

# Introduction to CIAO

# Chandra Interactive Analysis of Observations







CIAO: Chandra's data analysis system Fruscione et al. 2006, SPIE Proc. 6270, 62701V, D.R. Silvia & R.E. Doxsey, eds.



# What is CIAO?

First a linguistic note....

CIAO ..... from "s'sciavo", "I am your servant" in Venetian language

And CIAO has been at the service of X-ray astronomers for more than 25 years!

**CIAO 1.0 was released in October 1999** 

CIAO 4.17 was released in December 2024



If you're new to CIAO or unsure about how something works, the best place to start is always the help system (or ahelp). Let's try it now.

To learn what CIAO is, you can access the help file directly from the command line by running:

ahelp ciao

or you can read the same information online at: <u>cxc.harvard.edu/ciao/ahelp/ciao.html</u>

| AHELP for CIAO 4.17  | ciao | Context: <u>concept</u> |  |  |
|--|------|-------------------------|--|--|
| Synopsis   |      |                         |  |  |
| Chandra Interactive Analysis of Observations   |      |                         |  |  |
| Description  |      |                         |  |  |
| The remarkable science capabilities of the Chandra X-ray Observatory demanded new, flexible,<br>multi-dimensional, software to analyze the data it returned. The result is CIAO - the Chandra<br>Interactive Analysis of Observations - a system that has proven itself useful for the analysis of data<br>from other, non-X-ray missions, because of the mission independence that is the basis of the CIAO<br>design. [] |      |                         |  |  |



#### **AHELP CIAO - SUMMARY**

**Purpose**: CIAO (Chandra Interactive Analysis of Observations) is a software system designed for analyzing data from the Chandra X-ray Observatory.

**Flexibility**: It was developed to handle the new, flexible, multi-dimensional (initially 4D: 2 spatial, time, energy) data returned by Chandra.

**Mission Independence:** A key design feature of CIAO is its mission independence, making it useful for analyzing data from non-X-ray missions as well.

**N-Dimensional Data Handling**: CIAO tools are built to handle N-dimensional data without concern for the specific axes being analyzed.

**File Format Compatibility**: CIAO tools can read and write various formats, including FITS tables (event files), ASCII formats, and FITS images, allowing users to integrate pre-existing tools.



#### AHELP CIAO - SUMMARY (continue)

**Filtering and Binning**: The system allows for flexible filtering and binning of data (e.g., Chandra's 4D event data) into manageable sizes and arrays using a command-line 'regions' syntax. This is facilitated by the Data Model ("ahelp dm").

**Data Subspace Tracking**: CIAO keeps track of how data has been filtered and binned in a 'data subspace', which is automatically managed by the tools and allows users to review previous processing steps ("ahelp subspace").

**Tool Interconnection:** CIAO tools are designed for close interconnection, allowing output from one tool (e.g., source detection) to be used as input for another (e.g., `dmextract` for creating spectra, then fitting in Sherpa). This supports packages like `dax` for analysis directly from DS9.

**Modeling and Fitting with Sherpa**: Sherpa is the central modeling and fitting tool within CIAO, capable of forward fitting models to N-dimensional data.

**Resource for More Information:** More details are available on the CIAO website and through CIAO's command-line help system, `ahelp`.

CIAN



- A collection of Unix command line tools and Python applications
- Shares code with standard Chandra processing pipeline
- Allows Chandra instrument specific data reduction (eg ARF and RMF)
- Tailored to specialized X-ray astronomy data analysis, but not specific to Chandra (as been used with XMM, NuStar, etc.)

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- Coded with attention to standards and interoperability so that generic tools can be (and are) used for other X-ray data and even optical and radio data (e.g. multiwavelength analysis)
- Easy for beginners, yet powerful for advanced users
- Linux and Mac, annual releases
- Installed 1500+ times per year (single users to large institutions)

| What is Cl | AO in pra | actice? |
|------------|-----------|---------|
|------------|-----------|---------|

# cxc.harvard.edu/ciao

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| 21113  |   |   |   |
|--|---|---|---|
| INTRODUCTION >                                       | from  |   |   |
| Welcome  |   |   |   |
| Tools & Applications                                 | CIAO is the software package developed by the Chandra X-Ray Center for analys | ing data from the Chandra X-ray Telescope. It can also be used with data from oth | ner Astronomical observatories, whether ground or space based.  |
| Updated: 29 April 2025                               |   |   |   |
| DOWNLOAD CIAO ><br>Download CIAO 4.17                |   |   |   |
| Download CALDB                                       | Download CIAO/CALDR   | What has shanged?   | Where should I herin?   |
| Scripts & Modules Package                            | Download CIAO/CALDB   | what has changed?   | where should i begin:   |
| Installation Instructions                            |   |   |   |
| Platform Support                                     | Install CIAO 4.17 & CALDB 4.12.0  | Has there been a new release of CIAO, the contributed scripts, or the             | For those new to X-ray astronomy and data analysis  |
| Release Notes  |   | CALDB?  |   |
| Other Applicate Software                             | Read the CIAO 4.17 release notes for detailed information on this release,    |   | An X-ray Data Primer: what I wish I knew when Starting X-kay Astronomy  |
|  | including How CALDB 4.12.0 Affects Your Analysis.                             | What's New  | A Chandra Pocket Guide  |
| Analysis Guides                                      |   | "Watch Out" List  |   |
| Science Threads                                      | Does CIAO run on my operating system?   | - Hater our List  | Useful links for those people who have never used CIAO before.  |
| Visualizing data                                     | the second second second second   | How do I update CIAO?   | An and a second s |
| Why Topics<br>Halo Pages (AHELP)                     | What are the requirements for running CIAO?                                   |   | Welcome to CIAO   |
| Video Demos and Tutorials                            | How do Linstell Puthon nackages into CIAO2                                    | Version History: CIAO; Scripts & Modules.   | Introduction to the Tools & Applications  |
|  | How do Finstan Python backages into circo.                                    |   |   |
| Gallery of Examples                                  | CIAO 4.17 includes Python 3.11, whether installed using either of the ciao-   | Release Notes: CIAO; CALDB.   | Introductory Science Threads - Beginners should start here  |
| *Watch Out* List                                     | install or conda installation methods.  | CIAO 4.17 includes several important bug fixes as well as supports power          | Download CIAO 417 using the size install corint   |
| Help Pages (AHELP) Real List                         |   | compilers and undated Off the Shelf software. This includes Sherpa                | Download CIAO 4.17 using the crao-rinscarr script   |
| Frequently Asked Questions (FAQ)                     |   | compilers and updated on the shell software. This includes shelpa                 | Download CIAO 4.17 with conda   |
| Manuals & Memos                                      |   | improvements, containing the XSPEC 12.14.0k models, and SAOImage DS9              | Quick Start Guide   |
| Dictionary   |   | v8.6.   |   |
| Publications<br>Download the Website                 |   |   | All CIAO Threads  |
|  |   | Subscribe to the CIAO News RSS feed   |   |
| Sherpa website                                       |   |   | Analysis Guides   |
| Sherpa for Python users                              |   | Subscribe to Chandra/CIAO announcements   | YouTube videos  |
| Threads  |   |   | and the second design of the  |
|  |   |   | Chandra/CIAO Workshops  |
| Introduction   |   |   | Sherpa: Modeling and Fitting  |
| Modules  |   |   |   |
| Data I/O NEW   |   |   | DS9: Interactive image display and analysis   |
| Running Tools from Python                            |   |   |   |
| Using CIAO in a notebook NEW                         | I need help!  | I need more!  | Citing CIAO   |
| DATA PRODUCTS  |   |   |   |
| Data Basics<br>Data Products Guide                   | For anyone having trouble using CIAO or analysing Chandra data.               | For the expert CIAO user or person who needs more detailed information.           | If you are writing a paper and would like to cite the CIAO software, we   |
| Data Caveats   |   |   | recommend the following:  |
| Chandra Data Archive                                 | CIAO Software Help Pages  | Why Topics  | roominista are fonoming.  |
| TGCat: Gratings Catalog & Archive                    |   |   | CIAO: Chandra's data analysis system (ADS   PDF   PS)   |
| Understanding the Chandra DSE                        | Frequently Asked Questions (FAQ)  | Manuals   | Fruscione et al. 2006, SPIE Proc. 6270, 62701V, D.R. Silvia & R.E. Doxsey,  |
| Modeling the Chandra PSF                             | Known CIAO Burgs and Tool Caveats   | Inderstanding the Chandra DSE   | eds.  |
| Characterizing the Chandra PSF                       | Internet one only and tool caveats  | onderstanding and <u>chandra nor</u> .  |   |
| Using the Chandra PSF                                | If the above links do not help you, then please contact the CXC Helpdesk. To  | Galleries (Tips & Tricks): CIAO; Sherpa.  | \bibitem[Fruscione et al.(2006)](2006SPIE.6270E60F)   |
| MERGING CENTRAL                                      | help us help you, please include, where appropriate: the CIAO version         |   | Fruscione, A., et al.\ 2006, \procspie, 6270  |
| Data Preparation & Merging Chandra Data              | (ciaover -v), operating system, screen output (in a text format where         | The Chandra Instrument Calibration pages.   |   |
| Post-Merging Analyses                                | noesible) and information on what you were trying to do                       |   | The specific version of CIAO and CALDB used for the analysis should be  |
| Revising Astrometry for Imaging & Spatial            | prosining, and information on what you were trying to do.                     | Using Python with CIAO  | mentioned. The collect_chandra_dois ( NEW ) tool can be used to collect   |
| Combining Datasets for Imaging & Spatial             | Please include the actual text input and output (e.g. using copy and paste).  | CSC v2: Chandra Source Catalog 2.1  | the information needed by the Chandra Archive team to create a Chandra  |
| Analysis<br>Combining Datasate for Spantral Analysis | Do not send in screen shots of the terminal window, as they make it much      | see   | Data Collection DOI.  |
| Timing Analysis Across Multiple Observations         | harder to identify and track down the problem.                                | CSC v1: Chandra Source Catalog 1.1  |   |
| WORKSHOPS  | ,   | TGCat: Chandra Gratings Catalog   | Further guidelines are available from the Acknowledgment of Use of Chandra  |
| Program Information                                  |   |   | Resources.  |
| Provinue Workshone                                   |   |   |   |



- 1. File format
- 2. Parameter Files
- 3. Filtering and Binning (the Data Model)
- 4. Regions
- 5. Subspace
- 6. Good Times Intervals (GTI)
- 7. Scripting language (Python)



### 1. File Format

- Chandra data is stored in the **binary FITS format** (more on that later!), but many CIAO tools can also work with simple ASCII text files.
- When CIAO processes data, it **records processing state and metadata** directly in the file, using keywords and subspace information in the header so that history and information is preserved.
- A single Chandra FITS file can include multiple datasets, such as:
  - Event data
  - Good Time Intervals (GTIs)
  - Weight maps
  - Region definitions
- These datasets are stored in separate blocks within the file, each containing either image or table data.
- You can explore the contents of a file using:
  - dmlist a command-line tool
  - **prism** a graphical interface, which can be launched from DS9



#### The FITS format

Overview from https://heasarc.gsfc.nasa.gov/docs/heasarc/fits overview.html

- FITS stands for *Flexible Image Transport System*.
- It is the standard file format used in astronomy to store and share data.
- A FITS file contains one or more "data blocks", each starting with a "header" followed by the "data".
  - The header is made of readable text and describes the structure and contents of the data.
  - The data can include images, tables, or other arrays (1D, 2D, or more).
- FITS can store different types of information in extensions, such as:
  - Images (e.g., sky maps or detector frames)
  - Tables (e.g., event lists or catalogs)
- FITS is **platform-independent** and designed to be long-term and self-describing, so files can be understood decades later.
- It is supported by many tools and programming libraries used in astronomy (e.g., CIAO, Astropy, fv).
- FITS is **maintained by an international standards group** to ensure consistency across the field.



#### Antonella Fruscione





#### Chandra/CIAO workshop at UMass Lowell - May 2025



#### 2. Parameter Files

From: <u>http://cxc.harvard.edu/ciao/ahelp/parameter.html</u>

- CIAO tools use ASCII parameter files (e.g., dmcopy.par, specextract.par) to store and retrieve input settings for data processing.
- Users can **manage parameters** using command-line routines like **plist** (view), **pset** (set), and **punlearn** (reset), or via the Python interface (**paramio** module).
- Each parameter has a **mode** (e.g., query, automatic, hidden) that determines how it is accessed or prompted during tool execution.
- Some parameters **accept multiple values (stacks)**, as indicated in their help files (see **ahelp stack** for more on stack syntax).



#### Parameter file example: dmcopy.par

ciao% plist dmcopy

Parameters for /Users/antonella/cxcds\_param4/dmcopy.par

```
infile = acisf00459N004_evt2.fits.gz[REGION]Input dataoutfile = grating_reg.fitsOutput d(kernel = default)Output fil(option = )Option -(verbose = 0)Debug Le(clobber = no)Clobber(mode = ql)Clobber
```

Input dataset/block specification Output dataset name Output file format type Option - force output type Debug Level Clobber existing file

ciao% dmcopy Input dataset/block specification (acisf00459N004\_evt2.fits.gz[REGION]): Output dataset name (grating\_reg.fits): Clobber set to no, and output file grating\_reg.fits exists.

```
Cia0% pset dmcopy outfile=grating_reg2.fits
Cia0% dmcopy
```

Input dataset/block specification (acisf00459N004\_evt2.fits.gz[REGION]): Output dataset name (grating\_reg2.fits):

Note the required (infile, opt) and **optional** parameters (the ones in parenthesis)



### 3. Filtering and Binning (the "Data Model")

http://cxc.harvard.edu/ciao/ahelp/dm.html http://cxc.harvard.edu/ciao/ahelp/dmfiltering.html http://cxc.harvard.edu/ciao/ahelp/dmbinning.html http://cxc.harvard.edu/ciao/threads/filter/

- Filtering and binning are essential steps in X-ray data analysis.
  - Filtering is used to **remove unwanted events**—such as periods of high background, poor aspect solution, or irrelevant sources—from a dataset. This step helps ensure that the analysis focuses only on scientifically useful data.
  - Binning **transforms event lists into structured data** like histograms, 2D images, or 3D cubes. This is key for visualizing spatial, spectral, or temporal properties of the observation.
- These operations are powered by the CIAO Data Model (DM)—a versatile interface that allows users to work with both FITS and ASCII files using a consistent syntax. The Data Model hides the differences between file types, so a user can filter and bin data the same way no matter what kind of file they have.
- The Data Model is what makes CIAO tools powerful, portable, and format-independent.



column.

#### **BENEFITS OF THE DATA MODEL**

| • | Virtual                         | File                     |                                  | Access:                       |  |
|---|---------------------------------|--------------------------|----------------------------------|-------------------------------|--|
|   | Any CIAO tool that takes a file | lename can also accept   | a <i>virtual file</i> string. Th | is lets the tool operate on a |  |
|   | filtered view of th             | ne data-without          | creating a r                     | new file on disk.             |  |
| • | Optional                        | File                     |                                  | Creation:                     |  |
|   | The same syntax can             | also be used to          | create a filtered                | output file, if desired.      |  |
| • | Flexible                        | Binning                  | and                              | Filterina:                    |  |
|   | All columns in an event file a  | are treated equally-so y | vou can filter or bin c          | on spatial coordinates, time, |  |

energy, This enables the creation of multi-dimensional images, like space vs. energy or time vs. energy.

any

or

other



#### Data Model Syntax (ahelp dmsyntax)

All CIAO tools use the DM library and therefore accept "virtual files" as input

All CIAO tools use a common syntax to describe "virtual files":

### filename[block][filter][columns/binning][options]

**block** – the data section to use (e.g. [EVENTS])

filter – the condition(s) applied to rows (e.g. [energy<7000])

columns/binning – which columns to keep, or how to bin data (e.g. [bin x=::4])

**options** – advanced settings for DM tools (rarely needed)

The order of qualifiers generally matters, but not all are required.

Let's see some examples!



### Virtual File Examples (CIAO Data Model Syntax)

These examples show how to use CIAO's virtual file syntax to filter, select, and bin data from event files without creating intermediate files on disk.

Example 1: Select first 3 columns by number after time filtering

#### acisf01843N001\_evt2.fits[EVENTS][time=84245787:84247000][cols #1,#2,#3]

Block: [EVENTS] Filter: [time=84245787:84247000] Columns: [cols #1,#2,#3]

Example 2: Select columns by name after filtering on grade

#### acisf01843N001\_evt2.fits[EVENTS][grade=0,2,3][cols time,ccd\_id,node\_id]

Block: [EVENTS] Filter: [grade=0,2,3] Columns: [cols time,ccd\_id,node\_id]



Example 3: Create a PI spectrum for a specific region

#### acisf01843N001\_evt2.fits[EVENTS][sky=region(mysrc.reg)][bin pi=1:1024:1]

Block: [EVENTS] Filter: [sky=region(mysrc.reg)] *(the region)* Binning: [bin pi=1:1024:1] *(the binning specification)* 

Typical input to dmextract

Example 4: Create an image by filtering in energy and binning in (x,y) coordinates

acisf01843N001\_evt2.fits[EVENTS][energy<7000][bin x=320:480:4,y=320:480:4]

Block: [EVENTS] Filter: [energy<7000] *(the energy filter)* Binning: [bin x=320:480:4, y=320:480:4] *(the binning specification)* 

Typical input to dmcopy



#### Example: how to create a 2D image in sky coordinates from an ACIS event file using the dmcopy tool.

dmcopy "acisf06934N002\_evt2.fits[bin x=3500:4500:2,y=3500:4500:2]"
6934\_sky\_binsize.fits

Input file: acisf06934N002\_evt2.fits — an ACIS level 2 event file

**Virtual file syntax**: [bin x=3500:4500:2, y=3500:4500:2]

#### **Binning**:

X-axis: from pixel 3500 to 4500 in steps of 2 Y-axis: from pixel 3500 to 4500 in steps of 2

This creates a 2D image in sky coordinates with reduced resolution (2-pixel bins)

**Output file**: 6934\_sky\_binsize.fits — the new binned image





#### Example: how to use spatial filtering with a region file in CIAO's dmcopy command.

dmcopy "ngc1404.img[sky=region(ngc1404\_sample.reg)]" ngc1404\_regfile.img

**Input file:** ngc1404.img — an image file

Filter: [sky=region(ngc1404\_sample.reg)]

Applies a **spatial filter** using the region defined in *ngc1404\_sample.reg* 

The region file can define shapes like circles, boxes, ellipses, etc., in sky coordinates

**Output file:** ngc1404\_regfile.img — the filtered image, containing only the pixels within the region





#### **Example: Creating a 3D Image Cube**

dmcopy "06540\_evt.fits[(chipx,chipy)=box(8003.5,8137.5,512,512,0)] [bin chipx=::2,chipy=::2,time=::#50]" outfile=cube.fits

This example creates a **3D image (or cube)** of a point source using **chip coordinates** from an HRC event file.

Because **Chandra dithers** during observations, the point source moves slightly across the detector over time. This motion is captured as a third dimension in the cube.

The event file is **filtered on chip coordinates** to focus on the source region.

The data is binned into a cube:

X-axis: chipx, binned by 2Y-axis: chipy, binned by 2Z-axis: time, divided into 50 bins

This type of cube helps visualize how the source moves across the detector over the course of the observation.





## **Data Manipulation Tools**

• CIAO provides a powerful suite of tools for manipulating FITS and ASCII data, including four core Data Model (DM) tools: dmlist, dmcopy, dmextract, and dmstat and over 30 additional data manipulation tools

dmlist - Lists the contents, structure, or metadata of a file

View headers, column names, data blocks, etc.

dmcopy – Filters and bins data in tables or images

Create subsets of data or rebin for analysis and visualization

**dmextract** – Creates histogram-style tables from event data

Used to generate spectra (PHA files), lightcurves, or count profiles from event files

dmstat – Computes basic statistics on images or table columns

Returns mean, median, min/max, standard deviation, and pixel distributions



### 4. Regions

http://cxc.harvard.edu/ciao/ahelp/dmregions.html http://cxc.harvard.edu/ciao/threads/regions/

- **Regions** are 2D spatial filters used in CIAO to include or exclude specific areas of data.
- They are commonly used to define source and background areas in images or event files.
- Regions can be saved as text files or FITS files, and are often created interactively in DS9.
- You can apply a region as a filter using the CIAO Data Model syntax, e.g.: [sky=region(source.reg)]
- Multiple regions can be combined using:
  - AND for intersection
  - OR for union
- This makes region filtering flexible for a wide range of spatial analysis tasks.



#### circle(9:14:49.090,+8:53:21.231,4.083")



#### annulus(9:14:49.074,+8:53:20.987,9.064",46.425") # background



dmellipse a1664.asm a1664.ellipses "lgrid(0.1:0.96:0.05)" step=100 clob+





#### 5. Subspace

#### http://cxc.harvard.edu/ciao/ahelp/subspace.html

- The subspace stores information about filters applied to a dataset directly in the file's header.
- This metadata allows CIAO tools to automatically apply the correct calibration and maintain consistency in processing down the line.
- A file's subspace (ie. filtering history) can be viewed using:

dmlist <filename> opt=subspace

• This helps track how data has been filtered and ensures accurate, reproducible analysis.



#### **Example: Viewing Subspace with dmlist**

#### dmlist "acisf13736\_evt2.fits[ccd\_id=3,sky=circle(4324,3676,50)]" subspace

- Applies two filters to the event file:
  - ccd\_id=3 selects events from CCD 3
  - **sky=circle(4324,3676,50)** selects events within a circular region in sky coordinates
- Displays the subspace, which records these filtering operations in the file's metadata.

This allows CIAO tools to recognize what selections were applied, helping ensure correct calibration and consistent processing later on.

The command returns something like:

Data subspace for block EVENTS: Components: 1 Descriptors: 16

```
--- Component 1 ----
```

```
[...]
CCD_ID 3
SKY(X,Y) circle(4324,3676,50)
[...]
```

This shows the exact filters that were applied and stored as part of the file's "data subspace."



# 6. Good Time Intervals

http://cxc.harvard.edu/ciao/ahelp/times.html http://cxc.harvard.edu/ciao/dictionary/gti.html http://cxc.harvard.edu/ciao/ahelp/dmgti.html

- Chandra event files record timing information in both:
  - Header keywords (e.g. TSTART, TSTOP, EXPTIME)
  - GTI blocks (Good Time Interval tables) within the file
- **GTIs define the valid time periods of an observation**—intervals during which the data are considered reliable and can be used for scientific analysis.
- The dmgti tool allows to create new GTI files based on custom time filters (e.g., background flares, aspect quality).
   These GTIs can then be applied to filter the data accordingly.
- GTIs are critical for ensuring that analyses are based only on clean, usable time intervals.



### 7. Python: the scripting language in CIAO

- CIAO uses **Python as its scripting language**, allowing flexible, interactive analysis without compilation.
- CIAO 4.17 includes Python 3.11 and the CIAO Conda environment fully supports Python 3.11 and associated packages
- CIAO comes with its own Python environment, but users can choose to use a custom Conda installation if needed.
- Key CIAO Python libraries:
  - **CRATES** Provides access to the CIAO Data Model (DM) for working with FITS files
  - TRANSFORMS Enables World Coordinate System (WCS) transformations and coordinate handling
- The CIAO modeling and fitting application, *Sherpa*, is available as a fully importable Python module.
- You don't need to know Python to use Sherpa, but if you do know Python, you can script and automate complex modeling workflows with ease.

Antonella Fruscione



# Have fun using CIAO!

