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# spherical: A Comprehensive Database and Automated Pipeline for VLT/SPHERE High-Contrast Imaging

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**Software**

- Review
- Repository
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## Summary

The Spectro-Polarimetric High-contrast Exoplanet REsearch instrument (SPHERE; Beuzit et al. (2019)) at the Very Large Telescope (VLT) is among the most advanced ground-based instruments for coronagraphic imaging of exoplanets and circumstellar disks in the optical and near-infrared. Over the last decade, SPHERE has been extraordinarily productive, contributing to over 400 publications and leading one of the largest ground-based surveys of exoplanets and circumstellar disks (SHINE; see e.g., Chauvin et al. (2017); Chomez et al. (2025)). It has played a pivotal role in probing the outer regions of planetary systems, revealing both planetary-mass companions and intricate disk structures around nearby stars.

The spherical software package offers both a ready-to-use, searchable database of all SPHERE observations from the ESO archive—available via Zenodo—and a framework for generating and updating this database using the latest archive contents, allowing users to explore, download, and analyze high-contrast imaging datasets efficiently. The SPHERE instrument consists of three sub-instruments. The InfraRed Dual-band Imager and Spectrograph (IRDIS; Dohlen et al. (2008); A. Vigan et al. (2010)), the Integral Field Spectrograph (IFS; Claudi et al. (2008); Mesa et al. (2015)), and the optical Zurich Imaging Polarimeter (ZIMPOL; Schmid et al. (2018)). As of May 2025, the **spherical** database includes ~6000 IRDIS observations in the dual-band imaging (DBI) mode, ~1000 in the IRDIS dual-beam polarimetric imaging (DPI; de Boer et al. (2020); van Holstein et al. (2020a)) mode, and ~4500 in the IFS mode. As discussed in Section **Future work** below, the ZIMPOl instrument, IRDIS long-slit spectroscopy (LSS; A. Vigan et al. (2008)) mode, and Sparse Aperture Masking (SAM; Cheetham et al. (2016)) are not yet supported, but are planned to be included in future updates.

Unlike the ESO archive interface, **spherical** consolidates observational metadata (instrument setup, total exposure time, total parallactic angle rotation, quality flags), target star properties, and observing conditions into a single table, significantly simplifying the identification of optimal datasets for scientific analysis. It integrates an parallelized *end-to-end data reduction pipeline* specifically designed for SPHERE's IFS, enabling efficient spectral cube extraction, calibration, post-processing, and exoplanet characterization. For IRDIS, **spherical** supports the discovery and download of dual-band imaging and polarimetric sequences. By offering an intuitive path from archival data to calibrated products, **spherical** empowers researchers to maximize the scientific yield of SPHERE observations.

The SPHERE instrument will soon be equipped with a second-stage adaptive optics system (SAXO+; Stadler et al. (2022)) as part of the SPHERE+ upgrade (Boccaletti et al. (2020); Boccaletti et al. (2022)). This enhancement will ensure that SPHERE remains a highly relevant scientific instrument in the coming years and also serves as a pathfinder and demonstrator for the future Planetary Camera and Spectrograph (PCS; Kasper et al. (2021)) on the Extremely Large Telescope (ELT).

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## Statement of Need

The European Southern Observatory's (ESO) VLT/SPHERE archive hosts the largest collection of high-contrast imaging data in the world. Despite its scientific richness, accessing and processing these data remain challenging due to complex retrieval mechanisms, fragmented metadata, and different pipelines. In addition to directly downloading raw data and using the ESO pipeline—which requires substantial technical expertise and manual configuration—three primary tools currently exist for accessing and processing SPHERE data:

1. **High Contrast Data Center (DC)** (Delorme et al., 2017): A Java-based platform for obtaining reduced data that requires manual user interaction. The DC also offers support for reducing data using the ESO pipeline and a suite of post-processing algorithms. However, it lacks an efficient way to discover or cross-match available data, making it best suited for acquiring a small number of datasets or for assistance in analyzing one's own observing program.
2. **vlt-sphere** (Arthur Vigan, 2020): A Python wrapper for the official ESO Data Reduction and Handling (DRH; Pavlov et al. (2008)) pipeline, which processes user-downloaded raw data but lacks integration with post-processing tools and a structured overview of available datasets.
3. **IRDAP** (van Holstein et al., 2020b): A Python-based pipeline for analyzing IRDIS polarimetric observations. It pre-reduces and post-processes the data into scientifically useable data products. However, similarly to **vlt-sphere** requires the user to download and find the required raw data and calibrations.

**spherical** addresses these limitations by providing a searchable summary of all observation sequences, including detailed data on astrophysical targets, observing modes, instrument configurations, and atmospheric conditions. This database, cross-referenced with astronomical catalogs (e.g., SIMBAD), enables easy exploration of available data and seamless downloading of IRDIS and IFS sequences. In contrast to the **High Contrast Data Center** and the **vlt-sphere** package, **spherical** integrates with the open-source CHARIS pipeline for IFS pre-processing and TRAP for high-contrast exoplanet detection. **spherical** is designed for full automation. Its outputs are compatible with alternative post-processing tools like **VIP** (Gomez Gonzalez et al. (2017); Christiaens et al. (2023)) and **pyKLIP** (Wang et al. (2015)), offering flexibility for different scientific post-processing workflows.

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## Database Structure and Pipeline Automation

The database generated by **spherical** is hosted on Zenodo (DOI: `10.5281/zenodo.15147730`) and can be easily updated with new data. The processing workflow of **spherical** consists of several automated steps. A general user will likely start from Step 4.

1. **Database Generation:**
   - **spherical** retrieves header information for all VLT/SPHERE IRDIS and IFS files available in the ESO archive, compiling them into a main "table of files." This database is periodically updated as new observations are added. Detailed examples of the generation and update process are available in the repository documentation and *examples* folder.
2. **Cross-Matching with SIMBAD Catalog:**
   - Using header information, the software cross-matches observation epochs and telescope pointings with the Gaia catalog to identify the observed astrophysical targets. Proper motions are accounted for, and by default, matching is constrained to stellar objects with J-band magnitudes <15 mag and parallaxes within 1 kpc to increase fidelity. These parameters are customizable during database creation.

As an extreme adaptive optics instrument, VLT/SPHERE requires bright natural guide stars, which facilitates cross-matching with stellar targets.

3. **Observation Table Construction:**
   - After cross-matching, **spherical** generates a structured "table of observations" that includes stellar properties, observing conditions, setup parameters, metadata, and quality flags for each sequence. This table is accessible for exploration via the provided Jupyter notebooks and is also hosted on Zenodo.
4. **Data Retrieval:**
   - Users can filter observations by target, observing conditions, mode, or program ID. **spherical** then handles automated download and sorting of raw datasets directly from the ESO archive. The downloader currently supports IFS, IRDIS, and IRDIS polarimetry. An example of how to search and filter the datase is provided as a Notebook in the repository.
5. **Data Reduction for IFS:**
   - For IFS datasets, **spherical** performs spectral cube extraction using the improved open-source Python-based CHARIS pipeline (Samland et al., 2022), followed by custom photometric and astrometric calibration adapted from routines used in Arthur Vigan (2020). These reduction steps are fully automated, requiring minimal user input. Complete examples of the IFS reduction workflow are provided in the repository's example scripts.
6. **Post-Processing and Planet Detection:**
   - After calibration, **spherical** integrates with the TRAP algorithm (Samland et al., 2021) for high-contrast imaging post-processing, automatically detecting point sources and extracting their spectra. Detection is enhanced using spectral templates for L- and T-type companions provided by the **species** package (Stolker et al., 2020), leveraging the spectral dimension of the IFS data.

This structured workflow greatly simplifies handling of VLT/SPHERE data, allowing researchers to **discover and access** scientifically ready products with minimal overhead. For further technical details and hands-on examples, users are encouraged to consult the repository documentation and example notebooks.

# Scientific Use

This package provides the basis for efficient use of SPHERE data. It provides the foundation for the analysis of large number of exoplanet spectra, detection maps for population statistics of arbitrary samples, or pushing towards improved detection limits for lower mass objects using new methods.

# Future Work

The package framework is extensible. Currently, some SPHERE observing modes are not yet included in the database: Sparse Aperture Masking (SAM; Cheetham et al. (2016)) for all instruments, the long-slit spectroscopy mode for IRDIS, and ZIMPOL. Future updates will progressively expand **spherical**'s functionality, providing support for easily discovering and downloading these datasets. Existing pipelines for these other modes can easily be included for reduction in the **spherical** workflow.

# Software Attribution

The **spherical** package makes extensive use of **astropy** (Astropy Collaboration et al. (2013); Astropy Collaboration et al. (2018); Astropy Collaboration et al. (2022)), **astroquery** for interacting with the ESO archive and astronomical catalogs (Ginsburg et al., 2019), **NumPy** (Harris et al., 2020) for numerical operations, and **pandas** (The pandas development team, n.d.) for tabular data handling. For IFS pipeline steps, in addition to the CHARIS pipeline (Brandt et al. (2017); Samland et al. (2022)), several calibration routines adapted from Arthur Vigan (2020) are employed. These, in turn, include contributions from developers listed in the **vlt-sphere** package repository.

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