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The VISTA Star Formation Atlas (VISIONS)

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VISIONS is a public survey that explores five nearby star-forming molecular cloud complexes. The observing programme finished in March 2022, after collecting more than one million individual images in the near-infrared passbands *J*, *H*, and K_S over a period of five years. VISIONS aims to provide a comprehensive legacy archive similar to the Two Micron All Sky Survey. In addition, multi-epoch observations facilitate proper motion measurements for sources inaccessible to Gaia. VISIONS addresses science cases related to the identification of young stars, their 3D motions, the evolution of embedded star clusters, and the characteristics of interstellar dust.

Scientific context

Stars form deep within cold, filamentary molecular cloud complexes whose dust content shrouds young stars from observation at visible wavelengths. As a consequence, ESO facilities in particular continue to play a pivotal role in deepening our understanding of this intricate process, offering as they do large-aperture telescopes together with state-of-the-art instrumentation capable of high-resolution infrared imaging. The star formation sites in the solar neighbourhood have been popular targets for observational studies since they provide the only environment where the star formation process can be physically resolved, thereby enabling the study of individual sources.

VISIONS[1,a] (Meingast et al., 2023a,b) is a Cycle 2 Public Survey with the Visible and Infrared Survey Telescope for Astronomy (VISTA), which closely follows in the footsteps of a previous ESO observing programme, the Vienna Survey in Orion (Meingast et al., 2016; programme ID 090.C-0797A). The primary goal of these earlier observations was to characterise the young stellar object (YSO) population and the characteristics of dust in the Orion A molecular cloud. VISIONS substantially expands this pilot programme, as regards both the scientific context and the number of observed star formation sites.

VISIONS targets a total of five nearby star-forming complexes in the near-infrared (NIR) wavelength regime, using the VISTA telescope and the now decommissioned infrared camera VIRCAM[2] (Emerson, McPherson & Sutherland, 2006). Together, these sites harbour thousands of YSOs (see, for example, Evans et al., 2009; Dunham et al., 2015; Großschedl et al., 2019) which are themselves embedded in more than a hundred thousand solar masses of molecular gas and dust (see, for example, André et al., 2010; Lombardi, Alves & Lada, 2011; Alves, Lombardi & Lada, 2014). The targeted star-forming regions inherit their names from the constellations against which they are projected on the sky: Chamaeleon, Corona Australis, Lupus, Ophiuchus, and Orion. Figure 1 displays four *RGB* images assembled from the NIR VISIONS data. These examples showcase the Lupus III molecular cloud (top left), the spectacular infrared sources IRAS 11051-7706 (top right) and HH 909 A (bottom left) in Chamaeleon, and the Coronet cluster (bottom right), which is embedded in the Corona Australis molecular cloud complex[b].


ESO/Meingast et al. 2023a

Figure 1. Colour images assembled from VISIONS observations in the near-infrared bands *J* (blue channel), *H* (green channel), and K_S (red channel). The top left panel displays the Lupus III molecular cloud. At the top right, the infrared source IRAS 11051-7706 is visible. HH 909 A in the bottom left features a remarkable, cone-shaped reflection cavity. The bottom right depicts the Coronet cluster in the Corona Australis star-forming complex where it illuminates parts of the surrounding gas and dust.

The primary goal of VISIONS is to establish a NIR legacy archive, similar in structure and content to the Two Micron All Sky Survey (2MASS; Skrutskie et al., 2006). Particularly, the increased sensitivity limits (~ 6 magnitudes fainter than 2MASS), the sub-arcsecond resolution, and the provided absolute astrometry at the milli-arcsecond level make VISIONS a valuable foundation for future observations conducted at ESO. In particular, ESO's Extremely Large Telescope will also benefit from the survey for photometric and astrometric cross-calibration and for target selection purposes.

A key aspect of the survey relates to its design, that enables the proper motions of deeply embedded young stars to be measured, as well as sources with sub-stellar masses in the vicinity of the observed regions. VISIONS is therefore highly complementary to the Gaia mission (Gaia Collaboration et al., 2016), which has already proven to be instrumental in our understanding of local star-forming processes and the shape of the interstellar medium on large scales (see, for example, Zucker et al., 2022 and references therein). Yet, owing to the nature of Gaia's optical observations, the 3D dynamics of the most deeply embedded sources, which are still dynamically coupled to their natal molecular cloud, as well as of the low-mass stellar field population, remain largely unexplored as of today.

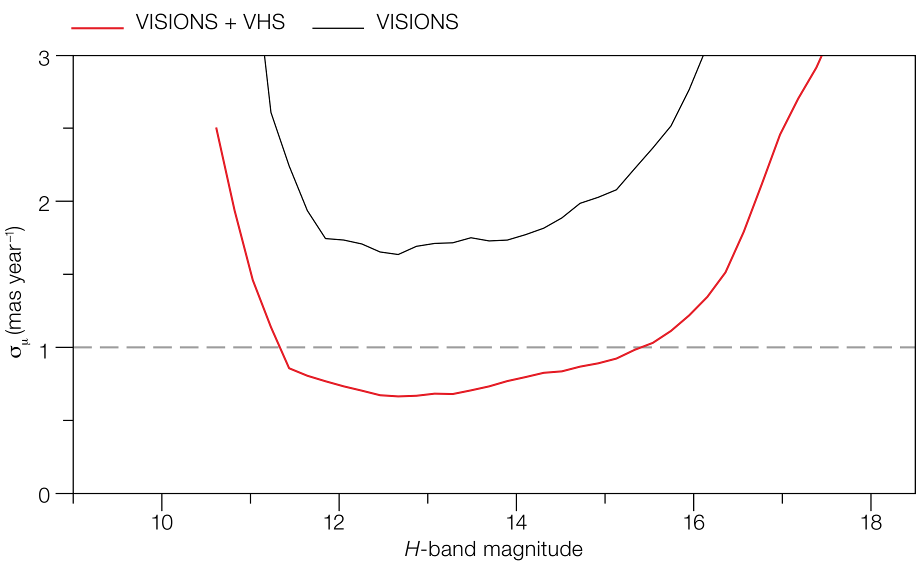
As regards the difficulty of making ground-based proper motion measurements, VISIONS was designed to be complementary to the VISTA Hemisphere Survey (VHS; McMahon et al., 2013), a previous-generation VISTA Public Survey which covers the entire southern hemisphere. Given that VHS observations began in 2009, for some areas VISIONS has access to a time baseline of more than 10 years. Based on previous experience (for example, Bouy et al., 2013), VISIONS was designed to reach a proper motion measurement precision on the order of 1 mas yr^{-1} for bright sources (H < 16 mag), corresponding to a physical velocity of 0.5 km s^{-1} at a distance of 100 pc. Based on VISIONS data obtained for a 1.5 × 1 degree large field in the Corona Australis region, Figure 2 shows the measured preliminary proper motion accuracy as a function of H-band magnitude. Results for about 30 000 sources are shown for both VISIONS data alone and the combination of VISIONS and VHS data. For a robust estimation of errors, the ordinate in this figure displays the standard deviation of the difference between VISIONS and Gaia proper motions, for sources detected in both surveys. The figure not only reveals that using VHS data is crucial to the accuracy of the proper motion measurements, but also that in this experiment VISIONS delivers proper motions with errors below 1 mas yr^{-1} only in an H-band magnitude range from about 11 mag to 16 mag. The cutoff at the bright end is a consequence of saturation, while the faint limit is given by the single-exposure sensitivity limit. In future we expect to reach similar precision for proper motions of fainter stars when using stacked image data. We note here that the used VHS data were reprocessed with the VISIONS pipeline for a much improved astrometric solution.

Another central pillar of the VISIONS science goals is related to the identification and characterisation of YSOs. The excellent quality of the optical system, that together with the excellent observing conditions at Paranal delivers images at sub-arcsecond resolution, permits the meticulous investigation of YSO morphology. In particular, light scattered off nebulae surrounding YSOs can be a useful tool for confirming their protostellar nature. Moreover, high-velocity jets and outflows, which are characteristic of early YSO evolutionary stages, are also accessible through the high-quality NIR imaging data.

Furthermore, with VISIONS it becomes possible to explore cluster formation processes and properties of the initial mass function. The survey's ability to detect young sources with masses of only a few M_{Jupiter} allows for a robust sampling of all star formation products, also enabling a study of regional variations in the mass function at the lowest substellar mass ranges. Furthermore, the interplay between localised feedback effects and the production of low-mass stars, and connection between the maximum stellar mass and the cluster size can be investigated.

Another integral aspect of the VISIONS scientific objectives addresses the dust content of the observed molecular clouds. In this regard, the high-sensitivity NIR observations of the VISIONS programme enable a comprehensive census of the background field population and consequently

Figure 2. VISIONS proper motion performance as a function of H-band magnitude. The performance metric σ_μ is calculated as the standard deviation of the difference between Gaia proper motions and VISIONS measurements, which were obtained from single (unstacked) exposures. The black line depicts σ_μ when calculated only from VISIONS data. The red line shows the performance when VHS data, which significantly extends the time baseline, are included. The cutoff at the bright end is due to saturation, the faint end is limited by the signal-to-noise ratio.



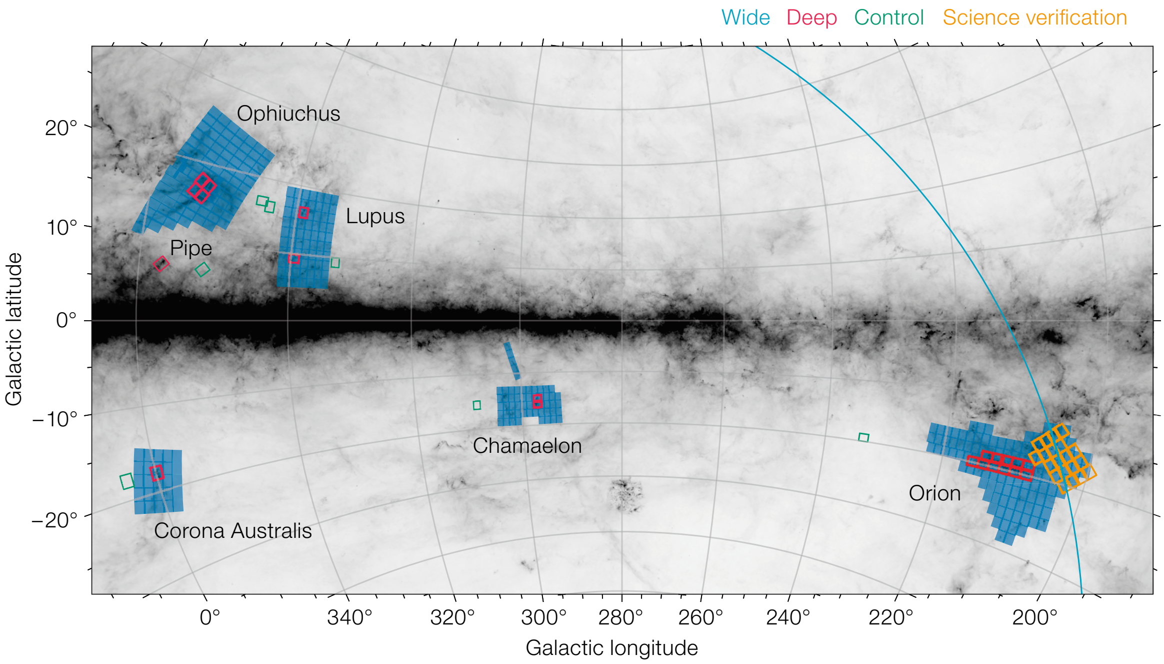


Figure 3. Spatial coverage of VISIONS. The filled blue boxes represent individual VIRCAM tiles in the wide subsurvey. These were revisited a total of six times over the course of the survey. The red boxes depict the pointings in the deep subsurvey, which includes high-sensitivity observations of the regions with the highest column-densities. The green boxes mark the control subsurvey which targeted areas with minimal dust extinction for statistical comparisons. Figure adapted from Meingast et al. (2023a)

the construction of high-resolution extinction maps using well-established methods (for example, Lombardi & Alves, 2001). These maps will enable an unbiased and well-sampled view of the clouds' core mass functions for comparison with their stellar counterparts. The maps will also help with investigating properties of dense cores, establishing a connection between dense cores and YSOs, and mapping their spatial distribution within clouds. In this context, VISIONS also aims to examine the universality of the NIR reddening law and the dust properties of the molecular clouds. The targeted regions are particularly well suited for this task, since they are largely isolated and found well outside the Galactic plane where multiple cloud complexes overlap along the line of sight. Combining the extinction data with emission maps obtained by the Herschel and Planck missions will also allow the ratio of the submillimetre dust opacity to the NIR extinction coefficient to be studied.

Survey overview

VISIONS observations include five prominent star-forming molecular cloud complexes that are situated within a distance of 500 pc (for example, Zucker et al., 2020). The observations were carried out between April 2017 and March 2022, acquiring more than 19 TB of raw data comprising more than a million individual images. The total covered area measures more than 650 deg^2 with a total on-sky exposure time of about 50 hours in the NIR passbands J (1.25 μm), H (1.65 μm), and K_S (2.15 μm).

The spatial coverage of the VISIONS survey is globally divided into three complementary subsurveys, referred to as wide, deep and control. Figure 3 displays the VISIONS coverage, separated into the subsurveys, on top of Planck 857-GHz data (Planck Collaboration et al., 2011). The figure shows the survey setup for the wide programme in blue, deep observations in red, and control data in green. In addition, the Orion B VISTA science verification data, captured in 2009, are shown in orange (Petr-Gotzens et al., 2011).

The wide subsurvey comprises the bulk of the VISIONS observing programme and covers the star-forming complexes on scales of several degrees. This part of the programme was executed six times during the survey in order to provide multiple epochs so as to facilitate measurements of stellar proper motions. Owing to its large extent, the observations were designed to be carried out swiftly with an effective on-sky exposure time of one minute. Additionally, all observations within the wide subsurvey were carried out in the H band. In this way, these data are complementary to the J- and K_S-band VHS observations. The 5-sigma sensitivity limit for these data was determined to be about 20 mag, albeit with a relatively large spread of about 0.5 mag, depending on atmospheric conditions during the observations.

The deep subsurvey includes observations in the J, H and K_S bands and targets areas with the highest column densities within the star-forming regions. This subsurvey utilises long exposure times to reach a sensitivity limit that is similar to that of the Orion A observations published by Meingast et al. (2016). The covered area amounts to about 36 deg^2 which is substantially smaller than for the wide observations. Moreover, to limit the execution time of the observation blocks, each deep field pointing was observed twice for a total exposure time of 10 minutes. These observations typically reach sensitivity limits six magnitudes fainter than 2MASS, or about 21.5 mag, 21 mag, and 19.5 mag in J, H and K_S, respectively.

Finally, the control subsurvey was designed to map regions with minimal dust extinction, collecting data on unextincted stellar field populations for statistical comparisons to the other observations in VISIONS. The individual field pointings were selected to collect data at the same galactic latitudes as the deep observations for each region, albeit shifted in galactic longitude to map largely extinction-free areas. With a coverage of only about 16 deg^2, the control observations comprise the smallest part of VISIONS.

Data processing and data releases

All data acquired within the VISIONS programme are processed with an optimised pipeline package that was specifically developed for the requirements of this survey. Details of the pipeline are given by Meingast et al. (2023b). Here we provide only an abbreviated overview of all procedures involved, particularly highlighting the performance with respect to image quality, photometry and astrometry. The pipeline itself is implemented in Python and relies heavily on vectorised computations for the required performance and on open source software, where, foremost, the AstrOmatic software tools are employed for source detection and extraction, computation of astrometric solutions, and optimised image stacking (Bertin & Arnouts, 1996; Bertin 2010a,b). The package is publicly available on GitHub[3] and can be easily accessed in a virtual environment provided by a Docker image[4].

The pipeline is designed to work out of the box with raw data downloaded from the ESO Science Archive[5]. It also generates its own calibration frames and tables, including bad pixel masks, dark frames, flat fields, non-linearity coefficients, gain and read-noise tables, weight maps, and illumination corrections. Furthermore, Gaia DR3 (Gaia Collaboration et al., 2021) and 2MASS serve as astrometric and photometric references, respectively. The science frames undergo a series of processing steps which largely remove the instrumental signature and employ a sophisticated multi-step background subtraction routine. In comparison to VIRCAM data products processed by other pipeline environments (for example those provided by the Cambridge Astronomical Survey Unit[6] [CASU]), we identify three major differences in our workflow.

Firstly, we employ a sophisticated resampling algorithm that uses Lanczos kernels, in contrast to bilinear interpolation, as employed by the CASU workflow. This leads to an improved resolution in the stacked data products where our methods typically produce 20% narrower point-source FWHMs.

Secondly, the astrometric solution is computed against an adaptive reference catalogue, generated from the Gaia DR3 database. Before cross-correlating sources detected on the VIRCAM images with the Gaia reference catalogue, our approach warps the reference frame to the epoch of the observations, a method that has only recently become possible thanks to the superb astrometric data quality provided by Gaia. In this way, our image products are not calibrated against a specific mean epoch given by the reference catalogue (for example, approximately J2000 for 2MASS, or J2016.0 for Gaia DR3). Instead, the VISIONS source position epochs correspond to the actual date of the observations. This not only enables a much more robust and precise astrometric calibration, but also offers the possibility of considering our position measurements absolute. Figure 4 visualises this characteristic, which shows the difference between source positions (right ascension and declination) measured on the (fully calibrated) Corona Australis control field and Gaia DR3. While Gaia DR3 positions refer to epoch J2016.0, VISIONS recorded these specific data at epoch J2018.36. This difference of about two years becomes evident in the offset of the shown distribution, which does not centre on the origin in this graph, but instead aligns well with the offset expected from the mean proper motion of this field (marked as dashed lines). Moreover, the standard deviation of this distribution is on the order of 10 milliarcseconds for all sources (and about 3 milliarcseconds for bright sources), highlighting the extraordinary performance of VISIONS astrometry.

Thirdly, because of the slightly different filter systems, VIRCAM measurements typically require a colour transformation to obtain photometry compatible with the 2MASS system (for example, Coccato, Freudling & Retzlaff, 2021). In contrast, our pipeline is principally designed to calibrate all photometric data against the 2MASS source catalogue and also produces only negligible residual colour terms (see Figure 8 of Meingast et al., 2023b).

So far, the VISIONS team has produced two major data releases. Data Release 1[7] includes only the deep and control field data for the Ophiuchus field. Data Release 2[8] features an already substantially larger data volume and was published in March 2022. This latest release includes all observed data in the three subsurveys related to the Corona Australis complex. All data (images and source catalogues) are available through the ESO Science Archive Facility. Details of the contents of these releases are available in the respective release documentation.

Outlook

The majority of the VISIONS observations have yet to be published. At the time of

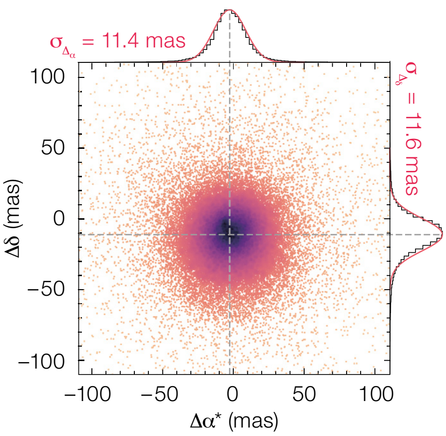


Figure 4. Comparison of source coordinates as determined by VISIONS and the Gaia DR3 catalogue for the Corona Australis control field. The axes represent the differences in right ascension (y-axis) and declination (x-axis) between the two datasets. All astrometric solutions for VISIONS were calculated against a Gaia frame (J2016.0) adjusted to the epoch of the VISIONS observation (J2018.36). Consequently, the distribution is not centred on the origin, but aligns with the expected mean shift, marked by grey dashed lines. The black histograms at the top and on the right of the plot align well with a Gaussian distribution (highlighted in red) that has a mean at the anticipated shift and a standard deviation that matches the statistical error as reported during the astrometric calibration. Figure adapted from Meingast et al. (2023b)

writing the VISIONS team is simultaneously working on future data releases, as well as testing proper motion measurements. Specifically, the team plans to publish all data for each star-forming region in separate data releases, with Data Release 3 focusing on the Chamaeleon observations. The order of subsequent publications is currently set by the expected data volume, i.e., Lupus will follow Chamaeleon (DR4), followed by Ophiuchus (DR5), and lastly the Orion data will be made public (DR6). In addition, the VISIONS team plans to reprocess the Orion A and B fields obtained by Meingast et al. (2016) and the VISTA Science verification efforts. Furthermore, in addition to the data releases through the ESO archive, we plan to reformat all source catalogues to match the 2MASS convention (with similar quality flags, for example), reprocess VHS observations with the VISIONS pipeline, and publish a band-merged catalogue via CDS[9].

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Links

1 VISIONS homepage: http://visions.univie.ac.at
2 VIRCAM webpage: https://www.eso.org/sci/facilities/paranal/instruments/vircam.html
3 Pipeline GitHub repository: https://github.com/smeingast/vircampype
4 Docker platform: https://www.docker.com/
5 ESO Science Archive Facility: http://archive.eso.org/
6 Cambridge Astronomical Survey Unit (CASU): http://casu.ast.cam.ac.uk/
7 DR1 description: https://www.eso.org/rm/api/v1/public/releaseDescriptions/123
8 DR2 description: https://www.eso.org/rm/api/v1/public/releaseDescriptions/190
9 Centre de Données astronomiques de Strasbourg https://cds.unistra.fr/

Notes

a VISIONS programme ID 198.C-2009
b The RGB images displayed in Figure 1 were published as an ESO press release (ID eso2307; https://www.eso.org/public/news/eso2307/)

Despite its name, ESO's Very Large Telescope, the VLT, is not a single telescope! It is in fact made up of an array of four 8.2-metre-diameter Unit Telescopes (UTs) (one of which is shown here) and four additional, movable, 1.8-metre-diameter Auxiliary Telescopes (ATs) (three of which are visible on the right side of this image).

Each UT has its own individual name in the Mapuche (Mapudungun) language. The star of this image is Antu (or UT1, the first of the UTs), and is pictured here sitting atop Cerro Paranal in Chile. This polychromatic image, taken by ESO Photo Ambassador Petr Horálek, also captures the beautiful colours of the cloudy night sky encircling Antu.

Many night-sky objects are visible here. Starting from the left we see the pink California Nebula, the Pleiades star cluster, the fiery river of the Milky Way, the constellation of Orion and its famous Belt, the looping Gum Nebula, the Carina Nebula and the Southern Cross. The most curious features are the green bands or stripes to the right of Antu's enclosure. They are atmospheric gravity waves, generated by storms forming ripples in the greenish layer of Earth's airglow in the upper atmosphere. This image also appeared in an ESOcast dedicated to Red Sprites, which can occur under similar conditions as gravity waves.

P. Horálek/ESO