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

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Software

- Review
- Repository
- Archive

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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 a leading facility for coronagraphic imaging of exoplanets and circumstellar disks in the optical and near-infrared. Over the last decade, SPHERE has contributed to hundreds of publications and major legacy surveys [e.g., SHINE; Chauvin et al. (2017); Chomez et al. (2025)].

`spherical` streamlines the end-to-end analysis of SPHERE data by integrating a curated, searchable database with an automated Python-based pipeline. The software enables users to filter the complete observation history by target properties or observing conditions, automatically download raw datasets from the ESO archive, and reduce Integral Field Spectrograph (IFS) data using the adapted CHARIS pipeline. Beyond basic reduction, the workflow handles astrometric calibration and post-processing via TRAP for companion detection, while also facilitating the discovery and retrieval of IRDIS dual-band and polarimetric imaging data for analysis with community tools.

As of May 2025, the database includes approximately 6000 IRDIS dual-band imaging (DBI) observations, ~1000 IRDIS dual-beam polarimetric imaging [DPI; de Boer et al. (2020); van Holstein et al. (2020a)] observations, and ~4500 IFS observations. SPHERE is undergoing the *SPHERE+* upgrade (Boccaletti et al., 2022, 2020), including a second-stage adaptive optics system [SAXO+; Stadler et al. (2022)], ensuring long-term scientific relevance and providing a pathfinder for the ELT's Planetary Camera and Spectrograph [PCS; Kasper et al. (2021)].

Statement of Need

The ESO VLT/SPHERE archive constitutes the world's largest collection of high-contrast imaging data to detect exoplanets, substellar companions, and circumstellar disks. However, utilizing this rich dataset for end-to-end research remains problematic. Researchers face challenges through need of manual identification and acquisition of available data and the lack of integration between various reduction pipelines. These barriers disproportionately affect researchers attempting to assemble large homogeneous samples for population studies, homogenous extraction of exoplanet spectra, and survey teams requiring rapid follow-up.

State of the Field

Several existing tools address isolated components of the SPHERE data workflow. The **High Contrast Data Center (DC)** (Delorme et al., 2017) provides Java-based access to reduce datasets using ESO's internal pipeline but offers limited capabilities for programmatic interaction or custom batch processing. **vlt-sphere** (Vigan, 2020) offers Python wrappers around the ESO pipeline for user-provided raw data, yet it lacks automated archival download and integrated post-processing features. For polarimetry, **IRDAP** (van Holstein et al., 2020b) serves as a robust automated pipeline, though it leaves dataset discovery and retrieval as manual user tasks.

`spherical` was build to fill the gap that a missing high level overview of what data SPHERE has taken over its lifetime leaves. It creates a unified workflow for identification of data, download, reduction and post-processing (via TRAP). From identification of observations of interest, all the way to the identification of exoplanets and extraction of their spectra `spherical` is an end-to-end farmework. `spherical` can also be used as infrastructure to download and pre-process data for alternative post-processing ecosystems such as VIP (Christiaens et al., 2023; Gomez Gonzalez et al., 2017), pyKLIP (Wang et al., 2015), and IRDAP.

Software Design

The architecture of `spherical` is designed as a high-level abstraction layer over the ESO raw archive, providing a systematic interface that currently does not exist for high-contrast imaging data. A central design choice was the decoupling of metadata curation from data reduction. This is achieved through a multi-stage process that ingests science headers from the ESO archive and cross-matches them with the Gaia catalog based on telescope pointings. To handle the inherent noise in archival metadata, the system employs a proximity, brightness, and object type-based resolution logic to resolve target ambiguities, accounting for epoch of observation of proper motion of stellar targets, ensuring the resulting database is both clean and astronomically accurate.

The core of the package is a structured, searchable observation table—archived on Zenodo (DOI: 10.5281/zenodo.15147730)—which aggregates information such as observing mode, total exposure time, parallactic angle coverage, and atmospheric conditions. By choosing a local, curated table over live archive queries, `spherical` enables rapid, complex filtering of the entire instrument history that would otherwise be difficult.

Technically, `spherical` adopts a wrapper-based architecture. Instead of reimplementing reduction algorithms, it provides a Pythonic interface to the Samland et al. (2022) IFS instrument pipeline. This design trade-off prioritizes scientific continuity and maintainability; by "gluing" the complex CHARIS instrumend-based SPHERE IFS pipeline and TRAP high-contrast imaging post-processing workflows into an object-oriented framework, `spherical` transforms specialized code into a user-friendly end-to-end workflow without sacrificing the precision of the original algorithms. This hybrid approach allows the software to act as a bridge between archival discovery and specialized community tools. Likewise, `spherical` can be used as an initial stage for post-processing frameworks like like VIP and IRDAP.

`spherical` relies purely on open-source software: `Astropy` (Astropy Collaboration et al., 2013, 2018, 2022), `astroquery` for ESO archive and catalog access [Ginsburg et al. (2019), `NumPy` (Harris et al., 2020) for numerical operations, and `pandas` (The pandas development team, n.d.) for tabular data handling. The IFS reduction uses the adapted `CHARIS` pipeline (Brandt et al., 2017; Samland et al., 2022), with calibration routines derived in part from Vigan (2020) (see the `vlt-sphere` repository for individual contributors). Post-processing employs `TRAP` (Samland et al., 2021).

Research Impact Statement

`spherical` has been used in several recently published peer-reviewed studies to analyse SPHERE IFS data (Franson et al., 2023; Hammond et al., 2025; Stolker et al., 2025), improving the extraction of spectra of exoplanetary atmospheres. At the time these works were published, the code had not yet been citable via an existing DOI. Since the database of existing observations has been made available on Zenodo, it has been downloaded more than 400 times. New exoplanet candidates identified through `spherical` have been accepted for follow-up observation in an ESO P117 proposal (117.2A06.001), awarding 28.5 hours—more than 60% of all time awarded in P117 to SPHERE observations.

The research impact of `spherical` is centered on enabling large-scale, reproducible science that was previously inhibited by the heterogeneous nature of the SPHERE archive. By lowering the technical barrier from raw archival to science-ready data products, the software facilitates the construction of homogeneous samples essential for statistically significant exoplanet occurrence rate and population studies. This systematic approach allows researchers to apply consistent algorithms across the entire instrument lifetime.

Furthermore, the integration of high-performance post-processing tools like TRAP within an automated framework enables the "mining" of archival data for low-mass companions that were missed by earlier, less sensitive reduction techniques. This capability is particularly timely as the astronomical community prepares for the SPHERE+ upgrade and future ELT-era observations; `spherical` provides the necessary infrastructure to benchmark current performance and develop the automated workflows required to handle the next generation of high-contrast imaging data. By shifting the focus from manual data curation to atmospheric characterization and spectral extraction, the package accelerates the transition from exoplanet discovery to detailed physical understanding.

Future Work

`spherical` is built with extensibility as a core tenet. Future development will focus on expanding database coverage and streamlining data retrieval for additional observing modes, specifically ZIMPOL, IRDIS LSS, and SAM, while integrating their respective community reduction pipelines into the established script-driven framework. To enhance software reliability and facilitate community contributions, we intend to provide a public test dataset for the continuous integration of selected pipeline stages. Furthermore, the package will evolve alongside the SPHERE+ upgrade; calibration and post-processing modules will be adapted to account for the instrument's enhanced performance and the new capabilities of the SAXO+ adaptive optics system.

AI Usage Disclosure

The authors acknowledge the use of generative AI (Large Language Models) in the development of `spherical` and the preparation of this manuscript. Specifically, AI tools were utilized to generate source code docstrings, draft the project README and release notes, and assist in refactoring existing code to improve maintainability. During the writing process, generative AI was used for language editing and to refine the manuscript's conciseness.

The authors certify that generative AI was not involved in the original conceptual design, the software architecture, or the underlying scientific methodology. All AI-generated outputs, including code and text, were manually reviewed, verified, and edited by the authors to ensure technical accuracy and integrity.

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References

Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., Earl, N., Starkman, N., Bradley, L., Shupe, D. L., Patil, A. A., Corrales, L., Brasseur, C. E., Nöthe, M., Donath, A., Tollerud, E., Morris, B. M., Ginsburg, A., Vaher, E., Weaver, B. A., Tocknell, J., Jamieson, W., … Astropy Project Contributors. (2022). The Astropy Project: Sustaining and Growing a Community-oriented Open-source Project and the Latest Major Release (v5.0) of the Core Package. *The Astrophysical Journal*, *935*(2), 167. https://doi.org/10.3847/1538-4357/ac7c74

Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., Günther, H. M., Lim, P. L., Crawford, S. M., Conseil, S., Shupe, D. L., Craig, M. W., Dencheva, N., Ginsburg, A., VanderPlas, J. T., Bradley, L. D., Pérez-Suárez, D., de Val-Borro, M., Aldcroft, T. L., Cruz, K. L., Robitaille, T. P., Tollerud, E. J., … Astropy Contributors. (2018). The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package. *The Astronomical Journal*, *156*(3), 123. https://doi.org/10.3847/1538-3881/aabc4f

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., Davis, M., Ginsburg, A., Price-Whelan, A. M., Kerzendorf, W. E., Conley, A., Crighton, N., Barbary, K., Muna, D., Ferguson, H., Grollier, F., Parikh, M. M., Nair, P. H., … Streicher, O. (2013). Astropy: A community Python package for astronomy. *Astronomy & Astrophysics*, *558*, A33. https://doi.org/10.1051/0004-6361/201322068

Beuzit, J.-L., Vigan, A., Mouillet, D., Dohlen, K., Gratton, R., Boccaletti, A., Sauvage, J.-F., Schmid, H. M., Langlois, M., Petit, C., Baruffolo, A., Feldt, M., Milli, J., Wahhaj, Z., Abe, L., Anselmi, U., Antichi, J., Barette, R., Baudrand, J., … Zurlo, A. (2019). SPHERE: the exoplanet imager for the Very Large Telescope. *Astronomy & Astrophysics*, *631*, A155. https://doi.org/10.1051/0004-6361/201935251

Boccaletti, A., Chauvin, G., Mouillet, D., Absil, O., Allard, F., Antoniucci, S., Augereau, J.-C., Barge, P., Baruffolo, A., Baudino, J.-L., Baudoz, P., Beaulieu, M., Benisty, M., Beuzit, J.-L., Bianco, A., Biller, B., Bonavita, B., Bonnefoy, M., Bos, S., … Zurlo, A. (2020). SPHERE+: Imaging young Jupiters down to the snowline. *arXiv e-Prints*, arXiv:2003.05714. https://doi.org/10.48550/arXiv.2003.05714

Boccaletti, A., Chauvin, G., Wildi, F., Milli, J., Stadler, E., Diolaiti, E., Gratton, R., Vidal, F., Loupias, M., Langlois, M., Cantalloube, F., N'Diaye, M., Gratadour, D., Ferreira, F., Tallon, M., Mazoyer, J., Segransan, D., Mouillet, D., Beuzit, J.-L., … Zanutta, A. (2022). Upgrading the high contrast imaging facility SPHERE: science drivers and instrument choices. In C. J. Evans, J. J. Bryant, & K. Motohara (Eds.), *Ground-based and airborne instrumentation for astronomy IX* (Vol. 12184, p. 121841S). https://doi.org/10.1117/12.2630154

Brandt, T. D., Rizzo, M., Groff, T., Chilcote, J., Greco, J. P., Kasdin, N. J., Limbach, M. A., Galvin, M., Loomis, C., Knapp, G., McElwain, M. W., Jovanovic, N., Currie, T., Mede, K., Tamura, M., Takato, N., & Hayashi, M. (2017). Data reduction pipeline for the CHARIS integral-field spectrograph I: detector readout calibration and data cube extraction. *Journal of Astronomical Telescopes, Instruments, and Systems*, *3*, 048002. https://doi.org/10.1117/1.JATIS.3.4.048002

Chauvin, G., Desidera, S., Lagrange, A.-M., Vigan, A., Feldt, M., Gratton, R., Langlois, M., Cheetham, A., Bonnefoy, M., & Meyer, M. (2017). SHINE, The SpHere INfrared survey for Exoplanets. In C. Reylé, P. Di Matteo, F. Herpin, E. Lagadec, A. Lançon, Z. Meliani, & F. Royer (Eds.), *SF2A-2017: Proceedings of the annual meeting of the french society of astronomy and astrophysics* (p. Di).

Chomez, A., Delorme, P., Lagrange, A.-M., Gratton, R., Flasseur, O., Chauvin, G., Langlois, M., Mazoyer, J., Zurlo, A., Desidera, S., Mesa, D., Bonnefoy, M., Feldt, M., Hagelberg, J., Meyer, M., Vigan, A., Ginski, C., Kenworthy, M., Albert, D., … Wildi, F. (2025). The SPHERE infrared survey for exoplanets (SHINE): IV. Complete observations, data reduction and analysis, detection performances, and final results. *Astronomy & Astrophysics*, *697*, A99. https://doi.org/10.1051/0004-6361/202451751

Christiaens, V., Gonzalez, C., Farkas, R., Dahlqvist, C.-H., Nasedkin, E., Milli, J., Absil, O., Ngo, H., Cantero, C., Rainot, A., Hammond, I., Bonse, M., Cantalloube, F., Vigan, A., Kompella, V., & Hancock, P. (2023). VIP: A Python package for high-contrast imaging. *The Journal of Open Source Software*, *8*(81), 4774. https://doi.org/10.21105/joss.04774

de Boer, J., Langlois, M., van Holstein, R. G., Girard, J. H., Mouillet, D., Vigan, A., Dohlen, K., Snik, F., Keller, C. U., Ginski, C., Stam, D. M., Milli, J., Wahhaj, Z., Kasper, M., Schmid, H. M., Rabou, P., Gluck, L., Hugot, E., Perret, D., … Beuzit, J.-L. (2020). Polarimetric imaging mode of VLT/SPHERE/IRDIS. I. Description, data reduction, and observing strategy. *Astronomy & Astrophysics*, *633*, A63. https://doi.org/10.1051/0004-6361/201834989

Delorme, P., Meunier, N., Albert, D., Lagadec, E., Le Coroller, H., Galicher, R., Mouillet, D., Boccaletti, A., Mesa, D., Meunier, J.-C., Beuzit, J.-L., Lagrange, A.-M., Chauvin, G., Sapone, A., Langlois, M., Maire, A.-L., Montargès, M., Gratton, R., Vigan, A., & Surace, C. (2017). The SPHERE Data Center: a reference for high contrast imaging processing. In C. Reylé, P. Di Matteo, F. Herpin, E. Lagadec, A. Lançon, Z. Meliani, & F. Royer (Eds.), *SF2A-2017: Proceedings of the annual meeting of the french society of astronomy and astrophysics* (p. Di). https://doi.org/10.48550/arXiv.1712.06948

Franson, K., Bowler, B. P., Bonavita, M., Brandt, T. D., Chen, M., Samland, M., Zhang, Z., Lueber, A., Heng, K., Kitzmann, D., Wolf, T., Jones, B. A., Tran, Q. H., Bardalez Gagliuffi, D. C., Biller, B., Chilcote, J., Crepp, J. R., Dupuy, T. J., Faherty, J., … Theissen, C. A. (2023). Astrometric Accelerations as Dynamical Beacons: Discovery and Characterization of HIP 21152 B, the First T-dwarf Companion in the Hyades. *165*(2), 39. https://doi.org/10.3847/1538-3881/aca408

Ginsburg, A., Sipőcz, B. M., Brasseur, C. E., Cowperthwaite, P. S., Craig, M. W., Deil, C., Guillochon, J., Guzman, G., Liedtke, S., Lian Lim, P., Lockhart, K. E., Mommert, M., Morris, B. M., Norman, H., Parikh, M., Persson, M. V., Robitaille, T. P., Segovia, J.-C., Singer, L. P., … a subset of astropy Collaboration. (2019). astroquery: An Astronomical Web-querying Package in Python. *The Astronomical Journal*, *157*(3), 98. https://doi.org/10.3847/1538-3881/aafc33

Gomez Gonzalez, C. A., Wertz, O., Absil, O., Christiaens, V., Defrère, D., Mawet, D., Milli, J., Absil, P.-A., Van Droogenbroeck, M., Cantalloube, F., Hinz, P. M., Skemer, A. J., Karlsson, M., & Surdej, J. (2017). VIP: Vortex Image Processing Package for High-contrast Direct Imaging. *The Astronomical Journal*, *154*(1), 7. https://doi.org/10.3847/1538-3881/aa73d7

Hammond, I., Christiaens, V., Price, D. J., Blakely, D., Trevascus, D., Bonse, M. J., Cantalloube, F., Marleau, G.-D., Pinte, C., Juillard, S., Samland, M., Thompson, W., & Wallace, A. (2025). Keplerian motion of a compact source orbiting the inner disc of PDS 70: a third protoplanet in resonance with b and c? *539*(2), 1613–1627. https://doi.org/10.1093/mnras/staf586

Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk, M. H. van, Brett, M., Haldane, A., Río, J. F. del, Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Kasper, M., Cerpa Urra, N., Pathak, P., Bonse, M., Nousiainen, J., Engler, B., Heritier, C. T., Kammerer, J., Leveratto, S., Rajani, C., Bristow, P., Le Louarn, M., Madec, P.-Y., Ströbele, S., Verinaud, C., Glauser, A., Quanz, S. P., Helin, T., Keller, C., … Raynaud, H.-F. (2021). PCS — A Roadmap for Exoearth Imaging with the ELT. *The Messenger*, *182*, 38–43. https://doi.org/10.18727/0722-6691/5221

Samland, M., Bouwman, J., Hogg, D. W., Brandner, W., Henning, T., & Janson, M. (2021).

TRAP: a temporal systematics model for improved direct detection of exoplanets at small angular separations. *Astronomy & Astrophysics*, *646*, A24. https://doi.org/10.1051/0004-6361/201937308

Samland, M., Brandt, T. D., Milli, J., Delorme, P., & Vigan, A. (2022). Spectral cube extraction for the VLT/SPHERE IFS. Open-source pipeline with full forward modeling and improved sensitivity. *Astronomy & Astrophysics*, *668*, A84. https://doi.org/10.1051/0004-6361/202244587

Stadler, E., Diolaiti, E., Schreiber, L., Cortecchia, F., Lombini, M., Loupias, M., Magnard, Y., De Rosa, A., Malaguti, G., Maurel, D., Morgante, G., Rabou, P., Rochat, S., Schiavone, F., Terenzi, L., Vidal, F., Cantalloube, F., Gendron, E., Gratton, R., … Boccaletti, A. (2022). SAXO+, a second-stage adaptive optics for SPHERE on VLT: optical and mechanical design concept. In L. Schreiber, D. Schmidt, & E. Vernet (Eds.), *Adaptive optics systems VIII* (Vol. 12185, p. 121854E). https://doi.org/10.1117/12.2629970

Stolker, T., Samland, M., Waters, L. B. F. M., van den Ancker, M. E., Balmer, W. O., Lacour, S., Sitko, M. L., Wang, J. J., Nowak, M., Maire, A.-L., Kammerer, J., Otten, G. P. P. L., Abuter, R., Amorim, A., Benisty, M., Berger, J.-P., Beust, H., Blunt, S., Boccaletti, A., … Yazici, S. (2025). Direct imaging discovery of a young giant planet orbiting on Solar System scales. *700*, A21. https://doi.org/10.1051/0004-6361/202555064

The pandas development team. (n.d.). *pandas-dev/pandas: Pandas*. https://doi.org/10.5281/zenodo.3509134

van Holstein, R. G., Girard, J. H., de Boer, J., Snik, F., Milli, J., Stam, D. M., Ginski, C., Mouillet, D., Wahhaj, Z., Schmid, H. M., Keller, C. U., Langlois, M., Dohlen, K., Vigan, A., Pohl, A., Carbillet, M., Fantinel, D., Maurel, D., Origné, A., … Beuzit, J.-L. (2020a). Polarimetric imaging mode of VLT/SPHERE/IRDIS. II. Characterization and correction of instrumental polarization effects. *Astronomy & Astrophysics*, *633*, A64. https://doi.org/10.1051/0004-6361/201834996

van Holstein, R. G., Girard, J. H., de Boer, J., Snik, F., Milli, J., Stam, D. M., Ginski, C., Mouillet, D., Wahhaj, Z., Schmid, H. M., Keller, C. U., Langlois, M., Dohlen, K., Vigan, A., Pohl, A., Carbillet, M., Fantinel, D., Maurel, D., Origné, A., … Beuzit, J.-L. (2020b). *IRDAP: SPHERE-IRDIS polarimetric data reduction pipeline*. Astrophysics Source Code Library, record ascl:2004.015.

Vigan, A. (2020). *vlt-sphere: Automatic VLT/SPHERE data reduction and analysis* (p. ascl:2009.002). https://doi.org/10.5281/zenodo.6563998

Wang, J. J., Ruffio, J.-B., De Rosa, R. J., Aguilar, J., Wolff, S. G., & Pueyo, L. (2015). *pyKLIP: PSF Subtraction for Exoplanets and Disks*. Astrophysics Source Code Library, record ascl:1506.001.