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VTSCat: The VERITAS Catalog of Gamma-Ray Observations

A. Acharyya,¹ C. B. Adams,² A. Archer,³ P. Bangale,⁴ J. T. Bartkoske,⁵ P. Batista,⁶ W. Benbow,⁷ A. Brill,⁸ R. Brose,⁹ J. H. Buckley,¹⁰ M. Capasso,¹¹ J. L. Christiansen,¹² A. J. Chromey,⁷ M. K. Daniel,⁷ M. Errando,¹⁰ A. Falcone,¹³ K. A. Farrell,¹⁴ Q. Feng,⁷ J. P. Finley,¹⁵ G. M. Foote,⁴ L. Fortson,¹⁶ A. Furniss,¹⁷ G. Gallagher,¹⁸ A. Gent,¹⁹ C. Giuri,⁶ O. Gueta,⁶ W. F. Hanlon,⁷ D. Hanna,²⁰ T. Hassan,⁶ O. Hervet,²¹ J. Hoang,²¹ J. Holder,⁴ G. Hughes,⁷ T. B. Humensky,²² W. Jin,¹ P. Kaaret,²³ M. Kertzman,³ D. Kieda,⁵ T. K. Kleiner,⁶ N. Korzoun,⁴ F. Krennrich,²⁴ S. Kumar,²⁵ M. J. Lang,²⁶ M. Lundy,²⁰ G. Maier,⁶ C. E. McGrath,¹⁴ M. J. Millard,²³ C. L. Mooney,⁴ P. Moriarty,²⁶ R. Mukherjee,¹¹ D. Nieto,²⁷ M. Nieves-Rosillo,⁶ S. O'Brien,²⁰ R. A. Ong,²⁸ A. N. Otte,¹⁹ D. Pandel,²⁹ N. Park,³⁰ S. R. Patel,⁶ S. Patel,²³ K. Pfrang,⁶ A. Pichel,³¹ M. Pohl,⁹ R. R. Prado,⁶ E. Pueschel,⁶ J. Quinn,¹⁴ K. Ragan,²⁰ P. T. Reynolds,³² D. Ribeiro,² G. T. Richards,⁴ E. Roache,⁷ A. C. Rovero,³¹ C. Rulten,¹⁶ J. L. Ryan,²⁸ I. Sadeh,⁶ M. Santander,¹ S. Schlenstedt,³³ G. H. Sembroski,¹⁵ R. Shang,²⁸ M. Splettstoesser,²¹ B. Stevenson,²⁸ D. Tak,⁶ V. V. Vassiliev,²⁸ S. P. Wakely,³⁴ A. Weinstein,²⁴ D. A. Williams,²¹ T. J. Williamson,⁴ L. Angelini,³⁵ A. Basu-Zych,^{35,36} E. Sabol,^{35,36} and A. Smale³⁷

¹*Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL 35487, USA*

²*Physics Department, Columbia University, New York, NY 10027, USA*

³*Department of Physics and Astronomy, DePauw University, Greencastle, IN 46135-0037, USA*

⁴*Department of Physics and Astronomy and the Bartol Research Institute, University of Delaware, Newark, DE 19716, USA*

⁵*Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA*

⁶*DESY, Platanenallee 6, 15738 Zeuthen, Germany*

⁷*Center for Astrophysics, Harvard & Smithsonian, Cambridge, MA 02138, USA*

⁸*N.A.S.A./Goddard Space-Flight Center, Code 661, Greenbelt, MD 20771, USA*

⁹*Institute of Physics and Astronomy, University of Potsdam, 14476 Potsdam-Golm, Germany and DESY, Platanenallee 6, 15738 Zeuthen, Germany*

¹⁰*Department of Physics, Washington University, St. Louis, MO 63130, USA*

¹¹*Department of Physics and Astronomy, Barnard College, Columbia University, NY 10027, USA*

¹²*Physics Department, California Polytechnic State University, San Luis Obispo, CA 94307, USA*

¹³*Department of Astronomy and Astrophysics, 525 Davey Lab, Pennsylvania State University, University Park, PA 16802, USA*

¹⁴*School of Physics, University College Dublin, Belfield, Dublin 4, Ireland*

¹⁵*Department of Physics and Astronomy, Purdue University, West Lafayette, IN 47907, USA*

¹⁶*School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

¹⁷*Department of Physics, California State University - East Bay, Hayward, CA 94542, USA*

¹⁸*Department of Physics and Astronomy, Ball State University, Muncie, IN 47306, USA*

¹⁹*School of Physics and Center for Relativistic Astrophysics, Georgia Institute of Technology, 837 State Street NW, Atlanta, GA 30332-0430*

²⁰*Physics Department, McGill University, Montreal, QC H3A 2T8, Canada*

Corresponding author: Gernot Maier

gernot.maier@desy.de

Corresponding author: Sameer Patel

sameer-patel-1@uiowa.edu

Corresponding author: Philip Kaaret

philip-kaaret@uiowa.edu

- ²¹*Santa Cruz Institute for Particle Physics and Department of Physics, University of California, Santa Cruz, CA 95064, USA*
- ²²*Department of Physics, University of Maryland, College Park, MD, USA and*
- ²³*Department of Physics and Astronomy, University of Iowa, Van Allen Hall, Iowa City, IA 52242, USA*
- ²⁴*Department of Physics and Astronomy, Iowa State University, Ames, IA 50011, USA*
- ²⁵*Department of Physics, University of Maryland, College Park, MD, USA*
- ²⁶*School of Natural Sciences, University of Galway, University Road, Galway, H91 TK33, Ireland*
- ²⁷*Institute of Particle and Cosmos Physics, Universidad Complutense de Madrid, 28040 Madrid, Spain*
- ²⁸*Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA*
- ²⁹*Department of Physics, Grand Valley State University, Allendale, MI 49401, USA*
- ³⁰*Department of Physics, Engineering Physics and Astronomy, Queen's University, Kingston, ON K7L 3N6, Canada*
- ³¹*Instituto de Astronomía y Física del Espacio (IAFE, CONICET-UBA), CC 67 - Suc. 28, (C1428ZAA) Ciudad Autónoma de Buenos Aires, Argentina*
- ³²*Department of Physical Sciences, Munster Technological University, Bishopstown, Cork, T12 P928, Ireland*
- ³³*CTAO, Saupfercheckweg 1, 69117 Heidelberg, Germany*
- ³⁴*Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
- ³⁵*NASA Goddard Space Flight Center, Code 662, Greenbelt, MD 20771, USA*
- ³⁶*Center for Space Science and Technology, University of Maryland Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA*
- ³⁷*ADNET Systems Inc., 6720B Rockledge Drive, Suite #504, Bethesda, MD 20817*

ABSTRACT

The ground-based gamma-ray observatory VERITAS (Very Energetic Radiation Imaging Telescope Array System^a), (Holder et al. 2006)) is sensitive to photons of astrophysical origin with energies in the range between ≈ 85 GeV to ≈ 30 TeV. The instrument consists of four 12-m diameter imaging Cherenkov telescopes operating at the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona. VERITAS started four-telescope operations in 2007 and collects about 1100 hours of good-weather data per year. The VERITAS collaboration has published over 100 journal articles since 2008 reporting on gamma-ray observations of a large variety of objects: Galactic sources like supernova remnants, pulsar wind nebulae, and binary systems; extragalactic sources like star forming galaxies, dwarf-spheroidal galaxies, and highly-variable active galactic nuclei. This note presents VTSCat: the catalog of high-level data products from all VERITAS publications.

Keywords: high-energy astrophysics — gamma-ray telescopes — catalogs

VTSCAT

VTSCat is inspired by various movements for open data, among them the initiative for data formats in gamma-ray astronomy¹ (Deil et al. 2017). It is built on an

^a) <https://veritas.sao.arizona.edu/>

¹ see <https://gamma-astro-data-formats.readthedocs.io/en/latest/>

early version of the gamma-ray catalog `gamma-cat`² and profited significantly from the input of the `gamma-cat` developers. All VTSCat data can be accessed file-by-file on GitHub (<https://github.com/VERITAS-Observatory/VERITAS-VTSCat>) or downloaded via Zenodo (VERITAS Collaboration et al. (2022), downloadable as a compressed file). The light curves and spectral results in VTSCat are also available through NASA’s High Energy Astrophysics Science Archive Research Center (HEASARC; <https://heasarc.gsfc.nasa.gov/W3Browse/all/verimaster.html>), thus providing an interface more familiar to astronomers (see next section).

The VTSCat data collection contains:

- high-level data such as spectral flux points, light curves, spectral fits in human- and machine-readable *yaml* and *ecsv* file formats³,
- table data such as upper limits from dark matter searches or results on the extragalactic background light in the *ecsv* file format,
- sky maps (wherever available) in the FITS file format.

The physical units are explicitly given in each file; the *ecsv*-files follow standards which allow them to be read by common tools such as the `astropy` python library (Astropy Collaboration et al. 2022).

The data files are organized in VTSCat by year and publication, using the ADS bibcodes as reference identifiers. Objects are identified by a running integer (labeled *source_id* in data files) following the scheme developed by `gamma-cat`. The description files for objects can be found in the `sources` subdirectory and include the most relevant names for a given object (common name in the field, VERITAS object identifier, primary identifier by SIMBAD), and the object coordinates.

For illustration, the data entry for the VERITAS publication Abeysekara et al. (2018) is discussed in the following (see the directory `2018/2018ApJ...861L..20A` on the repository to follow the discussion below). A `README` file provides an overview of all data products, figures, source names, and citations. For this example, the data files are:

- Observation data: `VER-000168.yaml`

Observational details and results like observation time, detection significance, and spectral models.

- Spectral flux points: `VER-000168-sed-1.ecsv`

Spectral flux points including errors and upper limits as published in Fig 2 of Abeysekara et al. (2018).

- Light-curve data: `VER-000168-lc.ecsv`

² see <https://gamma-cat.readthedocs.io/index.html>

³ <https://yaml.org/> and <https://github.com/astropy/astropy-APEs/blob/master/APE6.rst>

Light-curve data (integrated gamma-ray fluxes vs time) as published in Fig 3 of [Abeysekara et al. \(2018\)](#).

- FITS data: [VER-000168-signif-skymap.fits](#)

Statistical significance sky map as published in Fig 1 of [Abeysekara et al. \(2018\)](#)

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The yaml datatypes and spectral models used are explained in the documents [Formats_and_Models.md](#) and [SpectralModels.md](#). The data types and units used in *ecsv* files are described at the top of each data file; for FITS files this information is provided in the FITS header. Preview PNG images are included for all lightcurves and spectral energy distribution plots.

Translation of the data in the publications to a uniform catalog was a complex process, requiring significant manual effort and occasional addition of information. For example, we note the addition of the source name VER J1746-286 that refers to the diffuse emission of seven fields near the Galactic Center ([Adams et al. 2021](#)) with an average position of $(l, b) = (0^\circ.37257, -0^\circ.04588)$.

VTSCAT AT HEASARC

Most of the information contained in VTSCat is also archived and available at the HEASARC, which is familiar to a large part of the community of high-energy astrophysicists. Users can take advantage of the HEASARC through multiband data searches and VERITAS data can be included in these searches. The main catalog at the HEASARC will be a source catalog including all sources detected with VERITAS. The SEDs and light curve data for individual sources will be in individual files linked to the main source catalog. As in VTSCat, the objects and sources are identified by their source identifiers (IDs). All data fields along with their units are described in detail at <https://heasarc.gsfc.nasa.gov/W3Browse/all/verimaster.html>. Following VTSCat, the data files wrapped in FITS format contain lightcurve data (integrated gamma-ray fluxes vs time) and spectral flux points (including errors and upper limits). The data types and units for these data products are described in the FITS header.

OUTLOOK

VTSCat will be updated regularly with new publications of the VERITAS collaboration. Future structural updates of VTSCat may include multi-wavelength data presented in VERITAS publications including observations by e.g., radio, optical, or X-ray instruments, and may also allow to use tools like the SED builder provided through SSDC⁴. The effort of disseminating all VERITAS results in digital format will aid in multiwavelength analysis and input to the modeling of sources of high-energy gamma rays.

⁴ <https://tools.ssdc.asi.it/SED/>

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Facilities: VERITAS

REFERENCES

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| <p>Holder, J., Atkins, R. W., Badran, H. M., et al. 2006, <i>Astroparticle Physics</i>, 25, 391</p> <p>Deil, C., Boisson, C., Kosack, K., et al. 2017, 6th International Symposium on High Energy Gamma-ray Astronomy, AIP Conference Proceedings 1792</p> <p>VERITAS Collaboration, et al. 2022, Zenodo, doi:10.5281/zenodo.6163391</p> | <p>Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., et al. 2022, <i>ApJ</i>, 935, 167. doi:10.3847/1538-4357/ac7c74</p> <p>Abeysekara, A. U., Archer, A., Benbow, W., et al. 2018, <i>ApJL</i>, 861, L20</p> <p>Adams, C. B., Benbow, W., Brill, A., et al. 2021, <i>ApJ</i>, 913, 115. doi:10.3847/1538-4357/abf926</p> |
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