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Abstract

This document describes a proposed extension to the ObsCore specification for data description, discovery and selection of High Energy Astrophysics (HEA) data. The document includes proposed updates to the data product vocabulary, UCDs, and MIME-types to support discovery of HEA data.

Status of this document

This is an IVOA Proposed Endorsed Note for review by IVOA members and other interested parties. It is appropriate to reference this document only as a Proposed Endorsed Note that is under review and may change before it is endorsed or may not be endorsed.

A list of current IVOA Recommendations and other technical documents can be found in the IVOA document repository[1].

Contents

[1] https://www.ivoa.net/documents/

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Conformance-related definitions

The words “MUST”, “SHALL”, “SHOULD”, “MAY”, “RECOMMENDED”, and “OPTIONAL” (in upper or lower case) used in this document are to be interpreted as described in IETF standard RFC2119 (Bradner, 1997).

The Virtual Observatory (VO) is a general term for a collection of federated resources that can be used to conduct astronomical research, education, and outreach. The International Virtual Observatory Alliance (IVOA) is a global collaboration of separately funded projects to develop standards and infrastructure that enable VO applications.

1 Introduction

The International Virtual Observatory Alliance (IVOA) High Energy Interest Group (HEIG) was formed in the Fall of 2024, and developed an IVOA Note (Servillat and Boisson et al., 2024) that explores the connections between the VO and HEA. HEA covers experiments and observatories from the X-ray range up to the PeV range and beyond, as well as astrophysical neutrinos above the TeV range. These regimes are referred to here as the HEA domain. The HEIG Note includes an outline of several important topics that have formed a roadmap for the group. An ObsCore (Louys and Tody et al., 2017) extension for HEA data is the first priority in order to meet the needs of HEA, and to coincide with similar work being carried out by the Radio Interest Group, Time Domain Interest Group, and discussions on DataModel standards, such that current and future HEA experiments and observatories are able to release data through the VO.

The goal is to explore elements needed to reliably discover and select HEA data through IVOA interfaces. This requires defining an extension to ObsCore with the possibility to use the DataLink mechanism and to enhance vocabularies of keywords for ObsCore and DataLink. We suggest that if an attribute is unique to HEA data, then that element should appear in an HEA ObsCore extension. Whereas, if an attribute makes sense for more than one domain and can be shared across those domains, then that element should be added to the base ObsCore model. This note proposes recommendations in both of these categories. We also discuss enhancements to the vocabulary of data products, DataLink semantics, Unified Content Descriptors (UCDs), and MIME-types to correctly represent HEA data. Topics related to the Registry are currently outlined in the proposed Radio extension document and are not discussed here.

2 High Energy Astrophysics Data

HEA data include observations obtained using photon detectors covering X-ray (from $\sim$0.1 keV to $\sim$120 keV) through gamma-ray (from 120 keV up to $\gtrsim$ PeV) energies, as well as cosmic-ray and astrophysical neutrino ($\gtrsim$ TeV) detectors, or other messengers related to HEA phenomena. The domain is now sufficiently mature to provide open data that are science-ready and work with open analysis tools (*e.g.*, CIAO (Fruscione and McDowell et al., 2006) or Gammapy (Donath and Terrier et al., 2023)). The science output of the HEA domain already includes advanced products such as images, cubes, spectra, and time series such as light curves and time-resolved spectra. Additional data products include fitted sky models with spatial, spectral, and/or temporal component(s), along with their confidence intervals or confidence limits, and covariance matrices. Finally, multiple HEA instruments produce source catalogs and surveys covering up to the full the sky, which include maps of photon or particle flux, exposure, sensitivity, and aperture-photometry likelihood profiles.

Observations of the universe at the highest energies are based on techniques that are radically different compared to the UV through radio domains. HEA observatories[2] are generally designed to detect particles (*e.g.*, individual photons, cosmic-rays, or neutrinos) with the ability to estimate multiple observables for those particles. These detection techniques all rely on *event counting*[3], where an event has some probability of being due to the interaction of a particle from an astrophysical source with the detectors, but also has some probability of being from instrumental or background effects. The data corresponding to an event are first an instrumental signal, which is then calibrated and processed to estimate physical quantities such as a time of arrival, point-of-origin on the sky, and an energy proxy associated with the event. Several other intermediate and qualifying characteristics may be associated with a detected event, depending on the detection technique. The ensemble of events detected over a given time interval and spatial field-of-view is referred to as an *event list*, which we designate an **event-list** in this document.

Though **event-list**s *may* include estimators for calibrated physical values, they typically still have to be corrected for the photometric, spectral, spatial, and/or temporal responses of the telescope and detector combination to yield scientifically interpretable information. The mappings between physical measurements of the source properties and the observables are called Instrument Response Functions (IRFs[4]). Some IRFs are probabilistic in nature[5], and in addition may depend on the set of events selected for analysis by the end user. They are usually not invertible, so methods such as forward-folding fitting (using source models with any combination of spectral, spatial, temporal, and/or polarization components that are estimated) are needed to estimate physical properties, such as the true flux of particles from a source arriving at the instrument, given the measured observable quantities. The IRFs generally evolve over time with the instrument and observation char-

[2]For example, Chandra, XMM-Newton, Fermi, H.E.S.S., MAGIC, VERITAS, HAWC, LHAASO, IceCube, Auger and soon CTAO and KM3NeT, SWGO.

[3]As opposed to signal integrating (*e.g.*, using a detector that accumulates the total photon signal during an exposure).

[4]We try to avoid using the term IRF in a normative sense since historical usage across the broad HEA community (and from facility to facility) varies. In some cases, IRF has been used to mean specifically the X-ray product of the Ancillary Response File (ARF) and Redistribution Matrix File (RMF), whereas in other cases IRF has been used more generally to mean any instrumental response function regardless of type.

[5]For example, the energy matrix is a probability density function.

acteristics, and are usually defined for a specific time interval and may be decomposed into a standard set of independent components (see § 3.1.5 of (Servillat and Boisson et al., 2024)), such as the spatial point-spread function or the energy-migration matrix, where each component may be stored or computed separately. Since both IRFs and **event-list**s are required to analyze HEA data, some IVOA standards must be modified in order to expose both of them via the VO.

In the following, the current ObsCore standard will be discussed in § 3, focusing on attributes that need to be modified. Then, we propose the creation of a HEA extension of ObsCore in § 4, as some attributes are very specific to our domain. In these two sections, the discussion focuses on the attribute definitions rather on the attribute values. In § 5, enhancement of vocabulary is proposed for some ObsCore attributes, DataLink semantics, UCDs, and MIME-types.

3 ObsCore Attribute Definitions for High Energy Astrophysics Data

The ObsCore representation of any HEA **event-list** data products is described in terms of curation, coverage, and access. However, given the HEA data specificities, several properties, including resolutions, observable axis descriptions, and polarization states would be simply set to "NULL", and data axis lengths set to "-1". Therefore, for these data products and associated IRFs, the definitions of some ObsCore attributes should be adjusted so that they better represent the content of the data from the perspective of data discovery. We note that many properties, including spatial and spectral coverage and resolution can vary strongly with energy and off-axis angle. These adjustments will also typically apply to advanced, high-level data products derived from **event-list** data.

Currently, some ObsCore attributes (*dataproduct_type* and *calib_level*) are formally defined in the ObsCore Recommendation Version 1.1 (Louys and Tody et al., 2017) and also in the vocabularies documents (Demleitner and Gray et al., 2023, 2021)[6], which may be referenced in future versions of the ObsCore Recommendation. For completeness, we are proposing in this document modifications to both the existing ObsCore Recommendation and IVOA vocabularies.

3.1 *dataproduct_type*

The attribute *dataproduct_type* provides a scientific classification of the data product and is of primary importance for data discovery, especially when

[6] Primarily the Data Product Type Vocabulary, https://www.ivoa.net/rdf/product_type.

there may be many different types of data product associated with an observation[7] (as is often the case for HEA datasets).

The modifications/additions to the set of ObsCore Recommendation Version 1.1 (Louys and Tody et al., 2017) *dataproduct_type* (and, in some cases, *dataproduct_subtype*) terms described herein apply equally to the IVOA Data Product Type Vocabulary, and will therefore be repeated in § 5.

The ObsCore Recommendation Version 1.1 (Louys and Tody et al., 2017) defines an **event** *dataproduct_type* as:

> **event**: an event-counting (*e.g.*, X-ray or other high energy) dataset of some sort. Typically this is instrumental data, *i.e.*, "event data". An event dataset is often a complex object containing multiple files or other substructures. An event dataset may contain data with spatial, spectral, and time information for each measured event, although the spectral resolution (energy) is sometimes limited. Event data may be used to produce higher level data products such as images or spectra.

We propose to add the following *dataproduct_type* terms to ObsCore to better define a HEA **event-list** and an **event-bundle** that includes the **event-list** and associated data:

> **event-list**: a dataset that records a collection of observed particle-detection events, such as incoming high-energy particles, where an event is typically characterized by a spatial position, a time, and a spectral value (*e.g.*, an energy, a channel, a pulse height).
>
> **event-bundle**: a compounded dataset containing an **event-list** and multiple files or other substructures that are products necessary to analyze the event-list. Data in an **event-bundle** may thus be used to produce higher level data products calibrated in physical units when containing IRFs or other data products that can be used to construct IRFs.

We note that the term **event** has caused confusion in the past, since "event" may also used to describe notifications (*e.g.*, as in "VOEvent") of astrophysical events such as supernova explosions. Such "events" are quite different from the particle detection events being described herein. Using **event-list** will help to resolve this ambiguity.

In addition to *dataproduct_type* terms that focus on event data, we note that existing ObsCore definitions do not adequately span the breadth of "advanced data products" (typically with *calib_level* ≥ 3) that may be generated

[7] We use the term "observation" in the broad sense, as is done in the ObsCore Recommendation. We note that in this context an "observation" may not correspond to a single pointed observation defined in the traditional sense.

from astronomical observations by users or observatories. The computational complexity of analyzing HEA data robustly in the extreme Poisson regime (*e.g.*, Bayesian X-ray aperture photometry applied simultaneously to multiple overlapping detections and observations, or Frequentist adjustment of models of electron populations for multi-wavelength data spanning from X-rays to PeV gamma rays) means that data providers may choose to provide such analysis products directly to the end user. For example, the Chandra Source Catalog includes 38 types of advanced data products (for a total of $\sim$90 million files) and $\sim$50% of these data product types are not well represented by a *dataproduct_type* value that allows for meaningful data discovery. Users will certainly want to discover these data products independently from the associated progenitor observation data (and many of these data products combine data from multiple observations). We therefore propose the following additional *dataproduct_type* (or *dataproduct_subtype*) terms for these advanced data products, and note that these terms will certainly be useful independent of waveband (*i.e.*, they can be equally applicable to UV/optical, IR, and radio datasets):

> **draws**: a dataset that records statistical draws computed from a probability distribution, for example Markov chain Monte Carlo (MCMC) draws used when computing the Bayesian marginal probability density function for a random variable. The draws can be interpreted to provide a robust estimation of the probability distribution of variable, and correlations between the draws provide information about how well the draws converge to the parent probability distribution.[8]
>
> **pdf**: a dataset that records the probability density function of a quantity, for example the Bayesian marginal probability density function for a random variable, or the DeltaTS associated with a quantity from a Frequentist analysis. The probability density function provides a robust estimation of the variable and allows arbitrary confidence intervals to be computed directly from the distribution.
>
> **region**: a dataset that includes an encoding of (one or more) regions of parameter space, for example a spatial region or a region of phase space covered by a dataset. The set of dimensions represented by the region can be arbitrary.[9]

[8] As an example, within the standard ΛCDM cosmological model, estimates of the cosmological density parameters ΩM and $\Omega\Lambda$ can be derived from the intersection of confidence contours from Hubble diagram of quasars with those from the Type Ia supernovae (Czerny and Beaton et al., 2019). These contours are **draws**.

[9] One possible encoding is a Multi-Order-Coverage (MOC); however the vast majority of pre-existing region data products in HEA data archives currently use other encodings.

response-function: a dataset that records a mapping from a physical quantity to an observable quantity. For HEA, this may be the components of the composite IRF such as an Auxiliary Response File (**arf**), Redistribution Matrix File (**rmf**), Effective Area (**aeff**), Energy Dispersion (**edisp**), the Background Rate (**bkgrate**). The Point Spread Function (**psf**) is a response function that is generally applicable across multiple wavebands. While these datasets may generally be represented as an N-dimensional data cube, designating them as **response-functions** enhances data discovery for very common types of HEA dataset (see the use cases in Appendix A).

The **measurements** *dataproduct_type* is quite useful for many different types of advanced data products (which may be derived from multiple observations). But users of those products often may not be interested in the progenitor datasets, especially as multiple advanced data products may be extracted from the same single progenitor or a few progenitors (*e.g.*, measurements associated with multiple sources detected in a single observation field). We propose to delete the caveat associated with *dataproduct_type* = "measurements" in the ObsCore IVOA Recommendation (§ 4.1.1) that requires the derived data products be exposed "**together** with the progenitor observation dataset". The recovery of progenitor observation datasets may be achieved using provenance information, if desired.

3.2 *dataproduct_subtype*

The optional attribute *dataproduct_subtype* may be used by the data provider to specify more precisely the scientific nature of a data product. Although no vocabulary is defined for *dataproduct_subtype*, we recommend that data providers formulate and use a standardized vocabulary for this attribute for data products that are commonly used in HEA. We have proposed several terms in § 5 for commonly used HEA **response-function** types (*e.g.*, **aeff**, **edisp**, **psf**), but additional terms could be standardized for other common data products. For example, standardizing using **exposuremap** for an exposure map would enable queries such as (*dataproduct_type* = **image**) AND (*dataproduct_subtype* = **exposuremap**) to work across multiple facilities. Other possible terms could include (but are not limited to) **significancemap** for a significance map, **probabilitymap** for aprobability map, and **exclusionmap** for an exclusion map (*e.g.*, as used to adjust TeV background models).

3.3 *calib_level*

ObsCore defines calibration **Level 1** as "Instrumental data in a standard format (FITS, VOTable, SDFITS, ASDM, etc.) which could be manipulated with standard astronomical packages." and **Level 2** as "Calibrated, science ready data with the instrument signature removed."

However, some HEA **event-list**s include spatial and time axes that are calibrated physical quantities, but the spectral axis is instrumental and requires application of the IRFs to remove this signature. This is typically done because the **response-function**s can depend on the choice of region (spatial/time) from which the events are extracted (especially for telescope/detector combinations where the telescope position dithers on the sky during the exposure), which depends on the specific science case and therefore cannot be determined *a priori*. Such **event-list**s fall "between" *calib_level* 1 and 2.

On the other hand, other **event-list**s may not have any calibrated axes or may have all axes calibrated, and it is important to be able to differentiate between these for data discovery. While the value for *calib_level* for any data product is left for the data provider to determine, we suggest that individual data providers set *calib_level* = 1 if an **event-list** is considered to be "uncalibrated" according to normal usage for their data products, and set *calib_level* = 2 if an **event-list** is considered to be "calibrated" according to normal usage for their data products.

Also, we propose that the calibration status of the spatial/spectral/time data axes be identified using the appropriate axis ObsCore *calib_status* keyword (*s_calib_status* for the spatial axes, *em_calib_status* for the spectral axis, and *t_calib_status* for the time axis).

3.4 *access_url*

Given the complexity and number of HEA data products, the *access_url* may point either directly to a file (*e.g.*, to the **event-list** or an **event-bundle**), or to a DataLink service that will provide links to the data and to associated data (*e.g.*, **response-function**s).

If a DataLink is provided, *access_format* should be set to "application/x-votable+xml;content=datalink" to indicate that the URL points to a DataLink service.

If the *access_url* points to a bundle, the detailed content of the bundle is not exposed; therefore using a DataLink service has advantages.

3.5 *access_format*

The *access_format* attribute specifies the format of the data product when downloaded as a file from the *access_url*. The analysis of HEA data often requires use of multiple, related data products, for example an **event-list** combined with associated IRFs or ancillary files that can be employed by the user to create IRFs. These associated products are often bundled together with the **event-list** and we propose in § 3.1 to assign such bundles *dataproduct_type* = **event-bundle**. While these bundles are typically not standardized across different projects, knowledge of the bundle content is useful for client applications to properly handle the bundles (for example to send the data to an appropriate visualization tool). This is readily achieved by encoding an appropriate MIME-type using the *access_format* attribute. In Section 5.4 we propose additional MIME-types for some common **event-bundle**s.

3.6 *s_ra/s_dec*

We propose that the attributes *s_ra*/*s_dec* be redefined to be the ICRS right ascension and ICRS declination of "a reference position (typically the center)" of an observation on the sky, rather than the ICRS right ascension and ICRS declination of "the center" of the observation. For some facilities, the center (RA, Dec) may have a specific meaning (such as the location of the optical axis of the telescope), which often is not useful for advanced data products that may be extracted from a cut-out from the progenitor observation. Some facilities also allow an instrument to be displaced from the center of the focal plane, which means that the definition of "the center" of an observation may be unclear (especially when not tracking at sidereal rate or for facilities for which the PSF varies strongly across the telescope field of view). Since these cases effectively displace the observation field-of-view, ObsCore attributes such as *s_fov* that are implicitly referenced to (*s_ra*, *s_dec*) will continue to behave as expected using the revised definition.

For non-pointing instruments (which may include all-sky instruments such as KM3NeT or HAWC), these fields are poorly defined (as is the case, generally for observations that are drift scans). For the time duration of the observation, one can compute an effective center position of the exposure skymap and the maximum radius of the covered area (*i.e.*, for an all-sky instrument this would be 2π Sr solid angle in Alt/Az, which can be converted into a rotated area in RA/Dec). However, the utility of such a characterization depends on both the duration of the observation and the use case.

3.7 *s_calib_status*

We propose that *s_calib_status* encode the calibration status of an **event-list** dataset's spatial axes. Where multiple spatial axes are included in a dataset (*e.g.*, physical detector pixel coordinates, virtual detector coordinates corrected for distortions, world coordinates), we recommend that the data provider use the coordinate system that is most likely to be preferred by the end user (typically the most fully calibrated spatial axes) to define *s_calib_status*.

Under the (reasonable) assumption that an end-user searching for **event-bundle** datasets is typically querying based on the properties of the primary **event-list**, we suggest that those values also be used for the **event-bundle**. However, the data provider should ultimately decide which value best describes their **event-bundle** dataset.

For dataset types that do not encode sky coordinates, we suggest setting this value to “NULL”.

3.8 *t_calib_status*

We propose that *t_calib_status* encode the calibration status of an **event-list** dataset's time axis. Where multiple time axes are included in a dataset (*e.g.*, instrument counter, absolute time), we recommend that the data provider use the coordinate system that is most likely to be preferred by the end user (typically the most fully calibrated time axis) to define *t_calib_status*.

Under the (reasonable) assumption that an end-user searching for **event-bundle** datasets is typically querying based on the properties of the primary **event-list**, we suggest that those values also be used for the **event-bundle**. However, the data provider should ultimately decide which value best describes their **event-bundle** dataset.

For dataset types that do not encode time coordinates, we suggest setting this value to “NULL”.

3.9 *em_calib_status*

We propose that *em_calib_status* encode the calibration status of an **event-list** dataset's spectral axis. Where multiple spectral axes are included in a dataset (*e.g.*, PHA, PI, energy), we recommend that the data provider use the coordinate system that is most likely to be preferred by the end user (typically the most fully calibrated spectral axis) to define *em_calib_status*.

Under the (reasonable) assumption that an end-user searching for **event-bundle** datasets is typically querying based on the properties of the primary **event-list**, we suggest that those values also be used for the **event-bundle**. However, the data provider should ultimately decide which value best describes their **event-bundle** dataset.

For dataset types that do not encode spectral coordinates, we suggest setting this value to “NULL”.

3.10 *o_ucd*

For an **event-list**, we can consider that all measures stored in column values are observables. This is *the* fundamental difference between HEA **event-list**s and typical pixelated datasets. The current ObsCore Recommendation suggests that *o_ucd* be set to "NULL" for event lists. However this significantly hampers data discovery for HEA datasets. Since the data content of **event-list**s may vary significantly from facility to facility, meaningful discovery of HEA datasets *requires* the user be able to query the UCDs of the set of observables included in an **event-list**.

A natural way of doing this that is consistent with current usage would be to extend *o_ucd* to allow specification of *multiple* observables for **event-list**s (and **event-bundle**s), for example, *o_ucd = 'pos.eq;time;instr.event.pulseHeight'*.

We note that extending *o_ucd* to allow specification of multiple observables would require similar adjustments to the other observable axis attributes *o_unit*, *o_calib_status*, and *o_stat_err*.

Note that real **event-list**s may include an extensive set of columns (*e.g.*, a Chandra ACIS Level 1 **event-list** includes ∼20 columns, depending on observing mode) and several columns may represent similar (but not identical) observables (*e.g.*, event position in detector pixel coordinates, projected onto the focal surface, corrected for geometric distortions, corrected for spacecraft dither motion, mapped to world coordinates). Currently defined UCDs are not sufficiently fine-grained to be able to differentiate between these various cases. But that is very likely not necessary, since for data discovery purposes the user is typically interested in the "most calibrated" properties in each of the spatial/spectral/time(/polarization) axes (*e.g.*, world coordinates in the above example).

In the example *o_ucd* above, the UCD *instr.event.pulseHeight* is used to represent the detector Pulse Height Amplitude (PHA). There is currently no UCD defined for a raw measure like PHA, but we propose the addition of *instr.event.pulseHeight* to the UCDs list vocabulary, together with other UCDs that are relevant for HEA data, in § 5.3. Several additional UCDs, including electromagnetic spectrum, physical quantities, and statistical parameters UCDs, are also proposed in § 5.3 that are relevant for HEA data products but could also be of use for other domains such as cosmology.

Advanced data products may similarly record multiple observables that can only be differentiated through their UCDs. For example, a Chandra Source Catalog **pdf** dataset for a detection may include multiple marginalized probability density functions computed using a Bayesian X-ray aperture photometry algorithm in units of net counts, net count rates, photon fluxes, and energy fluxes in multiple apertures. The observables recorded in the different MPDFs may be distinguished by their UCDs which then become relevant for data discovery when a user is searching for specific aperture photometry datasets.

3.11 *proposal_id*

To support advanced data products that may be constructed using data from multiple progenitor observations, we propose to modify the ObsCore Recommendation for *proposal_id* to allow multiple values, similar to *facility_name* and *instrument_name*.

4 Extensions to ObsCore Specific to High Energy Astrophysics Data

4.1 *ev_xel*

The lengths of each data axis (spatial, spectral, time, polarization) captured in attributes *s_xel1*, *s_xel2*, *em_xel*, *t_xel*, *pol_xel* do not apply non-pixelated data including **event-list**s, and ObsCore recommends that these attributes be set to -1. However, the dimensionality of an event list is an important property for data discovery, as the number of events often scales with signal-to-noise (and also data volume scales with number of events). We propose to add a new, optional attribute *ev_xel* that records the number of events in an **event-list** (effectively, the length of the "events" axis in the **event-list**'s table).

4.2 *s_ref_energy/em_ref_energy/s_ref_oaa/em_ref_oaa*

For HEA datasets that typically span decades of energy, spatial resolution, sky coverage, and spectral resolution can be strongly dependent on particle energy. The ObsCore Recommendation suggests that in such circumstances a *characteristic* value be specified for the spatial and spectral characterization attributes (*e.g.*, *s_fov*, *s_region*, *s_resolution*, *em_res_power*, *em_resolution*). We propose adding optional attributes (*s_ref_energy* for spatial characterization attributes and *em_ref_energy* for spectral characterization attributes) that define the energy (in units of eV) at which these characteristic values are specified.

For some HEA datasets, these attributes vary strongly with position in the field of view, typically as a function of off-axis angle (*i.e.*, the angular separation of the target or source from the telescope optical axis). We similarly propose adding optional attributes (*s_ref_oaa* for spatial characterization attributes and *em_ref_oaa* for spectral characterization attributes) that define the off-axis angle (in units of degrees) at which these characteristic values are specified.

4.3 *t_intervals*

The global time bounds described by *t_min*/*t_max* in general are not sufficiently flexible when representing HEA datasets or advanced data products from any waveband. The former are typically composed of many Stable Time Intervals (STIs)/Good Time Intervals (GTIs), where data are only valid during the stable or good intervals, while advanced data products may be constructed from multiple progenitor observations that can span decades from the start time of the first observations to the stop time of the last observation (albeit very sparsely). For both cases, data queries using only *t_min*/*t_max* will not be adequate to determine whether useful scientific data coincide with a transient cosmic phenomenon. In such cases, a more detailed knowledge of the observation time coverage is necessary. We propose to add a new optional attribute *t_intervals* that would contain the list of observation intervals or STIs/GTIs as a TMOC description following the MOC IVOA standard (Fernique and Nebot et al., 2022). This element could then be compared across data collections to make the data set selection via simple intersection or union operations in TMOC representation.

We recognize that performing such queries will require enhancements to ADQL, but this capability is sufficiently important for some HEA data discovery scenarios that we have chosen to add *t_intervals*, in anticipation that ADQL will eventually provide this functionality.

4.4 *energy_min/energy_max*

The existing attributes *em_min* and *em_max* that define the coverage of the spectral axis (defined as wavelength expressed in units of m) are not user friendly for HEA where datasets are generally selected according to an energy range (*i.e.*, inverse wavelength) in units of eV (or scaled units of eV, for example keV, MeV, GeV, TeV, PeV). Unlike the radio domain where $\lambda = c/\nu$, where c is an almost universally remembered physical constant, the conversion $\lambda = hc/E$ is not simple for the user to express. As the spectral range covered by HEA data is many decades larger than for other wavebands, the accurate numerical representations of typical HEA spectral ranges as *em_min*/*em_max* requires quantities with many digits of precision and exponents ranging from $\sim 10^{-5}$–10^{-22}. Since specification of the spectral range is largely fundamental to data discovery in the HEA regime, we propose to add attributes *energy_min* and *energy_max* that specify the minimum and maximum spectral range values in units of eV. Note that the sense of these attributes is *opposite* that of *em_min* and *em_max* because of the inverse wavelength relationship between energy and wavelength, so numerical comparisons must be transposed (*e.g.*, $E > E_{\text{thresh}}$ becomes $\lambda < hc/E_{\text{thresh}}$). (An alternate approach would be to add attributes *em_min_energy* and *em_max_energy* that represent the energies corresponding to *em_min* and *em_max* in units of eV. This is less desirable since queries on an energy would need to be specified as $em\_max\_energy \leq E < em\_min\_energy$, which is likely confusing.)

The value of hc used to compute $\lambda = hc/E$ is $1.239841984332 \times 10^{-6}$ eV m based on the 2022 CODATA list of internationally recommended Fundamental Physical Constants[10] ($c = 299\,792\,458\,\mathrm{m\,s^{-1}}$ (exact); $h = 6.626\,070\,15 \times 10^{-34}\,\mathrm{J\,Hz^{-1}}$ (exact); $e = 1.602\,176\,634 \times 10^{-19}\,\mathrm{C}$ (exact)).

4.5 *obs_mode*

Many HEA instruments may be configured using multiple observing modes and these observing modes may significantly impact the structure and characteristics (*e.g.*, calibration accuracy) of the resulting observation datasets. For example, the Chandra ACIS instrument typically produces **event-list**s with 2-dimensional spatial coordinates (*i.e.*, imaging) but has an observation mode that continuously reads-out the detector, effectively producing an **event-list** with a single spatial dimension (the other spatial dimension is collapsed); users looking only for imaging data may want to restrict their queries to exclude the latter observing mode.

We propose to add an optional attribute *obs_mode* that allows the data provider to specify the observation mode for an observation. Constraints on observation mode can provide a simple way to discover data sets for a specific facility/instrument combination. We note that permissible *obs_mode* values will vary from facility to facility and from instrument to instrument.

4.6 *tracking_type*

Since most HEA facilities record the arrival times of particle events, data accumulated when the telescope pointing moves or rotates relative to the sky during an observation can be located on the sky. The way in which the telescope moves may impact how the data should be processed, especially for observations in which multiple different astrophysical sources may be present within the field of view (*e.g.*, a solar system target moving relative to the fixed celestial background). *Tracking* is defined by the normal motion of the optical axis of the telescope during an observation: fixed to a celestial coordinate (the most common case for ground telescopes with movable mounts, or those in space), fixed to a horizontal coordinate (also called a “drift scan”, and the standard case for telescopes without movable mounts), or fixed to a solar system body (*e.g.*, the moon, a planet, or a comet) position.

We propose to add an optional attribute *tracking_type* to distinguish these modes. Constraints on *tracking_type* can provide a simple way to

[10] https://physics.nist.gov/cuu/Constants/index.html

discover data sets for a specific facility/instrument combination. We propose predefined *tracking_type* values for HEA data include the following:

- `sidereal`: observations pointed at a fixed celestial target location on the sky;
- `fixed-az-el-transit`: observations fixed at a given elevation and azimuth;
- `solar-system-object-tracking`: observations pointed at a moving target, like the moon or other solar system bodies;
- `none`: observations with no telescope tracking.

We intend that the name of this attribute harmonizes with the name of the similar attribute in the proposed "IVOA Obscore Extension for Radio Data"[11] and note that the first three predefined values for *tracking_type* also harmonize with that proposal. The `none` *tracking_type* describes observations obtained while the telescope is not tracking (*e.g.*, observations obtained while the telescope is slewing). We further note that permissible *tracking_type* values may vary from facility to facility and from instrument to instrument and additional values beyond the predefined values are possible.

4.7 *scan_mode*

Some HEA facilities can obtain observations using different spatial scan modes that will affect the content of the observation, leading to different instrument responses and special analysis schemes. We propose to add an optional attribute *scan_mode* to distinguish these modes. Constraints on **scan_mode** can provide a simple way to discover data sets for a specific facility/instrument combination. We propose predefined *scan_mode* values for HEA data include the following:

- `on-source`: pointed observation;
- `on-off`: switched observations between two spatial positions (source and background);
- `raster-map`: observations on a predefined spatial mesh (generally regular and rectangular (*e.g.*, a grid observation for Imaging Atmospheric Cherenkov Telescopes (IACTs));
- `on-the-fly-cross-scan`: observations along a predefined spatial pattern;

[11] https://github.com/ivoa-std/ObsCoreExtensionForRadioData.

- `on-the-fly-cross-map`: observations along parallel directions (*e.g.*, a wobble observation for IACTs);
- `slew` : observations taken while the telescope is slewing.

We intend that the name of this attribute harmonizes with the name of the similar attribute in the proposed "IVOA Obscore Extension for Radio Data"[12] and note that the first five predefined values for *scan_mode* also harmonize with that proposal. The `slew` *scan_mode* describes observations obtained while the telescope is slewing (*i.e.*, where the field of view moves with arbitrary direction and speed while the telescope is repositioning), which is a mode used extensively by some satellite-based HEA facilities. We further note that permissible *scan_mode* values may vary from facility to facility and from instrument to instrument and additional values beyond the predefined values are possible.

4.8 *pointing_mode*

Some HEA facilities can obtain observations using multiple telescope simultaneously with the individual telescopes pointing in slightly different directions. For example, for the IACTs telescope array, the individual telescope pointings may be in the same direction, convergent, or divergent. We propose to add an optional attribute *pointing_mode*, with a default value of "NULL" to handle Water Cherenkov Detector (WCD) and neutrino instruments, to distinguish these modes. Constraints on *pointing_mode* can provide a simple way to discover data sets for a specific facility/instrument combination. We propose predefined *pointing_mode* values for HEA data include the following:

- `parallel`: the telescopes are all pointing in the same direction;
- `convergent[-ang]`: the telescope pointings are convergent;
- `divergent[-ang]`: the telescope pointings are divergent.

The optional suffix "[-ang]" specifies a reference angle for a convergent or divergent pointing, for example "convergent-5d". We note that permissible *pointing_mode* values may vary from facility to facility and from instrument to instrument.

4.9 *analysis_mode*

Most HEA instruments employ significant software processing to transform raw data into the **event-bundle** data exposed to users, including algorithms

[12] https://github.com/ivoa-std/ObsCoreExtensionForRadioData.

for calibration and event property reconstruction. The way in which this processing is configured therefore has a potentially large impact the content of the reduced datasets; indeed the same observation processed with two different configurations may result in different scientific performance. In some cases, multiple processing configurations within the same observation collection are used to provide users with a wider range of scientific coverage.

We propose to add an optional attribute **analysis_mode** that allows the data provider to specify the data reduction/analysis mode for an observation, in case more than one is applied. Constraints on analysis mode can provide a simple way to discover data sets for a specific facility/instrument combination. We note that permissible **analysis_mode** values may vary from facility to facility and from instrument to instrument.

4.10 *event_type*

Some HEA instruments allow particle events to be partitioned into separate subsets based on some set of defined criteria. This is typically based on a data analysis quality associated with the reconstruction and discrimination of the events, and analyses can flag each event by a quality label, effectively partitioning the dataset into strictly disjoint event subsets. For each subset, a set of associated **response-function**s can be separately computed[13].

We propose to add an optional attribute *event_type* that specifies the data quality flag for an observation. This attribute will allow the data provider to split the event list into several event lists labelled by an unique *event_type* for a given observation, and if appropriate to distribute their associated IRFs. Constraints on event type can provide a simple way to discover data sets for a specific facility/instrument combination and to reduce the downloaded data volume. We note that permissible *event_type* values may vary from facility to facility and from instrument to instrument.

4.11 Additional Columns

Similar to the ObsCore Recommendation, service providers may include additional columns to the ObsCore HEA Extension table to expose additional metadata. While the service provider may choose to add additional columns to either the main ObsCore table or the ObsCore HEA Extension table, we recommend that HEA-data specific metadata columns be added to the ObsCore HEA Extension table.

[13]For example, the Fermi-LAT collaboration produces separate IRFs for each event type; see https://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_LAT_IRFs/IRF_overview.html.

5 Vocabulary Enhancements

5.1 Evolution of the Data Product Type Vocabulary

The IVOA Data Product Type Vocabulary[14] provides terms, labels, and descriptions for many types of astronomical data products. However, there are some additions and changes that are appropriate to better support HEA datasets.

We propose to add vocabulary entries for the new data product types outlined in § 3.1 and also propose to slightly modify the existing definition of **event-list** so that it aligns more accurately with the definition in that section. Additionally, we propose to add several more specific entries to the data product type vocabulary that specialize these types (especially **response-function**).

5.1.1 Event List

We first propose to more precisely define an **event-list**:

> **event-list**: A dataset that records a collection of observed particle-detection events, such as incoming high-energy particles, where an event is typically characterized by a spatial position, a time, and a spectral value (*e.g.*, an energy, a channel, a pulse height).

5.1.2 Response Functions

We then propose to add the following data product type to define response functions (IRFs).

> **response-function**: A dataset that records the mapping from a physical quantity to an observable quantity. Narrower terms are preferred to indicate more precisely the type of **response-function**.

The following data product types specialize **response function**. Note that while most of these are primarily used in HEA, the point spread function (**psf**) is a **response-function** that is generally applicable across multiple wavebands.

> **aeff**: A dataset that records the "effective area" of a telescope and/or instrument. The effective area is the geometric area of the telescope and/or instrument reduced by efficiency factors such as reflectivity and vignetting, among other effects (Deil and Wood et al., 2022).

[14] See http://www.ivoa.net/rdf/product-type.

arf: A dataset that records the combined telescope/instrument effective area and detector quantum efficiency as a function of energy (George and Arnaud et al., 1998).

bkgrate: A dataset that models the rate of residual events that are not from the expected source type (*e.g.*, for gamma-ray instruments **bkgrate** measures residual non-gamma-ray events coming from charged cosmic rays) (Deil and Wood et al., 2022).

edisp: A dataset that records the probability density of detecting an event with an energy estimator (proxy) given the true energy of the event (Deil and Wood et al., 2022).

psf: A dataset that records the probability density function of spatial/angular spreading of incident particles from a point source caused by the instrument (detector and/or mirror and/or analysis) (Deil and Wood et al., 2022; George and Yusaf, 2011).

rmf: A dataset that records the probability density function mapping from energy space into detector pulse height (or position) space (George and Arnaud et al., 1998).

5.1.3 Event Bundle

Some use cases require access to a bundle of datasets that includes the **event-list** and associated data products. We define an **event-bundle**:

> **event-bundle**: A compounded dataset containing an **event-list** and multiple files or other substructures that are products necessary to analyze the event-list. Data in an **event-bundle** may thus be used to produce higher level data products calibrated in physical units when containing IRFs or other data products that can be used to construct IRFs.

An **event-bundle** might for example consist of an **event-list** and the associated **response-function**s used to calibrate the dataset, and may also contain provenance information, data quality time-series, and preview images or plots.

5.1.4 Advanced Data Products

In addition to data product types that focus on event data, we note that existing ObsCore definitions do not adequately span the breadth of advanced data products (typically with *calib_level* ≥ 3) that may be generated from astronomical observations. The computational complexity of analyzing HEA data robustly in the extreme Poisson regime (*e.g.*, Bayesian X-ray aperture photometry applied simultaneously to multiple overlapping detections and observations) means that data providers may choose to provide such analysis products directly to the end user.

Users will certainly want to discover these data products independently from the associated progenitor observation data (and many of these data products combine data from multiple observations). We therefore propose the following additional data product types for these advanced data products, and note that these data product types will certainly be useful independent of waveband (*i.e.*, they can be equally applicable to UV/optical, IR, and radio datasets):

draws: A dataset that records statistical draws computed from a probability distribution, for example Markov chain Monte Carlo (MCMC) draws used when computing the Bayesian marginal probability density function for a random variable. The draws can be interpreted to provide a robust estimation of the probability distribution of variable, and correlations between the draws provide information about how well the draws converge to the parent probability distribution.

pdf: A dataset that records the probability density function of a quantity, for example the Bayesian marginal probability density function for a random variable. The probability density function provides a robust estimation of the variable and allows arbitrary confidence intervals to be computed directly from the distribution.

region: A dataset that includes an encoding of (one or more) regions of parameter space, for example a spatial region or a region of phase space covered by a dataset. The set of dimensions represented by the region can be arbitrary.

5.1.5 Summary Table

The proposed vocabulary entries are listed in Table 1 with their labels and parents identified.

Term	Label	Description	Parent
aeff	Effective Area	A dataset that records the “effective area” of a telescope and/or instrument. The effective area is the geometric area of the telescope and/or instrument reduced by efficiency factors such as reflectivity and vignetting, among other effects	#response-function
arf	Ancillary Response File	A dataset that records the combined telescope/instrument effective area and detector quantum efficiency as a function of energy	#response-function
bkgrate	Background Rate	A dataset that models the rate of residual events that are not from the expected source type (*e.g.*, for gamma-ray instrument **bkgrate** measures residual non-gamma-ray events coming from charged cosmic rays)	#response-function
draws	Draws	A dataset that records statistical draws computed from a probability distribution, for example Markov chain Monte Carlo (MCMC) draws used when computing the Bayesian marginal probability density function for a random variable	#measurements
edisp	Energy Dispersion	A dataset that records the probability density of detecting an event with an energy estimator (proxy) given the true energy of the event	#response-function, #pdf
event-bundle	Event Bundle	A compounded dataset containing containing an **event-list** and multiple files or other substructures that are products necessary to analyze the **event-list**	

event-list	Event list	A dataset that records a collection of observed particle-detection events, such as incoming high-energy particles, where an event is typically characterized by a spatial position, a time, and a spectral value (*e.g.*, an energy, a channel, a pulse height)	#temporally-resolved-dataset
pdf	Probability Density Function	A dataset that records the probability density function of a quantity, for example the Bayesian marginal probability density function for a random variable	#measurements
psf	Point Spread Function	A dataset that records the probability density function of spatial/angular spreading of incident particles from a point source caused by the instrument (detector and/or mirror and/or analysis)	#response-function, #pdf
region	Region	A dataset that encodes (one or more) regions of parameter space, for example a spatial region or a region of phase space covered by a dataset. The set of dimensions represented by the region can be arbitrary	#measurements
response-function	Response Function	A dataset that maps a physical quantity to an observable quantitiy. This term is mainly intended for retrieval. To annotate datasets, use a narrower term Narrower terms are preferred to indicate more precisely the type of **response-function**	
rmf	Redistribution Matrix File	A dataset that records the probability density function mapping from energy space into detector pulse height (or position) space	#response-function, #pdf

Table 1: IVOA Data Product Type Vocabulary Extension

5.1.6 Clarification of "Flux" in Data Product Type Vocabulary Definitions

We propose to clarify the IVOA Data Product Type Vocabulary[15] definitions that use the word "flux" in the description of some terms, currently **light-curve**, **polarization-resolved-dataset**, **polarized-spectrum**, and **spectrum**, so that the definitions are applicable to HEA data products.

The issue is that the term "flux" is not defined in the vocabulary, and the standard astronomical definition of "flux" is an energy flux (with SI units $\mathrm{W\,m^{-2}}$). This interpretation is bolstered by the statements "flux or magnitude" applied to several of the descriptions since optical/IR magnitude and energy flux density are tightly related. However, with this definition, many HEA data products that may have fluxes defined using units of counts or particles (*e.g.*, photons), but not calibrated in units of energy, would not satisfy the current descriptions of (*e.g.*) **light-curve** or **spectrum**, even though that is how those products are used.

For HEA, because the mappings between observed counts, incident particles, and incident particle energy depend on the **response-function**s (which in some cases may not be determinable without knowledge of the individual science use case) we often use several definitions of photometric properties such as flux, radiance, and flux density:

- Counts flux, with units counts $\mathrm{m^{-2}\,s^{-1}}$,
- Counts radiance (flux per steradian), with units counts $\mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$,
- Counts flux density (differential flux), with units counts $\mathrm{m^{-2}\,s^{-1}\,eV^{-1}}$,
- Particle flux, with units particles $\mathrm{m^{-2}\,s^{-1}}$,
- Particle radiance (flux per steradian), with units particles $\mathrm{m^{-2}\,s^{-1}\,sr^{-1}}$,
- Particle flux density (differential flux), with units particles $\mathrm{m^{-2}\,s^{-1}\,eV^{-1}}$,
- Energy flux, with units $\mathrm{J\,m^{-2}\,s^{-1}}$,
- Energy radiance (flux per steradian), with units $\mathrm{J\,m^{-2}\,s^{-1}\,sr^{-1}}$,
- Energy flux density (differential flux), with units $\mathrm{J\,m^{-2}\,s^{-1}\,eV^{-1}}$.

The common HEA flux, radiance, and flux density definitions listed above are not all covered by the UCD vocabulary. We propose to add new UCDs in § 5.3 below to address this, and where appropriate refine the definitions of existing UCDs based on dimensionality. With the proposed additions and refinements, we can, for example, easily distinguish

[15] https://www.ivoa.net/rdf/product_type.

between a counts flux with UCD *phot.counts*, a photon flux with UCDs *phot.flux.particle;phys.particle.photon*, and an energy flux with UCD *phot.-flux.energy*. These refinement will also be particularly useful for cases where a HEA quantity should have the same UCD as (*e.g.*) a radio measurement but where very different units are used. For example, Jy (Jansky) and $\mathrm{erg\,cm^{-2}\,s^{-1}\,TeV}$ are both spectral flux densities but the unit analysis doesn't agree due to the frequency-energy equivalency.

Restating the existing IVOA Data Product Type Vocabulary descriptions that use the term "flux" to explicitly state "count/particle/energy flux or magnitude" where appropriate would resolve the concern raised above with the current use of the term "flux".

5.2 DataLink Vocabularies

For some use cases, we proposed to expose the different associated datasets via Datalink. Each Datalink is described by several attributes, including the mandatory *semantics* attribute and a *content_ qualifier*.

The terms defined for response functions (see § 5.1.2) may thus be used to fill the *content_ qualifier* attributes, with *semantics* = "#**calibration**".

5.3 UCD Enhancements

5.3.1 Electromagnetic Spectrum

We propose correcting and extending the current list of UCD gamma-ray domain definitions to include the High Energy (HE), Very High Energy (VHE), and Ultra High Energy (UHE) gamma-ray domains. Their associated energy ranges are described in Table 2.

5.3.2 Instrument-related Quantities

We propose to add a new UCD *instr.event* as the base of the hierarchy to describe instrument-related properties of particle events detected by HEA detectors. Initially, we propose a small set of event-related UCDs that identify key properties that are particularly important for HEA data analysis.

Event Grade For imaging X-ray instruments (especially those based on CCD detectors), detected events typically deposit charge into more than a single detector pixel. The events are assigned a "grade" based on how charge is deposited into the central pixel and surrounding pixels, and the grade information is essential for data analysis since typically only a subset of grades will correspond to valid events. We propose to add a new UCD *instr.event.grade* that identifies event grades.

Pulse Height For many X-ray and gamma-ray instruments, the signal observed in a given detector spectral channel is the result of event counting and would typically be recorded as a Pulse Height Amplitude (PHA), or perhaps a Pulse Invariant (PI) value that is calculated from PHA by applying an appropriate gain calibration. The PHA (or PI) can be related to the incident particle energy by applying the appropriate **response-function**, and higher data calibration level products may replace or augment these values with quantities such as energy, or perhaps particle or energy flux.

There is currently no UCD defined for a raw pulse height amplitude measure like PHA (or PI). PHA is such an important quantity to HEA datasets that we propose adding a new UCD *instr.event.pulseHeight* for these raw data values. We note that the background signal (both of instrumental and cosmological origin) may be significant for many HEA detectors and so the detected events may be unrelated to any observed source on the sky.

One previously proposed solution suggested using the combination of existing UCDs *src.var.amplitude;src.var.pulse;stat.uncalib* for PHA, but this is not appropriate since the connection to *src* ("observed source viewed on the sky") is misleading and *src.var.amplitude* is defined as the "amplitude of variation" of the source which is a completely separate concept from an astronomical perspective.

Event Type For Very High Energy (VHE) (and GeV) gamma-ray data, there is the notion of event type (see § 4.10) that can be mandatory for some data releases. We propose to add a new UCD *instr.event.type* that identifies these data values.

5.3.3 Physical Quantities

The messengers for HEA observations may include particles other than the ones currently described in the UCD list. Because some instruments can now distinguish electrons from positrons[16], as well antiprotons from protons[17], we also propose to add *phys.particle.positron* and *phys.particle.antiproton*, as well as *phys.particle.cosmicray* and unify them all under the *phys.particle* UCD hierarchy.

One should note that electrons are denoted by the UCD *phys.electron* in the current version of the UCD list (Cecconi and Louys et al., 2024) and are inappropriately not grouped under the *phys.particle* hierarchy. This causes some inconsistencies that could be solved by marking *phys.electron* (and *phys.electron.degen*) as obsolete or not recommended, and adding the term *phys.particle.electron* to the UCD list.

[16]For example, the Fermi-LAT instrument.
[17]For example, the AMS-2 experiment.

Finally, we propose to add the most commonly used astronomical messenger to the UCD list as *phys.particle.photon*.

5.3.4 Statistical Parameters

Since statistical lower and upper limits play a significant role in HEA data analysis, we propose adding new UCDs *stat.lowerlimit* and *stat.upperlimit* to explicitly identify data quantities as lower or upper limits. We suggest that the existing UCDs *stat.min* and *stat.max* be restricted to meaning the minimum and maximum statistic, rather than the current definitions "Minimum or lowest limit" and "Maximum or upper limit", which blend statistical confidence intervals and limits into a single UCD. A specification of a confidence level is necessary for the user to interpret both confidence intervals and lower/upper limits meaningfully, and this level can be described by the existing UCD *stat.confidenceLevel*.

The shape of any statistical distribution is an essential quantity for interpreting the meaning of any statistical properties. Too often a Gaussian distribution or a distribution that can be characterized by a simple set of moments (*e.g.*, mean, variance, skewness, kurtosis) are assumed, but in the extreme Poisson regime common in HEA these assumptions are often invalid. We propose adding a UCD *stat.distribution* to identify a quantity that defines the distribution of a statistical variable such as a likelihood profile.

5.3.5 Evolution of UCD list

The proposed new UCD entries are listed in Table 2 with their descriptions, while proposed revisions to existing UCD entries are listed in Table 3.

	UCD word	**Description**
S	*em.gamma.he*	High-Energy gamma ray (100 MeV – 10 GeV)
S	*em.gamma.vhe*	Very-High-Energy gamma ray (10 GeV – 100 TeV)
S	*em.gamma.uhe*	Ultra-High-Energy gamma ray ($>$ 100 TeV)
Q	*instr.event*	Particle event detection
Q	*instr.event.grade*	Particle event grade
Q	*instr.pulseHeight*	Pulse height amplitude measure
Q	*instr.event.type*	Particle event type
E	*phot.count.density*	Count flux density (dimensionality: $[\mathrm{L}^{-2}\,\mathrm{T}^{-1}\,\mathrm{E}^{-1}]$)
E	*phot.count.density.sb*	Count flux density surface brightness (dimensionality: $[\mathrm{L}^{-2}\,\mathrm{T}^{-1}\,\mathrm{E}^{-1}\,\mathrm{sr}^{-1}]$)
E	*phot.count.radiance*	Count flux radiance (dimensionality: $[\mathrm{L}^{-2}\,\mathrm{T}^{-1}\,\mathrm{sr}^{-1}]$)

E	*phot.count.sb*	Count flux surface brightness (dimensionality: $[\mathrm{L^{-2}\,T^{-1}\,sr^{-1}}]$)
E	*phot.flux.energy*	Energy flux or irradiance (dimensionality: $[\mathrm{M\,T^{-3}}]$)
E	*phot.flux.energy.density*	Energy flux density (dimensionality: $[\mathrm{M\,T^{-3}\,E^{-1}}]$)
E	*phot.flux.energy.density.sb*	Energy flux density surface brightness (dimensionality: $[\mathrm{M\,T^{-3}\,E^{-1}\,sr^{-1}}]$)
E	*phot.flux.energy.sb*	Energy flux surface brightness (dimensionality: $[\mathrm{M\,T^{-3}\,sr^{-1}}]$)
E	*phot.flux.particle*	Particle flux or irradiance (dimensionality: $[\mathrm{L^{-2}\,T^{-1}}]$)
E	*phot.flux.particle.density*	Particle flux density (dimensionality: $[\mathrm{L^{-2}\,T^{-1}\,E^{-1}}]$)
E	*phot.flux.particle.density.sb*	Particle flux density surface brightness (dimensionality: $[\mathrm{L^{-2}\,T^{-1}\,E^{-1}\,sr^{-1}}]$)
E	*phot.flux.particle.radiance*	Particle flux radiance (dimensionality: $[\mathrm{L^{-2}\,T^{-1}\,sr^{-1}}]$)
E	*phot.flux.particle.sb*	Particle flux surface brightness (dimensionality: $[\mathrm{L^{-2}\,T^{-1}\,sr^{-1}}]$)
S	*phys.particle.antiprotron*	Related to anti-proton
S	*phys.particle.cosmicray*	Related to cosmic rays particles
S	*phys.particle.electron*	Related to electron
S	*phys.particle.photon*	Related to photon
S	*phys.particle.positron*	Related to positron
P	*stat.distribution*	Type or shape of statistical distribution
P	*stat.error.negative*	Negative statistical error
P	*stat.error.positive*	Positive statistical error
P	*stat.lowerlimit*	Lower limit
P	*stat.upperlimit*	Upper limit

Table 2: Proposed New UCD Entries

	UCD word	**Description**
S	*em.gamma.hard*	Hard gamma ray (500 keV – 100 MeV)
P	*stat.confidenceLevel*	Level of confidence for a statistical measure, detection, or classification process
E	*phot.count*	Count flux (dimensionality: $[\mathrm{L^{-2}\,T^{-1}}]$)
E	*phot.fluence*	Radiant photon energy received by a surface per unit area or irradiance of a surface integrated over time of irradiation (dimensionality: $[\mathrm{L^{-2}}]$)

Q	*phot.flux.bol*	Bolometric flux (dimensionality: $[\mathrm{M\,T^{-3}}]$)
E	*phot.radiance*	Radiance as energy flux per solid angle (dimensionality: $[\mathrm{M\,T^{-3}\,sr^{-1}}]$)
S	*phys.electron*	Electron (not recommended/deprecate)
S	*stat.min*	Minimum value
S	*stat.max*	Maximum value

Table 3: Proposed Revised UCD Entries

5.4 MIME-type Enhancements

Data files used in the HEA domain should have appropriate MIME-types, so that they can be included in ObsCore tables or elsewhere.

Many HEA FITS format data products will comply with existing MIME-types discussed in the ObsCore Recommendation, such as **application/fits** or **application/x-fits-bintable**. However, the gamma-ray community has developed two additional data format standards and we propose to add the following MIME-types:

- **x-fits-gadf**: for FITS files following the Gamma-Astro-Data-Format (GADF) specification (Deil and Wood et al., 2022),
- **x-fits-vodf**: for FITS files following the Very-high-energy Open Data Format (VODF) specification (Khélifi and Zanin et al., 2023).

6 Proposed ivoa.obscore_hea Table Attributes

This section summarizes the proposal for the HEA extension of ObsCore. We use the term *ivoa.obscore_hea* to described the extension here and in Appendix A.

Column Name	**UType**	**Unit**	**Type**	**Description**	**MAN**
ev_xel	TBD	unitless	integer	Number of events in an event list	NO
s_ref_energy	TBD	eV	double	Energy at which the ObsCore spatial characterization attributes *s_fov*, *s_region*, *s_resolution* are defined	NO
em_ref_energy	TBD	eV	double	Energy at which the ObsCore spectral characterization attributes *em_res_power*, *em_resolution* are defined	NO
s_ref_oaa	TBD	deg	double	Off-axis angle (*i.e.*, the angular separation of the target or source from the telescope optical axis) at which the ObsCore spatial characterization attributes *s_fov*, *s_region*, *s_resolution* are defined	NO
em_ref_oaa	TBD	deg	double	Off-axis angle (*i.e.*, the angular separation of the target or source from the telescope optical axis) at which the ObsCore spectral characterization attributes *em_res_power*, *em_resolution* are defined	NO
t_intervals	TBD	unitless	string	List of observation intervals or stable/good time intervals describing the exact observation time coverage as a TMOC	NO
energy_min	TBD	eV	double	Energy associated to the ObsCore attribute *em_max*, describing the minimum energy of the dataset	NO
energy_max	TBD	eV	double	Energy associated to the ObsCore attribute *em_min*, describing the maximum energy of the dataset	NO
obs_mode	TBD	unitless	string	Observation mode of an observation	NO
tracking_type	TBD	unitless	string	Tracking type of an observation	NO
scan_mode	TBD	unitless	string	Scan mode of an observation	NO
pointing_mode	TBD	unitless	string	Pointing mode of an observation	NO
analysis_mode	TBD	unitless	string	Data reduction/analysis mode	NO
event_type	TBD	unitless	string	Event subset indicator (*e.g.*, data quality flag for the events)	NO

Table 4: Attributes for the HEA Extension of ObsCore

References

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A Detailed Science Use Cases for ObsCore

A.1 Event-List Data and Responses

A.1.1 Use Case — Search for event lists surrounding Sgr A*, for example for an X-ray morphological study

Identify all HEA event lists encompassing Sgr A for initial selection for subsequent X-ray morphological studies. Since the focus is on X-ray morphological studies, only the event lists and not the event bundles are desired.*

Find all datasets satisfying:

(i) Target name = "Sgr A*" or position inside 30 arcmin from (266.4168, −29.0078),

(ii) dataproduct_type = "event-list".

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(target_name = 'Sgr A*' OR
CONTAINS(POINT(s_ra, s_dec), CIRCLE, 266.4168, -29.0078, 0.5) = 1)
AND (dataproduct_type = 'event-list')
```

A.1.2 Use Case — Search for event lists that include a fully calibrated spectral axis for BL Lac for rapid X-ray spectrophotometric evaluation

Identify all event lists that include the BL Lac, have a fully calibrated spectral axis (i.e., spectral responses have already been applied), and have at least 10,000 events. These data will be used to prepare slides for a presentation. Note that since calib_status = 2 may not specify that the spectral axis is fully calibrated in physical units (HEA event lists are often considered "calibrated" even if the spectral axis is in pulse height units) the calibration status of the spectral axis must be checked explicitly.

Find all datasets satisfying:

(i) Target name = "BL Lac" or position inside 5 arcmin from (330.680338, +42.27777),

(ii) dataproduct_type = "event-list",

(iii) calib_level ≥ 2,

(iv) em_calib_status = "calibrated",

(v) ev_xel ≥ 10000.

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(target_name = 'BL Lac' OR
CONTAINS(POINT(s_ra, s_dec), CIRCLE, 330.680338, +42.27777, 0.083333) = 1)
AND (dataproduct_type = 'event-list')
AND (calib_level >= 2)
AND (em_calib_status = 'calibrated')
AND (ev_xel >= 10000)
```

A.1.3 Use Case — Search for SWGO event lists and their IRFs for the event type 'very-good' in the region of Cygnus loop for a TeV spectromorphology study

Identify all event lists and their associated IRFs of the region of Cygnus loop (3° diameter) taken with SWGO. Only data of the event type 'very-good' are selected, in order to limit the amount of downloaded data.

Find all SWGO datasets satisfying:

(i) s_region position intersects with the source modeled by a circle of 1.5 deg around (312.775, 30.683),

(ii) dataproduct_type = "event-list" or "aeff" or "edisp" or "psf" or "bkgrate",

(iii) obs_collection = "SWGO-DR1",

(iv) event_type = "very-good".

First, run the ObCore query:

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE (INTERSECTS(s_region, CIRCLE(312.775, 30.683, 1.5)) = 6)
AND (dataproduct_type = 'event-list' OR dataproduct_type = 'aeff'
  OR dataproduct_type = 'edisp' OR dataproduct_type = 'psf'
  OR dataproduct_type = 'bkgrate')
AND (obs_collection = 'SWGO-DR1')
AND (event_type = 'very-good')
```

Then, for each row of the output, we identify the nature of the data product, and retrieve them using the "access_url".

A.1.4 Use Case — Search for event bundles via DataLink that include Cas A for a TeV spectromorphology study

Identify all event bundles (event lists and their associated IRFs) that include the Cas A SNR for subsequent TeV spectromorphology studies from a VERITAS data release. Since the instrumental responses are mandatory to remove instrumental effects, the event bundles that include the IRFs are required.

Find all VERITAS datasets satisfying:

(i) Target name = “Cas A” or position inside 2.5 arcmin from (350.8584, +58.8113),

(ii) dataproduct_type = “event-bundle”,

(iii) obs_collection = “VERITAS-DR1”,

(iv) access_format = “datalink”.

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(target_name = 'Cas A' OR
CONTAINS(POINT(s_ra, s_dec), CIRCLE, 350.8584, +58.8113, 0.042) = 2)
AND (dataproduct_type = 'event-bundle')
AND (obs_collection = 'VERITAS-DR1')
AND (access_format = 'application/x-votable+xml;content=datalink')
```

Then, for each row of the output, we get the “access_url” of the DataLink to provide access to the data.

A.1.5 Use Case — Search for event bundles that include Cas A for X-ray spectrophotometric evolution studies

Identify all event bundles that include the Cas A SNR and have at least 1 million events for subsequent spectrophotometric studies of the SNR expansion. Since only a few observations are expected to match this request and because the focus is on X-ray spectrophotometric studies, the event bundles that include the responses or the ancillary products used to make the responses are required.

Find all datasets satisfying:

(i) Target name = “Cas A” or position inside 10 arcmin from (350.8584, +58.8113),

(ii) dataproduct_type = “event-bundle”,

(iii) ev_xel $\geq$ 1000000.

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(target_name = 'Cas A' OR
CONTAINS(POINT(s_ra, s_dec), CIRCLE, 350.8584, +58.8113, 0.16667) = 1)
AND (dataproduct_type = 'event-bundle')
AND (ev_xel >= 1000000)
```

A.1.6 Use Case — Search for event lists and their IRFs of CTAO South observations at energies above 10 TeV for blind search of PeVatrons from a data release using DataLink

Identify all event bundles (event lists and their associated IRFs) taken by CTAO South that contains events above 10 TeV. Data taken with the Small Size Telescopes or Medium Size Telescopes can be then selected.

Find all CTAO datasets satisfying:

(i) dataproduct_type = "event-bundle",

(ii) obs_collection = "CTAO-DR1",

(iii) access_format = "datalink",

(iv) instrument_name contains "CTAO-S",

(v) energy_max >= 10^{12}.

First, run the ObCore query:

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE (dataproduct_type = 'event-bundle')
AND (obs_collection = 'CTAO-DR1')
AND (access_format = 'application/x-votable+xml;content=datalink')
AND (instrument_name LIKE 'CTAO-S')
AND (energy\_max >= 1.0e+12)
```

The query output is a VOTable that follows the DALI specification.
We process this VOTABLE to access to the data:

(i) for each row of the query output, get the "obs_id" and the "access_url" of the DataLink,

(ii) get the VOTABLE associated with the "access_url",

(iii) for each row of the VOTABLE, get the "content_qualifier" and the "accessURL",

(iv) download the data associated to each "accessURL".

```
FOR EACH ROW OF OUTPUT_VOTABLE:
  OBS_ID = OUTPUT_VOTABLE['ID']
  DATALINK_TABLE = GET OUTPUT_VOTABLE['access_url']
  FOR EACH ROW OF DATALINK_TABLE:
    - IF ROW['content_qualifier'] = 'aeff'
     AEFF_FILE['OBS_ID'] = GET RAW['accessURL']
    - IF ROW['content_qualifier'] = 'edisp'
     EDISP_FILE['OBS_ID'] = GET RAW['accessURL']
    - IF ROW['content_qualifier'] = 'psf'
     PSF_FILE['OBS_ID'] = GET RAW['accessURL']
    - IF ROW['content_qualifier'] = 'bkgrate'
     BKGRATE_FILE['OBS_ID'] = GET RAW['accessURL']
    - IF ROW['content_qualifier'] = 'event-list'
     EVENT_FILE['OBS_ID'] = GET RAW['accessURL']
```

A.1.7 Use Case — Search for spatially resolved spectropolarimetric observations of the Crab with spectral resolution R > 100

Identify all event bundles for observations of the Crab that intersect the 1.0–100.0 keV energy range, have calibrated spatial and time axes, are spatially resolved in 2 dimensions in equatorial coordinates, have spectral resolution $R > 100$*, and include polarimetry measurements. Note that ObsCore specifies that the axes lengths — s_xel1, s_xel2, em_xel, t_xel, pol_xel — should be set to* -1 *for non-pixelated data like event lists, so these quantities are not useful for this query.*

Find all datasets satisfying:

(i) Target name = "Crab" or position inside 5 arcmin from (83.6324, +22.0174),

(ii) dataproduct_type = "event-bundle",

(iii) calib_level ≥ 2,

(iv) s_resolution > 100,

(v) energy_min < 100000,

(vi) energy_max > 1000,

(vii) o_ucd contains "phys.polarization",

(viii) o_ucd contains "pos.eq".

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(target_name = 'Crab' OR target_name = 'M1' OR
CONTAINS(POINT(s_ra, s_dec), CIRCLE, 83.6324, +22.0174, 0.083333) = 1)
AND (dataproduct_type = 'event-bundle')
AND (calib_level >= 2)
AND (s_resolution > 100)
AND (energy_min < 100000.0) AND (energy_max >= 1000.0)
AND (o_ucd LIKE '%phys.polarization%')
AND (o.ucd LIKE '%pos.eq%')
```

A.1.8 Use Case — Identify PSF response-functions for further analysis of previously downloaded data products

Identify all Chandra Source Catalog point spread functions for source detections that fall within 2 arcmin radius of (83.84358, −5.43639) in the Orion star-forming complex for Chandra observation 4374. These PSFs will be used to analyze previously downloaded catalog data products for the same field.

Find all datasets satisfying:

(i) Position inside 3 arcmin from (83.84358, −5.43639),

(ii) dataproduct_type = "response-function",

(iii) dataproduct_subtype = "psf",

(iv) obs_id = "4374",

(v) obs_collection = "CSC2".

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(CONTAINS(POINT(s_ra, s_dec), CIRCLE, 83.84358, -5.43639, 0.033333) = 1)
AND (dataproduct_type = 'response-function')
AND (dataproduct_subtype = 'psf')
AND (obs_id = '4374')
AND (obs_collection = 'CSC2')
```

A.1.9 Use Case — Get all the IRFs for a given CTAO observation, for simulation purposes

Simulations are frequently used to estimate the science performance for a given astrophysical use case. To realise such simulations, IRFs are required.

Find the CTAO datasets satisfying:

(i) dataproduct_type = "event-bundle" or dataproduct_type = "aeff" or dataproduct_type = "psf" or dataproduct_type = "edisp" or dataproduct_type = "bkgrate",

(ii) obs_id = "4374",

(iii) obs_collection = "CTAO-DR1".

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(dataproduct_type = 'event-bundle' OR dataproduct_type = 'aeff'
  OR dataproduct_type = 'edisp' OR dataproduct_type = 'psf'
  OR dataproduct_type = 'bkgrate')
AND (obs_id = '4374')
AND (obs_collection = 'CTAO-DR1')
```

A.2 Advanced Data Products

A.2.1 Use Case — Search for Chandra Source Catalog position error MCMC draws for X-ray detections in the vicinity of Gaia DR3 486718823701242368

Identify all Chandra Source Catalog position error MCMC draws for source detections that fall within 5 arcsec radius of (54.036061, +61.907633). The MCMC draws will be evaluated to establish whether there are potentially unresolved X-ray sources that may conincide with the white dwarf for observation planning.

Find all datasets satisfying:

(i) Position within 5.0 arcsec from (54.036061, +61.907633),

(ii) dataproduct_type = "draws",

(iii) dataproduct_subtype = "poserr",

(iv) obs_collection = "CSC2".

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(CONTAINS(POINT(s_ra, s_dec), CIRCLE, 54.036061, +61.907633, 0.0013888) = 1)
AND (dataproduct_type = 'draws')
AND (dataproduct_subtype = 'poserr')
AND (obs_collection = 'CSC2')
```

A.2.2 Use Case — Search for flux maps for CTAO-North observations between two observations ID

Identify all flux maps from the observation of CTAO-North between selected observation identifiers selected by the user .

Find all datasets satisfying:

(i) dataproduct_type = “image”,

(ii) dataproduct_subtype = “fluxmap”,

(iii) obs_collection = “CTAO-DR1”,

(iv) int(obs_id) > 4374,

(v) int(obs_id) ≤ 4379,

(vi) instrument_name contains “CTAO-N”.

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(dataproduct_type = 'image')
AND (dataproduct_subtype = 'fluxmap')
AND (obs_collection = 'CTAO-DR1')
AND (instrument_name LIKE 'CTAO-N')
AND (CAST(obs_id AS INTEGER) > 4374)
AND (CAST(obs_id AS INTEGER) <= 4379)
```

A.2.3 Use Case — Search for M31 source light curves and aperture photometry probability density functions that intersect a specific time interval

Identify all light curves and aperture photometry probability density functions of X-ray sources detected in the field of M31 covering the energy range 0.3–7.0 keV that include observation data in the interval MJD 56320–56325 TT during which interval a transient event was thought to have occurred. Because the data products are expected to include extremely sparse time axes, the t_intervals TMOC must be used for the query.

Find all datasets satisfying:

(i) Position within 1.5 degrees from (10.6847, +41.2688),

(ii) dataproduct_type = “timeseries” *or* “pdf”,

(iii) calib_level = 4,

(iv) energy_min ≤ 0.3 *and* energy_max ≥ 7.0,

(v) t_intervals TMOC intersects[18] MJD 56320–56325 TT.

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(CONTAINS(POINT(s_ra, s_dec), CIRCLE, 10.6847, +41.2688, 1.5) = 1)
AND ((dataproduct_type = 'timeseries') OR (dataproduct_type = 'pdf'))
AND (calib_level = 4)
AND (energy_min <= 300.0) AND (energy_max >= 7000.0)
AND (INTERSECTS(TMOC(17, t_intervals), ...) = 1)
```

A.2.4 Use Case — Search for the CTAO flux light curves of PKS 2155-304 in 2030

Identify all light curves obtained on the source PKS 2155-304 in 2030 with the CTAO observatory.

Find all datasets satisfying:

(i) dataproduct_type = "timeseries",

(ii) dataproduct_subtype = "flux",

(iii) obs_collection = "CTAO-DR1",

(iv) tmin $\geq$ 62502 (*i.e.*, 2030-01-01),

(v) tmax $\leq$ 62866 (*i.e.*, 2030-12-31),

(vi) target_name = "PKS 2155-304".

```
SELECT * FROM ivoa.obscore
NATURAL JOIN  ivoa.obscore_hea
WHERE
(dataproduct_type = 'timeseries')
AND (dataproduct_subtype = 'flux')
AND (obs_collection = 'CTAO-DR1')
AND (target_name = 'PKS 2155-304')
AND (tmin >= 62502)
AND (tmax <= 62866)
```

B Changes from Previous Versions

No previous versions yet.

[18] We note that this functiondoes not yet exist in ADQL

C Contributions to the Note

The authors of this Note contributed to the content and structure the text. However, the note was initiated and elaborated in several dedicated workshops, Interop meetings, and in specific IVOA HEIG group meetings, involving more people. The IVOA HEIG group keeps track of its activities on an IVOA web page: https://wiki.ivoa.net/twiki/bin/view/IVOA/HEGroup.

Further material can be found with those links:

- 2025-04-29: French ASOV workship "High Energy in the VO", https://indico.obspm.fr/event/2674/,
- 2024-11-16: IVOA Malta meeting, DM session with two High Energy presentations (B. Khélifi/I. Evans), https://wiki.ivoa.net/twiki/bin/view/IVOA/InterOpNov2024DM,
- 2024-11-15: IVOA Malta Plenary, CSP Plenary session, https://wiki.ivoa.net/twiki/bin/view/IVOA/InterOpNov2024CSPPlenary,
- 2024-05-21: IVOA Sydney meeting, DM Session High Energy focus, https://wiki.ivoa.net/twiki/bin/view/IVOA/InterOpMay2024DM,
- 2023-06-28: IVOA standards for High Energy Astrophysics (French VO Workshop), https://indico.obspm.fr/event/1963/,
- 2023-05-11: IVOA Bologna meeting: presentation ("DM for High Energy astrophysics", M. Servillat) and first IVOA HE group meeting, https://wiki.ivoa.net/internal/IVOA/IntropMay3023DM/2023-05-11_IVOA_meeting_-_VOHE.pdf,
- 2022-10-11: Virtual Observatory and High Energy Astrophysics (French VO Workshop), https://indico.obspm.fr/event/1489/.