the UKIDSS catalogue. In the UKIDSS image two more artefacts are visible: a beam across the image and two cross-talk images above and below the bright star. Within this area 68% of the sources are brighter than 17^m in K in the VVV survey catalogue, but only 48% in the UKIDSS catalogue.

In Fig. B.3 the two bright stars produce a hole in the UKIDSS catalogue and a cluster of non-stellar sources in the VVV catalogue. In Fig. B.3 the persistence image artefact of UKIDSS is also presented. Because of differences in the telescope and camera optics and observation procedures in the surveys, artefacts like the persistence image are not expected to happen at the same locations in the two surveys.

Appendix C: Known clusters

The longitude range $-2^\circ < l < 10.4^\circ$ has been surveyed by both the UKIDSS GPS and the VVV surveys which allows us to compare the two data sets (this area is not included in Fig. 1 in Paper I as no cluster candidates were found in this area). A sample of true positive clusters in the fields covered by both surveys are shown in Figs. C.1–C.3. The number of entries in the GPS survey is larger than in the VVV survey, but the fraction of sources brighter than 17^m in K is larger in the latter. Because of the lower background level (the surplus of faint sources in the GPS survey), the true positive clusters trigger the search algorithm used in this work more often.

The clusters [BDS2003] 112 and [BDS2003] 113 are shown in Fig. C.1 and the cluster [DB2000] 26 is shown in C.2. The UKIDSS catalogue has more entries, but the cluster of non-stellar sources is much clearer in the VVV catalogue. The K -band image and false colour images are very similar for UKIDSS and VVV. For the area around clusters [BDS2003] 112 and 113, 98% of the sources are brighter than 17^m in K in the VVV survey catalogue, but only 69% in the UKIDSS catalogue.

Fig. C.1. Clusters [BDS2003] 113 in the centre and [BDS2003] 112 1.1' south-west from the centre. In the *upper row* are the images and plots from UKIDSS and in the *lower row* from VVV. In the *first column* are the catalogue plots, in the *middle column* the corresponding *K*-band image, and in the *right column* false colour images produced from *J*, *H*, and *K*-band images. Image orientation is north up and east left. Image size is 4' by 4'. Plot markers (dots and crosses) are as in Fig. B.1.

Fig. C.2. As Fig. C.1 for cluster [DB2000] 26.

Fig. C.3. Cluster UKS 1751-24.1 in the *first two columns* and cluster [BDB2003] G000.16-00.06 in the *last two columns*. In the *upper row* are the images and plots from UKIDSS and in the *lower row* from VVV. Image orientation is north up and east left. Image size is 4' by 4' for UKS 1751-24.1 and 2' by 2' for [BDB2003] G000.16-00.06. Blue crosses are sources listed in 2MASS but not in UKIDSS or VVV. Other plot markers (dots and crosses) are as in Fig. B.1.

The cluster UKS 1751-24.1 is shown in the first two columns in Fig. C.3 and the cluster [BDB2003] G000.16-00.06 in the last two columns. The globular cluster UKS 1751-24.1 produces a hole in the UKIDSS catalogue and a cluster of non-stellar sources in the VVV catalogue. The cluster [BDB2003] G000.16-00.06 produces a hole in the VVV catalogue, but leaves no

clear traces in the UKIDSS catalogue. Sources listed in 2MASS but not in UKIDSS or VVV are plotted with blue crosses. The 2MASS sources clearly fill the empty spaces in the UKIDSS and VVV survey catalogues. Particularly in the case of UKS 1751-24.1 this bright object produces a fairly large gap in the UKIDSS catalogue.