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The VISTA Variables in the Vía Láctea eXtended (VVVX) ESO public survey: Completion of the observations and legacy*

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ABSTRACT

Context. The ESO public survey VISTA Variables in the Vía Láctea (VVV) surveyed the inner Galactic bulge and the adjacent southern Galactic disk from 2009–2015. Upon its conclusion, the complementary VVV eXtended (VVVX) survey has expanded both the temporal as well as spatial coverage of the original VVV area, widening it from 562 to 1700 sq. deg., as well as providing additional epochs in JHK_s filters from 2016–2023.

Aims. With the completion of VVVX observations during the first semester of 2023, we present here the observing strategy, a description of data quality and access, and the legacy of VVVX.

Methods. VVVX took ~2000 h, covering about 4% of the sky in the bulge and southern disk. VVVX covered most of the gaps left between the VVV and the VISTA Hemisphere Survey (VHS) areas and extended the VVV time baseline in the obscured regions affected by high extinction and hence hidden from optical observations.

Results. VVVX provides a deep JHK_s catalogue of $\gtrsim 1.5 \times 10^9$ point sources, as well as a K_s band catalogue of $\sim 10^7$ variable sources. Within the existing VVV area, we produced a $5D$ map of the surveyed region by combining positions, distances, and proper motions of well-understood distance indicators such as red clump stars, RR Lyrae, and Cepheid variables.

Conclusions. In March 2023 we successfully finished the VVVX survey observations that started in 2016, an accomplishment for ESO Paranal Observatory upon 4200 h of observations for VVV+VVVX. The VVV+VVVX catalogues complement those from the *Gaia* mission at low Galactic latitudes and provide spectroscopic targets for the forthcoming ESO high-multiplex spectrographs MOONS and 4MOST.

Key words. surveys – Galaxy: bulge – Galaxy: disk – Galaxy: stellar content – infrared: stars

* Based on observations taken within the ESO VISTA Public Survey VVV and VVVX, Programmes ID 179.B-2002 and 198.B-2004, respectively.

1. Introduction

Despite large-scale optical surveys over many decades, the internal structure of the inner regions of the Milky Way (MW) and the details of its formation and evolution were poorly understood. The main reason is the severe and non-uniform interstellar extinction and crowding towards the MW bulge and inner disk, which complicates observations, especially at the optical wavelengths. These inner regions are the most complex of our Galaxy to study, with a mixture of stellar populations from the inner disk, bulge, and halo, which exhibit a variety of physical properties.

This situation has improved in recent years, with several projects studying the inner regions of the MW (e.g. Barbuy, Chiappini, & Gerhard 2018; Saviane et al. 2020, and references therein). The VISTA Variables in the Vía Láctea (VVV) survey (Minniti et al. 2010) was designed to resolve the 3D structure of the MW by searching, precisely parameterising, and studying the distributions of known distance indicators such as RR Lyrae, Cepheids, and red clump stars in the inner Galaxy. By using observations at near-infrared wavelengths, VVV observations minimise the problems of extinction and crowding. Among many results, the VVV data have enabled the construction of high-resolution extinction and photometric metallicity maps (e.g. Gonzalez et al. 2012, 2013), the discovery of stellar clusters (e.g. Borissova et al. 2014), and the production of 3D spatial structure maps based on red clump and RR Lyrae stars (e.g. Dékány et al. 2013; Wegg & Gerhard 2013).

In 2016, the VVV eXtended (VVVX) survey started operating. The VVVX survey was designed to ensure the long-term legacy of the VVV survey, characterising the structure and time domain properties of the inner Galaxy. The project is one of seven large public surveys (Arnaboldi et al. 2019) commissioned by the European Southern Observatory (ESO). The VVV+VVVX surveys were awarded about 4200 h of observing time over a timespan of ~ 13 years at the 4-metre Visible and Infrared Survey Telescope for Astronomy (VISTA; Emerson, McPherson, & Sutherland 2006) telescope at ESO Paranal Observatory, and were finally completed in March 2023, before the VISTA InfraRed CAMera (VIRCAM; Dalton et al. 2006; Emerson & Sutherland 2010) instrument was decommissioned from the VISTA telescope. Both surveys combined cover the Galactic bulge, as well as the adjacent disk towards the Galactic quadrants I and IV.

The VVV survey pioneered the discovery of variable stars, transients, and a select number of new clusters across a significant region around the Galactic centre and plane. VVVX bridges the gap between VVV findings and other surveys, extending into obscured regions. This aids in estimating survey completeness and mapping distributions of various tracers from the halo to the Galactic centre. The VVVX survey was designed to connect the VVV survey area with the VISTA Hemisphere Survey (VHS; McMahon et al. 2013) and the UKIDSS Galactic Plane Survey (Lucas et al. 2008). VVVX overlaps with the VST Photometric Hα Survey (VPHAS+; Drew et al. 2014) and the DECam Plane Survey (DECaPS; Schlafly et al. 2018), providing complementary near-IR imaging for those regions (see Fig. 1) as well as variability information. In addition, by re-observing the area of the original VVV, VVVX extends both the time baseline as well as reaches fainter flux limits, complementing other public optical and far-IR surveys. In particular, the mapped regions are located between Galactic longitudes $l = -130$ degrees and $l = +20$ degrees, detecting $\gtrsim 1.5 \times 10^9$ point sources in an area of around 1,700 square degrees, including more than 50 known globular clusters and 1,000 open clusters. The specific goals of the VVVX survey stated in the original proposal are:

- To map the structure of the optically obscured populations in position and velocity.
- To find pulsating variable stars (RR Lyrae, Classical Cepheids, Type 2 Cepheids, Miras) as distance indicators probing the 3D structure of the inner MW.
- To physically characterise known and newly detected star clusters (open star clusters as well as globular clusters), measuring their distances, extinctions, reddenings, sizes, and estimating their metallicities and ages.
- To explore the stellar populations and variable stars of the Sagittarius dwarf galaxy located beyond the Galactic bulge.
- To find rare variable sources such as transients and WIT ('What Is This?') objects, and also to identify the near-IR counterparts of benchmark high-energy sources discovered by recent X-ray missions.
- To build a catalogue with the classification of dwarf stars beyond the peak of the luminosity function and their companions.
- To detect heretoforth unknown background galaxies and QSOs in the Galactic Zone of Avoidance (ZoA).
- To probe the Galactic structure close to the Galactic centre using near-IR microlensing.

VVVX observations provide essential input targets for spectroscopic surveys based on multiplexing spectrographs such as the SDSS-IV/V (Sloan Digital Sky Survey-IV/V; Blanton et al. 2017; Kollmeier et al. 2019), the Galactic 4MOST surveys (4-metre Multi-Object Spectroscopic Telescope; de Jong et al. 2019)[1] and MOONS Galactic survey (Multi-Object Optical and Near-infrared Spectrograph; Gonzalez et al. 2020). In addition, our database complements measurements from important current and future space missions such as the *Hubble* Space Telescope (HST), *Gaia*, *James Webb* Space Telescope (JWST), *Euclid*, and *Nancy Grace Roman* Space Telescope.

There is a variety of final products, including deep JHK_s images, multi-band JHK_s and multi-epoch K_s band time series catalogues, and proper motions for $\gtrsim$1.5 billion sources. Moreover, VVVX catalogues millions of variable stars, extend the VVV extinction and reddening maps, and increase the completeness and source density maps, thus presenting a treasure trove for the whole astronomical community. The VVVX public database will offer the possibility to explore a wide variety of scientific objectives, from those we listed previously to new ones, including serendipitous discoveries.

Due to its larger survey area VVVX provides a more complete picture of the inner MW than its predecessor VVV: a deep bulge map to establish structure differences between the oldest and younger populations, a map of the Sagittarius dwarf from its core across the whole bulge, and a much more extended disk map that probes star formation (SF) activity, disk stellar populations, and spiral arms structure. VVVX provides a public multicolour time domain database within the optically hidden MW regions, including 3D extinction maps that trace the non-stellar baryonic matter. Additionally, the VVVX survey provides observational constraints for the present-day MW structure as presently known (e.g., thin and thick disk structure, number of spiral arms and their locations), and even more importantly, provides insights into the assembly history of the MW.

The aim of this article is to describe the VVVX survey design, observations, data processing, and final status of

[1] https://www.4most.eu/cms/science/galactic-community-surveys/

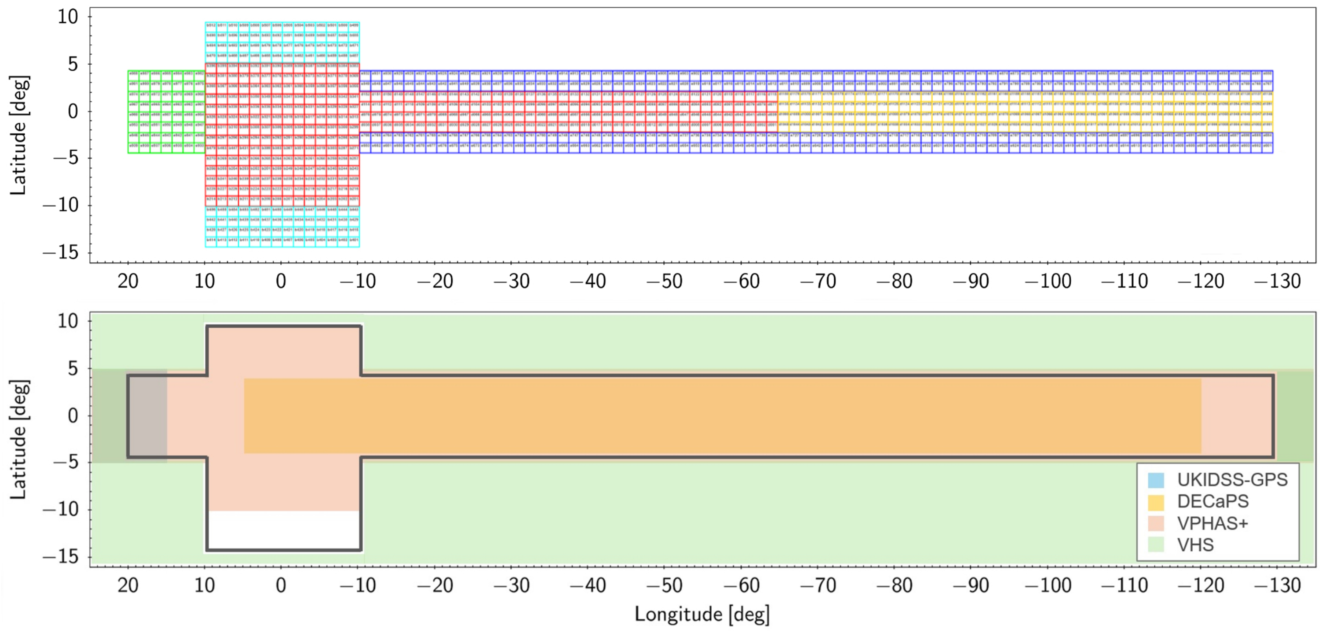

Fig. 1. VVV+VVVX survey coverage of the MW bulge and southern plane. Top: the surveyed area shown Galactic coordinates. Our near-IR survey covers ~1700 sq. deg. in total, and the different regions are colour-coded according to the location, baseline, and number of observations (see Sect. 4). In red is the original VVV Bulge and VVV Disk, with observations from years 2010 and 2016 using the $ZYJHK_s$ filters, and VVVX observations between years 2016 and 2022 using the JHK_s filters. Other colours mark the VVVX areas, observed with JHK_s filters between years 2016 to 2022. Yellow is the Disk to Longitude +230, dark blue is the Low and High Extended Disk, green is the Disk to Longitude +20, and in light blue is the Low and High Extended Bulge. A zoomed view of the image with the tile names is presented in Appendix A. Bottom: Schematic representation of the areal coverage compared with the other selected complementary surveys mentioned in Sect. 1.

the VVVX survey, emphasising the observation strategy and describing the observed data available to the astronomical community through the VISTA Science Archive (VSA) and ESO Science Archive. We also describe some usage examples of VVVX data within the MW and beyond. In the ESO Science Archive the VVV and VVVX data are published in the data collections identified by `doi.eso.org/10.18727/archive/67` and `doi.eso.org/10.18727/archive/68`.

2. Telescope and instrument

The VVVX observations were carried out with Visible and Infrared Survey Telescope for Astronomy (VISTA), an ESO telescope located at the Cerro Paranal Observatory in the Atacama Desert, northern Chile. For all VISTA photometric surveys, the VIRCAM camera was used (Dalton et al. 2006; Emerson & Sutherland 2010). VIRCAM was equipped with sixteen 2048 × 2048 science detectors, arranged in a 4 × 4 array, with a large spacing of 90% and 42.5% of the detector size along the X and Y axes. Each individual detector covered ~694 × 694 arcsec^2 on the sky, with 0.″339 average pixel scale. Its filter wheel was equipped with five broad-band filters (Z, Y, J, H, and K_s) and two narrow-band filters centred at 0.98 and 1.18 μm. For the VVVX observations only JHK_s were used. Table 1 shows the centre wavelengths of each filter.

In all VIRCAM observations, each pointing of the telescope is a so-called a pawprint, which covers 0.59 sq. deg. and provides partial, coverage of the field of view. By combining six pawprint exposures with appropriate offsets, the contiguous coverage of a field is achieved with at least two exposures on separate pixels, except at the edges. That is called a tile and covers a field of view of 1.109 × 1.475 = 1.646 sq. deg., the largest unvignetted field of view in the near-IR regime on 4-m class telescopes.

Table 1. VISTA filters used in the VVVX observations.

Filter	$\lambda_{\rm eff}$(μm)	A_X/A_V	$A_X/E(B-V)$
J	1.254	0.280	0.866
H	1.646	0.184	0.567
K_s	2.149	0.118	0.364

Notes. The effective wavelengths for the three VISTA filters used in the VVVX observations are shown along with the relative extinction for each filter based on the Cardelli et al. (1989) extinction law (from Catelan et al. 2011).

In 2023, VIRCAM was decommissioned and will subsequently be replaced by the fibre-fed spectrograph 4MOST (de Jong et al. 2019). In fact, various 4MOST surveys will collect complementary spectroscopic data to VVV and VVVX. For details about the telescope and instrument, we refer the interested reader to Sutherland et al. (2015) and the VIRCAM instrument web-pages[2], and the VISTA/VIRCAM user manual (Ivanov et al. 2021).

3. Survey area

The VVV survey observed ~562 sq deg in the MW bulge and the adjacent southern Galactic plane. The area was divided in bulge, with ~300 sq. deg. within $-10.0° \lesssim l \lesssim +10.4°$ and $-10.3° \lesssim b \lesssim +5.1°$, hereafter called 'VVV Bulge', and ~220 sq. deg. within $294.7° \lesssim l \lesssim 350°$ and $-2.25° \lesssim b \lesssim +2.25°$, hereafter 'VVV Disk' (see Fig. 1). For the VVV Disk there is a total of 38 × 4 = 152 tiles while the VVV Bulge is filled up by

[2] `https://www.eso.org/sci/facilities/paranal/decommissioned/vircam.html`

$14 \times 14 = 196$ tiles. The tile sides are aligned with the Galactic coordinates for coverage optimisation.

The VVVX survey expanded the area of the original VVV footprint in both Galactic longitude and latitude, with an area of ~480 deg^2 in the Galactic bulge plus ~1170 deg^2 in the inner plane (including the original VVV), from $l = -130$ deg to $l = +20$ deg (7 h <RA< 19 h). For contiguous observations of large areas, the covering process was carried out using the 'Survey Area Definition Tool' (SADT[3]), which maximises the efficiency of VISTA observations by minimising the number of tiles needed to cover a given area, providing the tile centres and the guide and active optics stars necessary for the execution of the survey Observing Blocks (OBs). The new areas – with their respective tiles – were labelled as following:

- Low extended disk (disk-low, for short): area with the lowest latitudes along the disk, located within $+230° \lesssim l \lesssim +350°$ and $-4.5° \lesssim b \lesssim -2.25°$, totalling ~266 sq. deg. To cover the area, $83 \times 2 = 166$ tiles were needed, with the tile names ranging from e0601 to e0766.
- High Extended Disk (Disk-high): symmetrical area to the Low Extended Disk at higher latitudes, $+230° \lesssim l \lesssim +350°$ and $+2.25° \lesssim b \lesssim +4.5°$, comprising ~ 266 sq. deg. Tile names range from e0767 to e0932.
- Disk to longitude +20 (Disk20): extended the disk coverage to the north within $+10° < l < +20°$ and $|b| \lesssim 4.50°$. A total of $7 \times 8 = 56$ tiles were used to fill the area of ~90 sq. deg. The area has ~ 90 sq. deg. Tile names in this region are e0933 to e0988.
- Disk to longitude +230 (Disk230): extended area to the southern disk coverage within $+230° < l < +295°$ and $|b| \lesssim 2.25°$. This is the largest new area, with ~292 sq. deg. A total of $45 \times 4 = 180$ tiles are in this region and labelled from d1001 to d1180.
- Low extended bulge (bulge-low): extended the bulge area within $-15° < b < -10°$ and $|l| \lesssim 10°$ with ~ 90 sq. deg. in size. There is a total of $14 \times 4 = 56$ tiles, labelled from b0401 to b0456.
- High Extended bulge (bulge-high): extended the bulge within $+5° < b < +10°$ and $|l| \lesssim 10°$. The area has also ~90 sq. deg. A total of $14 \times 4 = 56$ tiles filled the area and are named from b0457 to b0512.

The VVVX footprint along with the VVV original coverage is shown in Fig. 1, along with a comparison with other complementary surveys, while the list of the tile names with the central coordinates are presented in Appendix A (first ten rows) and in electronic form[4]. Both VVV and VVVX have a total of 1028 tiles. There are no tiles with names d0153–d0200, b0397–b0400, b0513–b0600 and d0989–d1000. The absence of tile numbers is attributed to the naming conventions, which are based on the regions covered by the tiles. The new VVVX areas added up to ~2000 h of observations, split between ~450 h for JHK_s and ~1550 h for the multi-epoch K_s.

4. Observing strategy

The VVVX survey was carried out in service mode, which is the standard for all VISTA observations. The observational blocks (OBs) were prepared by the VVVX team using the P2PP/P2 tools[5] and sent to ESO for validation and observation at the site.

Table 2. Total exposure time for the VVVX observations.

Filter	DIT (s)	NDIT	Njitter	Exposure time per pixel (s)
J	10	3	2	120
H	6	2	2	48
K_s	4	1	2	16

Notes. For each OB the DIT is the detector integration time, NDIT is the number of the detector integration time, and Njitter is the number of offsets executed at each of the six pawprint positions. Njitter=2 applies for most of the tile area. Due to the tiling process, for a small fraction of ~8% of the tiles, the Njitter varies from Njitter=1 (at the edges) to Njitter=3, 4 or 6 (in the regions where the pawprints overlap). For details about the tile areas covered for each Njitter value, see Fig. 20 in VISTA/VIRCAM user manual (Ivanov et al. 2021).

Observing blocks for each tile were defined for: a single K_s band observation (used in the variability campaign), multicolour JHK_s observations (in a quasi-simultaneous schema: ~10 min for the sequence $H \rightarrow K_s \rightarrow J$), and additional J band observations to be combined for the multicolour observations. Due to scheduling constraints the multicolour observations had to be split into two separate observing blocks, including JHK_s and J band observations, respectively. We note that depending on the region, between 2 and 8 adjacent tiles were combined in a concatenation and observed back-to-back. Minimum concatenation of 2 tiles was necessary to achieve a satisfactory background sky subtraction, and at the same time it reduced observational overheads.

All observations were carried out using a 2-point dither due to the variable and high sky background in the near-IR and to enable cosmic rays rejection and pixel defect correction. As a consequence, the total time per OB for an individual source (e.g., star) and filter is: DIT (detector integration time) × NDIT (number of detector integration time) × Njitter=2 (number of offsets executed at each of the six pawprint positions) × Npaw=6 (number of pawprints that together make a tile). These OB setups lead to a total time on the source in each OB of 120 s (J), 48 s (H) and 16 s (K_s), as presented in Table 2.

The number of epochs observed during the VVVX campaign in each of the new areas ranged between 23 and 50 epochs (see Appendix A). In the original VVV region, typically 3–12 new epochs were acquired by the VVVX campaign, except in the inner Galactic bulge, where in a few tiles up to 100 additional epochs have been secured. In the region around the Baade's window, eight tiles covering ~13 sq. deg. in the VVV bulge reached up to 352 epochs, summing up the VVV and VVVX variability campaigns. Figure 2 shows the number of epochs observed for each tile while Fig. 3 illustrates the cadences for the K_s band variability campaign across the original VVV bulge area. Due to our flexible observing strategy, the observational sequence for all tiles is different, and the ranges of time separations between observations are also variable from tile to tile. Therefore, for variability studies, we recommend that each tile should be treated separately, as, for example, aliasing in the periods are tile dependent.

[3] https://www.eso.org/sci/observing/phase2/SMGuidelines/SADT.html

[4] The full table with the tile names and the central coordinates is available at https://zenodo.org/records/12587535

[5] https://www.eso.org/sci/observing/phase2/p2intro.html

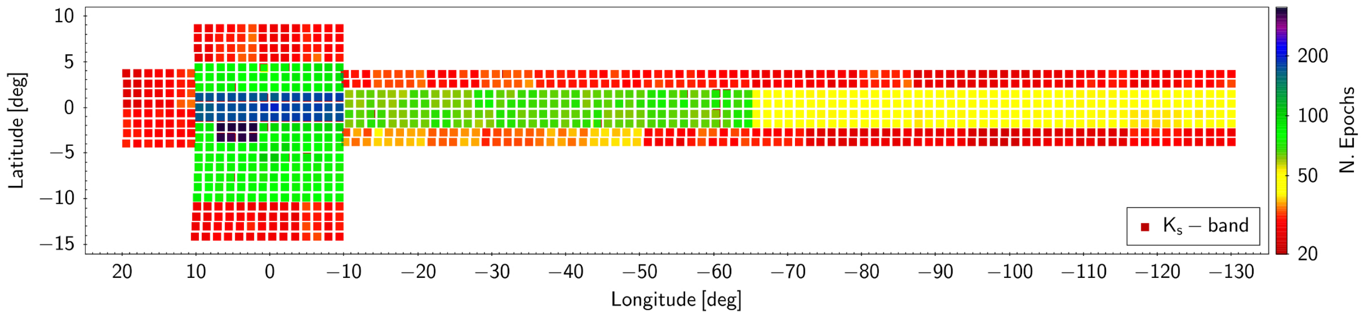

Fig. 2. Number of epochs in the K_s band observed by VVV+VVVX. The mean baseline for the original area is ~12 yr, with up 352 epochs for selected tiles in the inner bulge. For the outer bulge and disk the number of epochs are in the range 23–106 for the VVVX observations solely, varying according with the observational strategy.

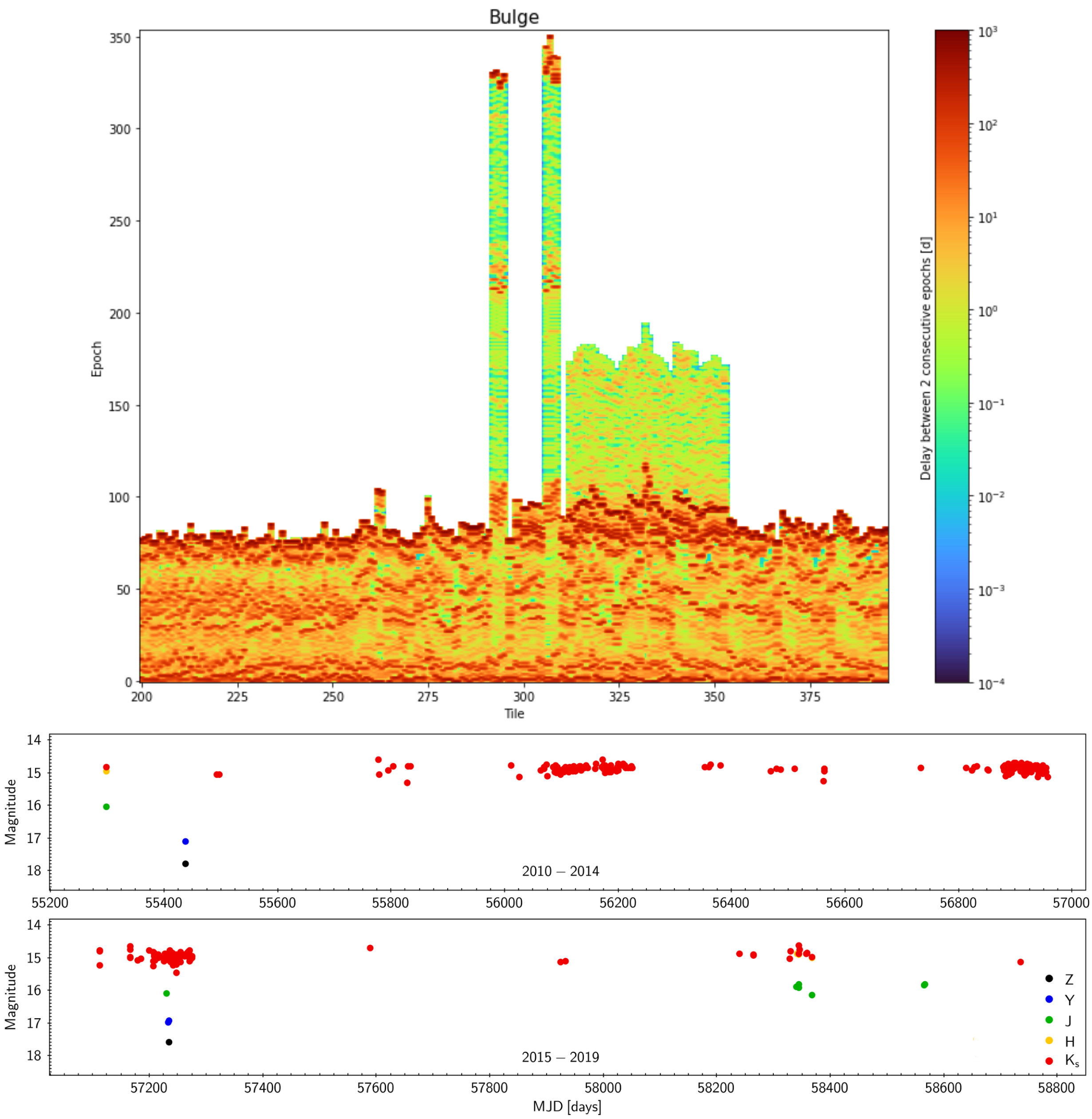

Fig. 3. Cadence of the VVV+VVVX bulge observations. Top: density plot showing the cadence of the bulge observations in both VVV and VVVX campaigns. Bottom: light curve example for the source VVV-VIVACE ID 533558 (K_s ~ 14.9 mag; Molnar et al. 2022), observed by VVV+VVVX in the five VISTA broad band filters in the bulge field b307. There are a total of 363 observations in the five filters along years 2010 to 2019. The coordinates for the target are RA, Dec (J2000) = 18:00:11.48, −28:25:13 (corresponding to l, b = 2.0688, −2.4904 deg.).