Overdensity of VVV galaxies behind the Galactic bulge

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ABSTRACT

Context. The extragalactic vision we have through the Milky Way is very unclear. There is significant extinction of the optical emission from objects located in the region called the zone of avoidance (ZOA). NIR wavelengths are less affected by extinction, and therefore the infrared surveys in this zone are a potential source of astronomical discoveries. Nevertheless, these observations need to be compared with cosmological simulations in order to carry out high-accuracy studies.

Aims. Our aim is to identify extragalactic sources in the ZOA, using infrared images of the VVV survey. We consider mock galaxy catalogues in order to interpret observational results.

Methods. We studied a region of 1.636 square degrees corresponding to the VVV tile b204. Using SExtractor, we analysed photometric data generating a catalogue of extended sources in this area. In order to confirm these sources as galaxy candidates we visually inspected RGB images looking for typical galaxy features. Using 2MASX and GCMW catalogued sources we tested completeness and contamination of our catalogue and define suitable colour cuts to select galaxies. We also compared the observational results with those obtained from two semi-analytical models on Dark Matter simulations. One galaxy catalogue was constructed with the Sagittarius dwarf galaxy, and the other one was constructed with the L-Galaxies semi-analytic model.

Results. By adopting CLASS_STAR < 0.5, r12 > 0.7 arcsec and specific colour cuts (J − Ks > 0.97, J − H > 0 and H − Ks > 0) we generated an automatic catalogue of extended sources. After visual inspection we identified 624 sources with 10 < Ks < 17 as galaxy candidates. The contamination of the automatic catalogue is 28% when considering visually confirmed galaxies as reliable objects. The estimated completeness is 87% up to magnitude Ks = 13.5. We analysed the spatial distribution of galaxy candidates, finding a high concentration of galaxies in a small region of 15 arcmin radius. This region has three times higher density than similar areas in the sky. We compared the number of galaxies in this small area with the mean density values obtained from a suitable sample of galaxies from semi-analytic models finding that our results are consistent with an overdensity region.

Conclusions. Using VVV near-infrared data and mock catalogues we detect new extragalactic sources that have not been identified by other catalogues. We demonstrate the potentiality of the VVV survey in finding and studying a large number of galaxy candidates and extragalactic structures obscured by the Milky Way.

Key words. catalogs – Galaxy: bulge – surveys – galaxies: photometry – galaxies: statistics – methods: numerical

1. Introduction

The discovery of new extragalactic astronomical objects is a topic of interest in the mapping of large-scale structures and the distribution of mass in the universe. Therefore, several large astronomical surveys have been developed with the aim being to detect new sources at different wavelengths (e.g., Sloan Digital Sky Survey-SDSS, Blanton et al. 2017; Faint Images of the
hampered and gathering of information is hampered by Galactic absorption. Furthermore, near-infrared (NIR), X-ray and HI radio surveys (Roman et al. 1998; Ebeling et al. 2002; Vauglin et al. 2002; Koribalski et al. 2004; Paturel et al. 2005; Skrutskie et al. 2006; Huchra et al. 2012) have detected galaxies and galaxy clusters at low Galactic latitude.

During the last two decades, enormous efforts have been made to reveal the extragalactic structures behind the ZOA. For example Jarrett et al. (2000a) developed basic algorithms and operations toward detection, identification, characterisation, and extraction of extended sources from the Two Micron All-Sky Survey (2MASS) catalogue. Also, Nagayama et al. (2004) presented deep near-infrared survey with 19 obvious galaxies and 38 galaxy candidates in a $36 \times 36$ arcmin$^2$ region centred on the giant elliptical radio galaxy PKS 1343−601, which was found to be the core of an unknown rich cluster located in the Great Attractor region and Skelton et al. (2009) published a deep $K$-band photometric catalogue with 390 sources (235 galaxies and 155 galaxy candidates) around the core of the rich nearby Norma cluster (ACO3627), in a region of $45 \times 45$ arcmin$^2$.

More recently, using the HI Parkes All-Sky Survey, Staveley-Smith et al. (2016) identified new structures in the Great Attractor region, although there is still a huge area that has not been explored. Moreover, Schröder et al. (2019a) published a catalogue with 170 galaxies located in the northern region of the ZOA, extracted from the shallow version of the blind HI survey with the Effelsberg 100 m radio telescope, EBHIS. These large-scale structures could be part of possible filaments at the edge of the local volume. In addition, Macri et al. (2019) presented redshifts for 1041 2MASS Redshift Survey galaxies that previously lacked this information and updated measurements for another 27.

In particular, the near infrared public survey VISTA Variables in Via Láctea (VVV: Minniti et al. 2010; Saito et al. 2012) has proven to be an excellent tool finding and studying extragalactic sources. Moreover, we use mock catalogues to statistically predict the properties and counts of galaxies to provide an approximate estimate of the total number of galaxies hidden behind the Milky Way, (referred to as background galaxies hereafter) per VVV tile. The results from observations and simulations are compared in order to find overdensity regions in the VVV survey. This research represents a pilot test in a bounded region, such as a tile, with the aim of exploring the efficiency of the method. In the future, this technique could be automated and applied to larger regions of the VVV and VVVX surveys.

This paper is structured as follows: in Sect. 2 we describe the VVV survey. Afterwards, in Sect. 3 we explain the method to obtain the automatic catalogues with software SExtractor and the correspondent procedure used to analyse the VVV images. We present our general results in Sect. 4. The SAMs and construction of a mock background galaxy catalogue and the results obtained from them are described in Sect. 5. In Sect. 6 we discuss the existence of an overdensity region in tile 6204. Finally, we summarise our main conclusions in Sect. 7. The adopted cosmology throughout this paper is $\Omega = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 100\,\text{km s}^{-1}\,\text{Mpc}^{-1}$.

2. The VVV survey

The VVV survey is a NIR ESO (European Southern Observatory) public survey setup to map the Milky Way bulge ($-10^\circ < l < +10^\circ$ and $-10^\circ < b < +5^\circ$) and disk ($-65^\circ < l < -10^\circ$ and $-22.5^\circ < b < +22.5^\circ$) areas close to its centre obtained using the 4.1 m ESO VISTA (Visual and Infrared Survey Telescope for Astronomy; Emerson et al. 2004, 2006; Emerson & Sutherland 2010) telescope, located in the Atacama Desert of northern Chile on Cerro Paranal at 2635 m altitude. VISTA was built by a consortium of 18 universities from the United Kingdom. The telescope is 4 m class with an altitude-azimuth mount, and quasi-Ritchey-Chretien optics. The instrument includes a wide-field corrector lens system, autoguider and active optics sensors. Observations were carried out with the VISTA IR CAmera (VIRCAM), which is composed by 16 Raytheon VIRGO 2048 $\times$2048 HgCdTe on CdZnTe substrate science detectors, with a mean pixel scale of 0.339 arcsec px$^{-1}$ and a field of view per exposure of 0.59 square degrees. The detectors are arranged in a grid with spaces in between detectors of 90% of the detector width in the x-direction and 42.5% in the y-direction. Six exposures are required to make a contiguous area of 1.636 square degrees. The individual exposure is known as a ‘pawprint’ and the final area as a ‘tile’.

The VVV area covers 562 deg$^2$, with 196 tiles needed to map the bulge and 152 tiles for the disk, and is fully imaged in five photometric bands: $Z$, $Y$, $J$, $H$, and $K_s$. Furthermore, the survey has up to 80 multi-epoch $K_s$ observations spread over approximately 7–8 years, for variability and proper motion studies. More details can be found in Minniti et al. (2010) and Saito et al. (2012). The observations were processed within the VISTA Data Flow System (VDFS) pipeline at the Cambridge Astronomical Survey Unit (CASU); Lewis et al. (2010). The VDFS provides object catalogues automatically generated for each target frame with astrometric and photometric calibration information into FITS binary tables. Standard object descriptors are used for morphological object classification, such as aperture flux measurements, intensity-weighted centroid estimates, and shape information including half-light radius and class star parameter.

\footnote{1 http://casu.ast.cam.ac.uk/surveys-projects/vista}
In the present work, we use data from the tile b204 located in the Galactic bulge at \( l = 355.182^\circ \) and \( b = -9.68974^\circ \) (\( \alpha = 273.72^\circ \) and \( \delta = -37.87^\circ \)). This tile was selected because of its position at the edge of the bulge, which implies a low stellar density and also low extinction, relative to the tiles in the center of the bulge and disc, within the VVV survey area. Searching for extragalactic sources in the tile b204 allows us to test a reliable method for galaxy identification in the bulge area of the VVV survey.

In addition, the tile b204 represents a region where 13 galaxies have already been catalogued by 2MASX\(^2\) (Jarrett et al. 2000a) and five galaxy candidates were discovered by Saito et al. (1990)\(^3\). The results obtained from this research can therefore also be compared with a very well-known sample of bright extended sources.

### 3. Source detection

The VVV survey was optimised to detect stars in the Milky Way, but nevertheless the automatic catalogues provide a flag for non-stellar objects (\( CS = \pm 1 \), Saito et al. 2012). For the tile b204 we download CASU catalogues finding that about 70 000 sources have this flag category in \( J \), \( H \), and \( K_S \) bands, and therefore it is expected that this parameter is unreliable for the identification of extended sources as galaxy candidates. In the present work, we create a new catalogue from the VVV images, using SExtractor (Bertin & Arnouts 1996), because it is better suited to treating extended sources. To this end we download \( J \), \( H \), and \( K_S \) images of the tile b204 from CASU.

In this section, we describe the techniques used to identify sources in the observational data from the VVV survey.

#### 3.1. Automatic detection

The SExtractor software was developed to detect, deblend, measure and classify sources from astronomical images. Several steps are followed to identify and separate objects from the background noise, where different parameters should be settled (see Bertin & Arnouts 1996 for more details). Moreover, crowded fields are very common in the VVV sky area and the deblending advantage from SExtractor is a useful feature to analyse overlapping objects.

In order to generate a multi-wavelength catalogue for the analysis, we used SExtractor in double-image mode with the \( K_S \) image as a reference because of its better quality. A \( K_S \) image is used for source detection, and the second, \( H \) or \( J \)-band image for measurements only. It is necessary that all images have identical size and be perfectly aligned. The number of detected sources will not affect their positional or basic shape parameters if we change the \( H \) or \( J \) images. With this procedure it is not necessary to make a correlation between objects of different filters because all of them are in the same position.

In this way, we generated a multi-band catalogue with all detected sources. SExtractor recognised and separated from the background noise all the objects with a threshold more than twice the medium brightness of the sky and spanned over at least ten connected pixels on the VVV images (Coldwell et al. 2014; Baravalle et al. 2018). A filter convolution was applied over the images by SExtractor with the aim being to efficiently separate low-surface-brightness objects from spurious detections. For a proper detection of extended and faint sources we adopt a Gaussian filter, with \( 3 \times 3 \) pixels with a convolution mask of a full width half maximum of three pixels. In addition, for the deblending process we used the default values, because, according to our tests, they allowed the overlapped stars to be efficiently separated from galaxies in this tile.

Following the procedure suggested by CASU, we used the zero point magnitude\(^4\) to calibrate the magnitudes estimated by SExtractor. The output parameters selected from SExtractor catalogues were equatorial coordinates, \( J \), \( H \), and \( K_s \) magnitudes (total and three-pixel-radius circular aperture), and for star-galaxy separation parameters, we used CLASS_STAR and half-light radius (\( r_{\text{1/2}} \)). For the total magnitudes, we used the MAG_AUTO, which is based on Kron’s algorithm (Kron 1980). We calculated the colours with \( J \), \( H \), and \( K_s \) magnitudes in three-pixel radius apertures to compare with colours obtained from CASU (Coldwell et al. 2014).

For the extinction correction we used the procedure described in Gonzalez et al. (2012) adopting the Nishiyama et al. (2009) extinction law because it is in good agreement with the measurements taken from Gonzalez et al. (2012), where \( E(J−H) = 0.671 E(J−K_s) \). This high-resolution extinction map covers the complete region of the VVV survey, in particular the Galactic bulge. The map is available to the community in the web BEAM (Bulge Extinction And Metallicity) calculator\(^5\). This tool provides a lower limit for the mean extinction, \( AK_s \), and the colour excess, \( E(J−K_s) \), for a given set of coordinates and radius of the region.

In Fig. 1 we show the extinction map constructed for the VVV bulge region using the data from Gonzalez et al. (2012). From the extinction maps, the reddening in tile b204 is fairly low and uniform. The average values of the extinction corrections are 0.0051, 0.0028, and 0.0018 mag for \( J \), \( H \), and \( K_s \) filters, reaching maximum values of 0.041 in \( J \), 0.023 in \( H \), and 0.014 in \( K_s \) bands, respectively. This can be seen clearly in the zoom-in of Fig. 1.

\(^{2}\) 2MASXJ18132343−3759580, 2MASXJ18130421−3740314, 2MASXJ18131374−3743504, 2MASXJ18131474−3740354, 2MASXJ18132074−3739236, 2MASXJ18144659−3739470, 2MASXJ18144727−3744140, 2MASXJ18145268−3716080, 2MASXJ18154360−3835824, 2MASXJ18161057−3729587, 2MASXJ18164121−3816133, 2MASXJ18164505−3747263, 2MASXJ18172135−3721158.

\(^{3}\) CGMW4-00457, CGMW4-00298, CGMW4-00340, CGMW4-00408, CGMW4-00415.

\(^{4}\) http://casu.ast.cam.ac.uk/surveys-projects/vista/technical/catalogue-generation

\(^{5}\) https://www.oagonzalez.net/beam-calculator
Subsequently, considering all the mentioned issues, we obtained a total of 309976 sources with SExtractor, including stellar and extended objects. In Sect. 4, we detail the procedure used to classify these sources taking into account the parameters obtained with the software. In order to make our final catalogue more solid, it was indispensable to verify the object classification and generate a visual catalogue. We describe our visual inspection in Sect. 4.2.

### 3.2. Photometric and astrometric comparison

In order to estimate the accuracy of our photometric and astrometric measurements we compared the SExtractor magnitudes and positions with those obtained from CASU using only point sources.

The CASU catalogue provides a stellar classification through a flag indicating the most probable morphological classification. To this end, we downloaded CASU data for tile b204 and constructed a VVV catalogue with stellar information in this region. Then we selected sources, classified as stellar ($\text{CLASS\_STAR} = -1$) that are fainter than $K_s = 12$ to avoid saturated stars and brighter than $K_s = 15$ which corresponds to the completeness limit for this tile.

On the other hand, from the automatic catalogue obtained using SExtractor, we used the $\text{CLASS\_STAR}$ parameter to eliminate all objects with very high likelihood of being extended by adopting $\text{CLASS\_STAR} > 0.8$. Moreover, in order to make a suitable comparison, we applied an aperture correction for the aperture magnitudes of these stellar objects by considering the apcor parameter provided by CASU. To perform the comparison of magnitudes and positions between CASU and SExtractor catalogues, we identified common objects as those within a radius of 2 arcsec.

To estimate magnitude differences, we used the three-pixel radius circular aperture magnitude for each filter in both catalogues. We obtained acceptable agreement between the VVV system and SExtractor magnitudes with an average and standard error of the mean of $\Delta K_s = 0.0071 \pm 0.0005$, $\Delta H = -0.0038 \pm 0.0018$ and $\Delta J = -0.0215 \pm 0.0017$, respectively. These results are shown in Fig. 2.

![Fig. 2. Differences in magnitudes between SExtractor and CASU stellar objects for filters $J$, $H$, and $K_s$ as a function of CASU magnitudes. Dashed lines show 1σ boundaries and the thickness of the coloured line represents the standard error of the mean.](image)

Furthermore, we calculated the difference between SExtractor and CASU coordinates in order to check the position exactitude of our measurements. The SExtractor astrometry shows excellent agreement with the CASU data mean, reaching values of $\Delta \alpha = 1.0 \times 10^{-4}$ and $\Delta \delta = 0.5 \times 10^{-4}$ arcsec.

### 4. Results

#### 4.1. Automatic catalogue of extended sources

In order to derive a catalogue of automatically selected extended sources, we consider different parameters. We used the star classification parameter $\text{CLASS\_STAR}$ given by SExtractor. This parameter takes values of between 0 and 1 where the extended objects, with characteristics typical of galaxies, have values close to 0 and objects with values close to 1 have a high likelihood of being stars. Figure 3 shows the relation between the $\text{CLASS\_STAR}$ parameter and the total $K_s$ magnitude for our dataset; in this figure and the successive ones the magnitudes and colours have been corrected by extinction. For the total magnitudes we used the MAG\_AUTO. The colours were obtained using the circular aperture magnitudes within a diameter of three pixels. Taking into account the presence of two sequences, we removed star-like sources from our catalogue by adopting a conservative limit of $\text{CLASS\_STAR} < 0.5$.  

![Fig. 3. SExtractor stellarity index CLASS\_STAR vs. the total $K_s$ band source magnitude. The circles correspond to galaxy candidates. Galaxies catalogued by other surveys are shown as squares. The colour scale corresponds to number counts (bar on the right).](image)
We also used another classification parameter in order to strengthen the separation between stars and galaxies. This parameter is the half–light radius ($r_{1/2}$), which encloses 50% of the total flux and is a good parameter to complement the classification criteria (Coldwell et al. 2014). Objects with CLASS_STAR = 0 are expected to have values $r_{1/2} > 0.7$ arcsec because they are extended, reaching values of around 8 arcsec. In Fig. 4 we show the half–light radius versus total $K_s$ magnitude for the whole sample of sources detected in the tile $b204$. The points are colour-coded according to the stellarity parameter CLASS_STAR (the bar on the right).

Additionally, we consider different colour cuts to identify galaxy candidates. According to Finlator et al. (2000) objects with $J−K_s < 1$ are probably stellar objects with spectral types later than G5 and earlier than K5. Moreover, Jarrett et al. (2003) found that galaxies with different Hubble morphological types derived from 2MASS show colours with a mean $J−K_s ≈ 1$ and $H−K_s = 0.27$. Taking into account the star-galaxy separation, Lucas et al. (2008) found that the external galaxies form a well-defined region located at $1.5 < J−K < 3.0$, $K > 14$, on the $J−K$ colour-magnitude diagram, based on data from the UKIDSS Galactic plane survey. Furthermore, when these authors included only defined galaxies from visual inspection, they considered a constraint of $J−K > 1.9$. However, these magnitudes and colours have no extinction corrections applied. Recently, Schröder et al. (2019b) presented a homogeneous 2MASS bright galaxy catalogue at low Galactic latitudes ($|b| < 10.0^\circ$) and used an unobscured high-latitude sample to compare the dependence of the extinction correction. The authors found that, although the scatter in the colours is large since they are sensitive to extinction, the mean value is well defined: $(J−K_s) = 0.938 ± 0.002$. Nevertheless, the improved extinction correction changes the mean colour to 0.988 with a standard deviation of ±0.12, which is in good agreement with the high-latitude sample. Baravalle et al. (2018) also define similar colour cuts to separate star from galaxy candidates. In addition, Amôres et al. (2012) and Coldwell et al. (2014) found that objects selected as galaxy candidates from the VVV survey show mainly $J−K_s > 1.0$ colours.

Taking this into consideration, in the present work we considered $J−K_s > 0.97$, $J−H > 0$ and $H−K_s > 0$ to separate galaxy candidates from the stellar locus. These cuts agree well with an intrinsic galaxy colour of $J−K ≈ 1.0$. The colour cuts adopted in this work were chosen to improve the reliability of our catalogue. A detailed description of completeness and contamination analysis can be found in Sect. 4.3.

Using the constraints described above we obtain a final sample of 2439 automatically identified extended sources.

4.2. Visual catalogue of galaxy candidates

Following Amôres et al. (2012), Coldwell et al. (2014) and Baravalle et al. (2018), we carried out a visual inspection in order to verify the automatic detection made with SExtractor. We performed a visual identification of galaxy candidates using Aladin (Bonnarel et al. 2000). We constructed a false-colour RGB image with filters $J$, $H$, and $K_s$. The objects with morphological features and surface brightness corresponding to galaxies were identified as visual galaxy candidates. With this procedure, from the 2439 objects automatically classified as extended sources, 624 could be considered as visual galaxies (hereafter galaxy candidates), with $K_s$ magnitude in the range $10 < K_s < 17$. This is about ±25% of the sample of the automatic extended sources. We show examples of these galaxy candidates in Fig. 5.

Table 1 lists the main parameters of ten galaxy candidates ordered by Right Ascension. The list includes an identification number, sexagesimal equatorial coordinates, three pixel aperture magnitudes, total magnitudes, CLASS_STAR parameter and, half–light radius.

Extinction corrections have not been applied to the listed magnitudes, leaving the choice of the extinction map to the reader. The preferred extinction map can be obtained from different authors, for example Gonzalez et al. (2012) and Schlafly & Finkbeiner (2011)\(^6\). The full table is available at the CDS.

4.3. Completeness and contamination analysis

In order to test the reliability of our methods, we used 13 2MASX and five CGMW galaxies catalogued in our field. We matched the equatorial coordinates of these objects with the sample of automatic extended sources detected by SExtractor, before the colour cut, considering a separation lower than $3 * r_{1/2}$. Because most of the catalogued objects in $b204$ tile are 2MASX galaxies we considered the completeness limit of this sample ($K_s = 13.5$, Jarrett et al. 2000a) and restricted our analysis of completeness and contamination to the magnitude range $10 < K_s < 13.5$. Under these constraints we have 15 catalogued sources (13 2MASX and two CGMW galaxies) to be compared with 76 automatically detected extended objects and 29 visually confirmed galaxy candidates in our field.

Given that the adopted $J−H > 0$ and $H−K_s > 0$ limits are conservative values, the completeness and contamination of

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6. [https://irsa.ipac.caltech.edu/applications/DUST/]
compromise between completeness and contamination adopting 1.0 sources catalogue are 28%, 23%, and 21% for the 0.94, 0.97,ies as reliable objects, the contamination rates of the extended galaxy with $J−K_s$ = 0.94 we include all 2MASX sources, but the contamination of extended sources is 60% and we identify 93% of the catalogued galaxies. For $J−K_s$ < 13.5 and $J−K_s$ < 0.97, finding 29 of these objects associated to bright stars (the bright extended sources in the bottom left region of Fig. 6) and six linked to image artefacts. Only two objects present galaxy features: one is an uncatalogued source with $J−K_s$ < 13.5 and $J−K_s$ = 0.97 the automatic catalogue of extended sources has a contamination of 60% and we identify 93% of the catalogued galaxies. If we adopt a colour cut of $J−K_s$ = 1.0, the contamination of the extended sources catalogue is 60% but completeness drops to 85%. Moreover if now we consider visually confirmed galaxies as reliable objects, the contamination rates of the extended sources catalogue are 28%, 23%, and 21% for the 0.94, 0.97, and 1.0 $J−K_s$ limits, respectively. Therefore, we find a good compromise between completeness and contamination adopting $J−K_s$ = 0.97 (red line in Fig. 6). Moreover, the election of this colour cut in the identification of galaxies using VVV data is reinforced from the Mock analysis (see Sect. 5).

In addition to the above analysis, we visually explored the RGB images of 37 SExtractor extended sources with $10 < K_s < 13.5$ and $J−K_s < 0.97$, finding 29 of these objects associated to bright stars (the bright extended sources in the bottom left region of Fig. 6) and six linked to image artefacts. Only two objects present galaxy features: one is an uncatalogued source with $J−K_s$ = 0.82 and the other is the 2MASX J18131374–3743504 galaxy with $J−K_s$ = 0.94. Therefore, with our colour cuts we lose one 2MASX catalogue source and one extended object that was visually confirmed as a galaxy, and therefore the completeness of our visual catalogue can be estimated as 87% (we identify 14 of 16 galaxies), up to magnitude $K_s = 13.5$.

Given that the reliability of our catalogue grows with visual inspection, it is important to estimate how confident we are that these objects are real galaxies. To this end we explore galaxy images as a function of $K_s$ magnitude. In Fig. 7 (bottom panel) we plot $K_s$ distribution of visually confirmed galaxies and example images with different magnitudes. From this analysis we find that our visual inspection is confident up to magnitude,

Table 1. Galaxy candidates catalogue.

| ID  | RA (J2000) | Dec (J2000) | $K_s$(3) (Aperture) | $H$(3) (Aperture) | $J$(3) (Aperture) | $K_s$ (Total) | $H$ (Total) | $J$ (Total) | CLASS_STAR | $\sigma_{1/2}$ (arcsec) |
|-----|------------|-------------|---------------------|------------------|------------------|--------------|------------|------------|-------------|------------------------|
| 01  | 18:10:50.63 | −38:13:13.4 | 16.43 ± 0.07        | 17.12 ± 0.06     | 17.80 ± 0.04     | 15.23 ± 0.06  | 15.94 ± 0.06 | 17.07 ± 0.04 | 0.05         | 1.95                   |
| 02  | 18:10:54.29 | −38:07:00.7 | 13.90 ± 0.02        | 14.23 ± 0.01     | 14.90 ± 0.01     | 13.17 ± 0.01  | 13.46 ± 0.01 | 14.05 ± 0.01 | 0.05         | 1.21                   |
| 03  | 18:10:55.41 | −38:16:54.6 | 14.19 ± 0.02        | 14.50 ± 0.01     | 15.16 ± 0.01     | 13.45 ± 0.01  | 13.72 ± 0.01 | 14.61 ± 0.01 | 0.03         | 1.22                   |
| 04  | 18:10:59.23 | −38:13:00.8 | 15.88 ± 0.05        | 16.64 ± 0.05     | 17.61 ± 0.04     | 15.57 ± 0.05  | 16.26 ± 0.04 | 16.85 ± 0.03 | 0.07         | 1.21                   |
| 05  | 18:11:12.33 | −38:19:06.7 | 16.19 ± 0.06        | 17.01 ± 0.06     | 17.83 ± 0.04     | 15.80 ± 0.06  | 16.33 ± 0.05 | 17.51 ± 0.04 | 0.16         | 0.85                   |
| 06  | 18:11:13.22 | −38:04:33.4 | 16.65 ± 0.08        | 17.49 ± 0.08     | 18.30 ± 0.06     | 16.28 ± 0.07  | 17.04 ± 0.07 | 17.65 ± 0.05 | 0.01         | 0.89                   |
| 07  | 18:11:13.27 | −38:04:06.0 | 16.27 ± 0.06        | 17.12 ± 0.06     | 17.71 ± 0.04     | 15.93 ± 0.07  | 16.52 ± 0.06 | 16.95 ± 0.04 | 0.13         | 0.85                   |
| 08  | 18:11:14.48 | −38:04:32.5 | 16.13 ± 0.05        | 16.78 ± 0.05     | 17.55 ± 0.03     | 15.92 ± 0.06  | 16.45 ± 0.05 | 16.67 ± 0.04 | 0.44         | 0.71                   |
| 09  | 18:11:14.52 | −37:58:06.5 | 16.00 ± 0.05        | 16.62 ± 0.05     | 17.37 ± 0.03     | 14.71 ± 0.04  | 15.21 ± 0.03 | 16.05 ± 0.02 | 0.01         | 1.84                   |
| 10  | 18:11:18.36 | −38:05:41.2 | 16.29 ± 0.06        | 16.96 ± 0.05     | 17.82 ± 0.04     | 15.74 ± 0.07  | 16.50 ± 0.06 | 17.44 ± 0.04 | 0.04         | 1.00                   |

Notes. The full table is available at the CDS.
Fig. 6. Colour-magnitude diagram ($J-Ks$ vs. $Ks$) of automatically detected extended sources, visually confirmed galaxy candidates, and catalogued sources in our field. The lines in this figure represent the different colour cuts used in the completeness and contamination analysis. The red line corresponds to the adopted limit $J-Ks = 0.97$.

Table 2. Number of objects with $10 < Ks < 13.5$ in the different samples used in the completeness and contamination tests.

| Colour cut | Extended sources | Visually confirmed galaxies | Catalogued galaxies |
|------------|-----------------|-----------------------------|---------------------|
| $J-Ks > 0.94$ | 39              | 28                          | 15                  |
| $J-Ks > 0.97$ | 35              | 27                          | 14                  |
| $J-Ks > 1.0$  | 33              | 26                          | 13                  |
| $J-Ks < 0.97$ | 37              | 2                           | 1                   |

$Ks = 16.2$. It is important to highlight that $90\%$ of visually confirmed galaxies are brighter than this limit.

As a complementary study we calculated the contamination of the automatic catalogue of extended sources before visual inspection. In Fig. 7 (top panel) we plot contamination as a function of increasing $Ks$ total magnitude. From this figure, the contamination can be seen to grow toward fainter magnitudes and is higher than $50\%$ for galaxies with $Ks > 16.2$. Therefore, visual inspection is a crucial step in the identification of galaxies using VVV images.

In addition, we analysed the reliability of the photometry of extended objects depending on the stellar density in the field. The tile analysed in this work is located at the edge of the Galactic bulge, where the stellar density is lower than in the central region. We find no extended sources with a star at $d < 1 + r_1/2$ in the b204 tile. Furthermore, of a total of 624 objects identified as galaxy candidates, only five have a star closer than $d = 3 + r_1/2$. These five objects are also galaxies catalogued by 2MASX.

Subsequently, considering both VVV and 2MASX, we calculated the magnitude differences in $J$, $H$, and $Ks$ filters for these five galaxy candidates following González-Fernández et al. (2018). We obtain good agreement in magnitudes between both catalogues, with an average difference of around 0.13 mag considering $J$, $H$, and $Ks$ filters.

4.4. Galaxy colours

Galaxies and stars have different colour distributions, and therefore we analysed photometric relations of galaxy candidates using the colour-colour and colour-magnitude diagrams.

Figure 8 shows the $J-Ks$ versus $H-Ks$ diagram. A remarkable difference between stellar objects and extended sources is observed, the galaxy candidates being the farthest away from the whole sample. These results are in agreement with those of Amôres et al. (2012) and Coldwell et al. (2014); in both cases, we observe a significant separation of galaxy candidates from the stars sample.

Figure 9 shows the $J-Ks$ colour–magnitude diagram. We observe that the galaxy candidates occupy a particular position consistent with the results from Amôres et al. (2012) and Coldwell et al. (2014). Most galaxies lie above the threshold $J-Ks = 0.97$ with a mean colour of 1.45 and a dispersion...
of 0.23. Galaxies catalogued by other surveys are in general brighter than the remaining galaxy candidates which demonstrates the potential of VVV data to identify fainter extended sources.

5. Mock catalogues

In order to estimate the total number of background galaxies to be found in the VVV bulge region, we constructed mock galaxy catalogues from two different SAMs of galaxy formation: L-Galaxies and SAG.

L-Galaxies (Guo et al. 2011; Henriques et al. 2012) is applied to the dark matter subhaloes identified in the Millennium N-body simulations (Springel et al. 2005; Lemson & Virgo Consortium 2006). Millennium cosmological simulations follows the evolution of $2160^3$ dark matter particles with masses of $8.6 \times 10^8 \ M_\odot$ in a comoving box of $500 \ h^{-1} \ Mpc$ on a side, adopting a flat $\Lambda$CDM cosmological model.

On the other hand, a Semi-Analytic Galaxies (SAG) model has been developed from the version of Springel et al. (2001), and improved as described in Cora (2006), Lagos et al. (2008), Tecce et al. (2010), Orsi et al. (2014), Padilla et al. (2014), Ruiz et al. (2015) and Gargiulo et al. (2015). The catalogue used in this work was constructed applying the latest version of SAG (Cora et al. 2018, 2019; Collacchioni et al. 2018) to the Small MultiDark Planck simulation’ (SMDPL, Klypin et al. 2016). The SMDPL simulation follows the evolution of $3840^3$ dark matter particles within a box of side-length $400 \ h^{-1} \ Mpc$, resulting in a mass resolution of $m_\rho = 9.63 \times 10^7 \ h^{-1} \ M_\odot$ per particle. The cosmological parameters adopted in this simulation correspond to a flat $\Lambda$CDM model consistent with the results of Planck Collaboration XVI (2014). Both semi-analytic galaxy catalogues include SDSS magnitudes, star formation histories, stellar masses of the disk and bulge components, dark matter host halo masses, and galaxy type, among other properties.

To construct the mock catalogues, we first transformed the SDSS magnitudes to 2MASS magnitudes using the relations presented in Bilir et al. (2008), and then from 2MASS to VVV magnitudes with the relations described in González-Fernández et al. (2018). Afterwards, we placed a virtual observer in a corner of the simulation box at $z = 0$ and applied an angular mask of the size of a VVV tile: $1.475 \times 1.109 \degree^2$. For each galaxy, we computed an observational redshift given by

$$z_{\text{obs}} = z_{\text{cos}} + \frac{v_{\text{pec}}}{c}(1 + z_{\text{cos}}),$$

where $z_{\text{cos}}$ is the cosmological redshift computed using the distance between the galaxy and the virtual observer, $v_{\text{pec}}$ is the peculiar velocity of the galaxy in the direction of the line of sight, and $c$ is the speed of light.

Taking into account that our mocks cover a range in redshift up to $z = 0.2$, we applied inverse K-correctors to the apparent magnitudes following the model of Chilingarian et al. (2010). The next step is to compute apparent magnitudes from the absolute magnitudes provided by both SAMs. In addition to the dust extinction models implemented by each SAM to correct their magnitudes, our mock catalogues seek to simulate a very specific region of the sky, where the line of sight points to the Milky Way bulge, and therefore the dust absorption is higher than usual. For this reason, two extinction models were adopted, namely those of Schlafly & Finkbeiner (2011) and Gonzalez et al. (2012), in order to obtain different estimations. In addition, for the sake of consistency, we applied cuts in apparent magnitude $10 < Ks < 17$ and colour $J−Ks > 0.97$, $J−H > 0$ and $H−Ks > 0$ to limit the mock catalogue galaxies to have similar photometric properties to the observational sample of galaxy candidates. We found that more than 95% of the galaxies from the mock catalogues fit in the adopted ranges used to define VVV galaxy candidates.

Due to the fact that our mock catalogues cover a small area in the sky, the cosmic variance must be taken into account. For each simulation, we performed 190 galaxy mocks, changing the line of sight direction, and then applied the angular mask of the VVV. As we do not have spectroscopic information for the galaxy candidates, for each of these mocks, we computed and reported the integrated mean number of galaxies we find up to the redshift limit used to construct the light cones. This procedure allows us to take into account the cosmic variance of the simulations when we consider small volume samples such as the one we used in our analysis.

Figure 10 shows the integrated number of background galaxies per $1.636 \degree^2$ as a function of the light cone redshift limit. As mentioned above, for both simulated catalogues we considered all galaxies with $Ks < 17$ and two bulge extinction maps, as indicated in the key of the figure. In all cases, error bars were computed using the jackknife method. Although the two synthetic galaxy catalogues were built with different SAMs applied on two different numerical cosmological simulations, the results are statistically consistent.

On the other hand, the observed differences, within the error bars, between the two extinction models can be explained from their mean extinctions. For $Ks < 17$ and $Ks < 15$ galaxies, Gonzalez et al. (2012) find an average extinction of 0.23. Galaxies catalogued by other surveys are in general brighter than the remaining galaxy candidates which demonstrates the potential of VVV data to identify fainter extended sources. On the other hand, a Semi-Analytic Galaxies (SAG) model has been developed from the version of Springel et al. (2001), and improved as described in Cora (2006), Lagos et al. (2008), Tecce et al. (2010), Orsi et al. (2014), Padilla et al. (2014), Ruiz et al. (2015) and Gargiulo et al. (2015). The catalogue used in this work was constructed applying the latest version of SAG (Cora et al. 2018, 2019; Collacchioni et al. 2018) to the Small MultiDark Planck simulation’ (SMDPL, Klypin et al. 2016). The SMDPL simulation follows the evolution of $3840^3$ dark matter particles within a box of side-length $400 \ h^{-1} \ Mpc$, resulting in a mass resolution of $m_\rho = 9.63 \times 10^7 \ h^{-1} \ M_\odot$ per particle. The cosmological parameters adopted in this simulation correspond to a flat $\Lambda$CDM model consistent with the results of Planck Collaboration XVI (2014). Both semi-analytic galaxy catalogues include SDSS magnitudes, star formation histories, stellar masses of the disk and bulge components, dark matter host halo masses, and galaxy type, among other properties.

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redshift \( z_{\text{lim}} = 0.10 \) and \( z_{\text{lim}} = 0.20 \), respectively. For the sake of clarity, in Table 3 we also show the integrated average number of galaxies behind the bulge within 1 deg\(^2\).

Furthermore, we performed the counts by directing the line of sight of the mock catalogues towards an overdense region in the simulation in order to estimate the galaxy counts in an area of enhanced density. The values are also reported in Table 3. In addition, even though redshift information is not available for galaxies in our sample, the measured photometric properties of these candidates are consistent with an average redshift within the analysed range, in agreement with the work of Coldwell et al. (2014).

Notably, in this study we found more than 600 galaxy candidates in the \( b204 \) VVV tile, which is clear independent evidence of galaxy overdensity if we consider the expected integrated number of galaxies from the lowest or highest redshift used to build the mock catalogues, that is \( z_{\text{lim}} = 0.10 \) or \( z_{\text{lim}} = 0.20 \), respectively. It is important to note that this finding is consistent with the number of galaxies per 1 deg\(^2\) obtained when the light cones points towards overdense regions (see Table 3). This result may indicate the presence of a galaxy cluster in the \( b204 \) VVV tile.

In order to compare the observational data with those derived from the Mock catalogue, the normalised distributions of \( K_s \) magnitude for the SAMs with the Gonzalez et al. (2012) extinction model and the galaxy candidates at redshift limit \( z = 0.20 \) are plotted in Fig. 11 (the two extinction models show similar behaviour). We find reasonable agreement between the magnitude distributions of both models, although there are differences in the distribution of the observed galaxy candidates. In addition, the average values of \( J - K_s \) for both SAMs (1.43 ± 0.51 and 1.46 ± 0.52 for L-Galaxies and SAG with Gonzalez et al. 2012, respectively) are in good agreement with the observational data supporting the results. The observed discrepancies can be traced back to the choices made in the SAMs (e.g., the stellar population synthesis model used to build up the galaxy luminosity, and the evolution of the properties of galaxies with time, which may be affected by the physical recipes used in these models).

6. Galaxy overdensity

We constructed a density map of visually confirmed galaxies to reveal the distribution of the sources in the plane of the sky (Fig. 12). We find some regions of high concentration. In particular, the zone with major overdensity close to coordinates \( l = 354.66^\circ \) and \( b = -9.85^\circ \) (\( \alpha = 273.6^\circ \) and \( \delta = -38.4^\circ \)) occupies an approximate area with a radius of 15 arcmin (the circle in Fig. 12). This area represents approximately 12% of the tile and contains at least 19% (\( \approx 118 \)) of the visual galaxies in our catalogue.

In order to validate this finding, we calculated the number of galaxies in 20 random circular regions of 15 arcmin radius within the tile. On average, each one of these random regions contains only 6.7% (\( \approx 42 \)) of the galaxy candidates. This result shows that the region of major overdensity is approximately three times denser than the randomly selected areas, confirming that this latter region contains a genuine overdensity of galaxies.

We also explored the distribution of 2MASX galaxies from Jarrett et al. (2000a) and galaxy groups from Tempel et al. (2018) around tile \( b204 \) (Fig. 13). The sample of galaxies is complete up to magnitude \( K_s = 13.5 \) and galaxy groups are detected from the 2MRS data set described in Huchra et al. (2012), which includes galaxies brighter than \( K_s = 11.75 \). We find in Fig. 13 that number counts of 2MASX galaxies seem to increase towards higher Galactic latitudes, finding more galaxies at \( b < -10^\circ \). This is in agreement with results from Jarrett et al. (2000b), who found a 30%–50% decline in source counts for Galactic latitudes between 5 and 12\(^\circ\), as a consequence of an increment in stellar density that affects the identification of extragalactic objects. Only two galaxy groups are catalogued in the area studied, both with only two galaxy members and none of them associated with the overdensity described above.

On the other hand, Amôres et al. (2012) catalogued 214 new galaxy candidates in a tile area near the Galactic plane using the VVV data in the disk tile \( d003 \) centred at \( l = 298.356^\circ \) and \( b = -1.650^\circ \) where the extinction is also relatively low and uniform, reaching a mean value of \( A_{K_s} = 0.549 \), in agreement with the expected one by Millennium simulations used in their analysis. These latter authors identified 72 objects as Type I sources (possible galaxies) and 142 as Type II (likely galaxies). In addition, Coldwell et al. (2014) examined the VVV \( b261 \) tile centred at \( l = 356.597^\circ \) and \( b = -5.321^\circ \) with NIR photometry of VVV survey data. The mean values of extinction were \( A_J = 0.26 \), \( A_H = 0.14 \), and \( A_{K_s} = 0.09 \). The authors detected at least fifteen galaxies in the central area (350 kpc from the X-ray peak emission) of the X-ray–detected galaxy cluster \( \text{A146} \) (\( J2000 \)).

In a recent study, Baravalle et al. (2018) studied two disk tiles, \( d010 \) centred at \( l = 308.569^\circ \) and \( b = -1.650^\circ \) and \( d115 \) centred at \( l = 295.438^\circ \) and \( b = 1.627^\circ \). The obtained median \( A_{K_s} \) values were 0.86 ± 0.32 and 0.42 ± 0.08 for the \( d010 \) and \( d115 \) tiles, respectively. The authors found 345 and 185 extragalactic candidates in \( d010 \) and \( d115 \), respectively, making a total of 530 sources detected with the VVV survey in two regions of the disk.

With the present study, we reveal more than 600 galaxy candidates, a higher number than in previous works. Nevertheless the extinction for \( b204 \) tile is lower than for the disk tiles \( d003 \), \( d010 \), and \( d115 \), and therefore galaxy number counts in \( b204 \) could be similar to the disk ones at comparable extinction levels. However, it is worth noting that we identify a high concentration of galaxies in a small region of 15 arcmin radius with three times higher density than the remaining area, even though the whole tile has a uniform extinction. Also, galaxy number counts
are approximately three times the amount estimated by our mock catalogues for a mean background region despite the fact that the star density is much higher in a bulge tile than in a disk tile which may be detrimentally affecting our search for galaxies. Furthermore, the density in tile b204 is consistent with the mock counts calculated by directing the line of sight towards an overdense region in the simulation. Therefore, we speculate on the existence of an overdensity of galaxies, considering this finding as a possible cluster.

7. Summary

The Milky Way represents an obstacle for observations at optical wavelength of extragalactic sources. For this reason clear information about the galaxies and large extragalactic structures in this region is lacking. To obtain information for this area, we used the VVV survey data and analysed the tile b204 located in the central region of the Milky Way.

We setup an automatic detection procedure using the software SExtractor. In this way, we generated a multi-band catalogue with stellar and extragalactic sources. This sample was calibrated with the CASU catalogue in order to improve photometric and astrometric precision. This step was carried out using bright but non-saturated stars.

In order to obtain a catalogue of automatically selected extended sources we used the star classification parameter, CLASS_STAR, and the half-light radius, r₁/₂, given by SExtractor. In this sense we considered objects with CLASS_STAR < 0.5 and r₁/₂ > 0.7 arcsec as likely extended. In addition, to separate galaxy candidates from the stellar locus we selected objects with Ks > 10 and considered specific colour cuts (J−Ks > 0.97, J−H > 0 and H−Ks > 0), following previous works (Amôres et al. 2012; Coldwell et al. 2014; Baravalle et al. 2018). We also performed a visual inspection in false-colour RGB images constructed from filters J, H, and Ks. We select as visual galaxy candidates those objects showing morphological features and surface brightness corresponding to galaxies. Following this procedure, we obtained 624 galaxy candidates behind the Galactic bulge.

### Table 3. Integrated number of galaxies per 1 deg² for different redshift limits toward the mean and overdense line-of-sight directions.

|               | L-Galaxies with Gonzalez et al. (2012) | L-Galaxies with Schlafly & Finkbeiner (2011) | SAG with Gonzalez et al. (2012) | SAG with Schlafly & Finkbeiner (2011) |
|---------------|----------------------------------------|---------------------------------------------|---------------------------------|---------------------------------------|
| z             | Mean background region                  | Mean background region                      | Mean background region          | Mean background region                |
|               | Overdense region                        | Overdense region                            | Overdense region                | Overdense region                      |
| 0.10          | 34.5 ± 1.8                             | 33.2 ± 1.8                                  | 37.2 ± 2.2                     | 34.9 ± 2.2                            |
| 0.12          | 50.5 ± 2.3                             | 48.8 ± 2.4                                  | 49.8 ± 2.9                     | 46.3 ± 2.8                            |
| 0.14          | 66.6 ± 3.4                             | 65.0 ± 3.5                                  | 67.6 ± 3.4                     | 63.7 ± 3.6                            |
| 0.16          | 78.8 ± 3.4                             | 76.1 ± 3.5                                  | 77.6 ± 3.2                     | 72.1 ± 3.4                            |
| 0.18          | 92.6 ± 4.3                             | 88.3 ± 4.4                                  | 88.4 ± 4.0                     | 82.7 ± 4.2                            |
| 0.20          | 105.3 ± 4.8                            | 101.5 ± 4.8                                 | 101.3 ± 4.4                    | 94.8 ± 4.6                            |

Fig. 11. Normalised distributions of Ks magnitude of galaxy candidates in tile b204 (blue dashed line), compared with those from L-Galaxies and SAG with the Gonzalez et al. (2012) extinction model (continuous lines of orange and green colours, respectively).

Fig. 12. Density map of visually confirmed galaxies. Filled contours are colour-coded according to number counts in pixels of 4 arcmin×4 arcmin. Dots indicate the positions of the 30% brightest galaxies (dot sizes are weighted according size is proportional to Ks magnitude). The dashed circle, of 15 arcmin radius is centred at the position of the overdense region in the tile.
In total, we find 624 extended sources (including 607 new galaxy candidates that have been catalogued for the first time and 17 galaxies catalogued by other surveys). In addition, we did not identify any X-ray or radio sources in this region. Moreover, our study is the first of its kind to cover the bulge region, whereby a systematic search for extragalactic sources was performed using the VVV survey. We wish to highlight the fact that the methods used in this work are a starting point in the development of techniques devoted to identifying extragalactic sources, such as galaxies, groups, and clusters, in the bulge area mapped by the VVV survey. Also, in future works we will use the VVVX survey (Minniti 2016), which will cover a larger area (three times that of the VVV), making it possible to search for more structures behind the bulge.

It is worth noting that by using the VVV NIR images, we were able to detect new extragalactic sources that have not been detected with other surveys. Moreover, we implemented mock catalogues to statistically define an overdensity region probably corresponding to a galaxy system like a group or galaxy cluster. Therefore, this paper and previous works demonstrate the potentiality of the VVV survey to find and study a large number of galaxy candidates and extragalactic structures obscured by the Milky Way.

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