TOPCAT Introduction and Tutorial

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Young Indian Astronomers Team
Online

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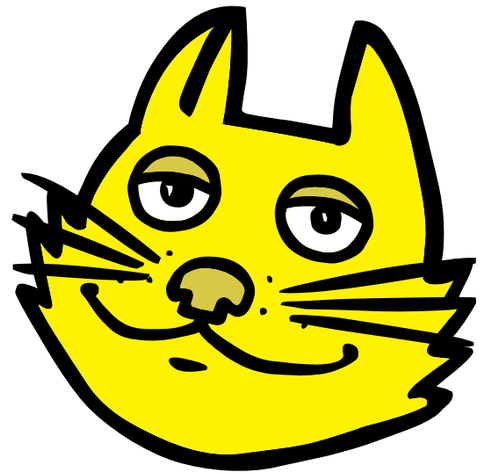

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Outline

TOPCAT

- What is it?
- What can it do?

Gaia mission overview

Questions?

Hands-on demos using Gaia DR3

Overview

TOPCAT = Tool for OPerations on Catalogues And Tables

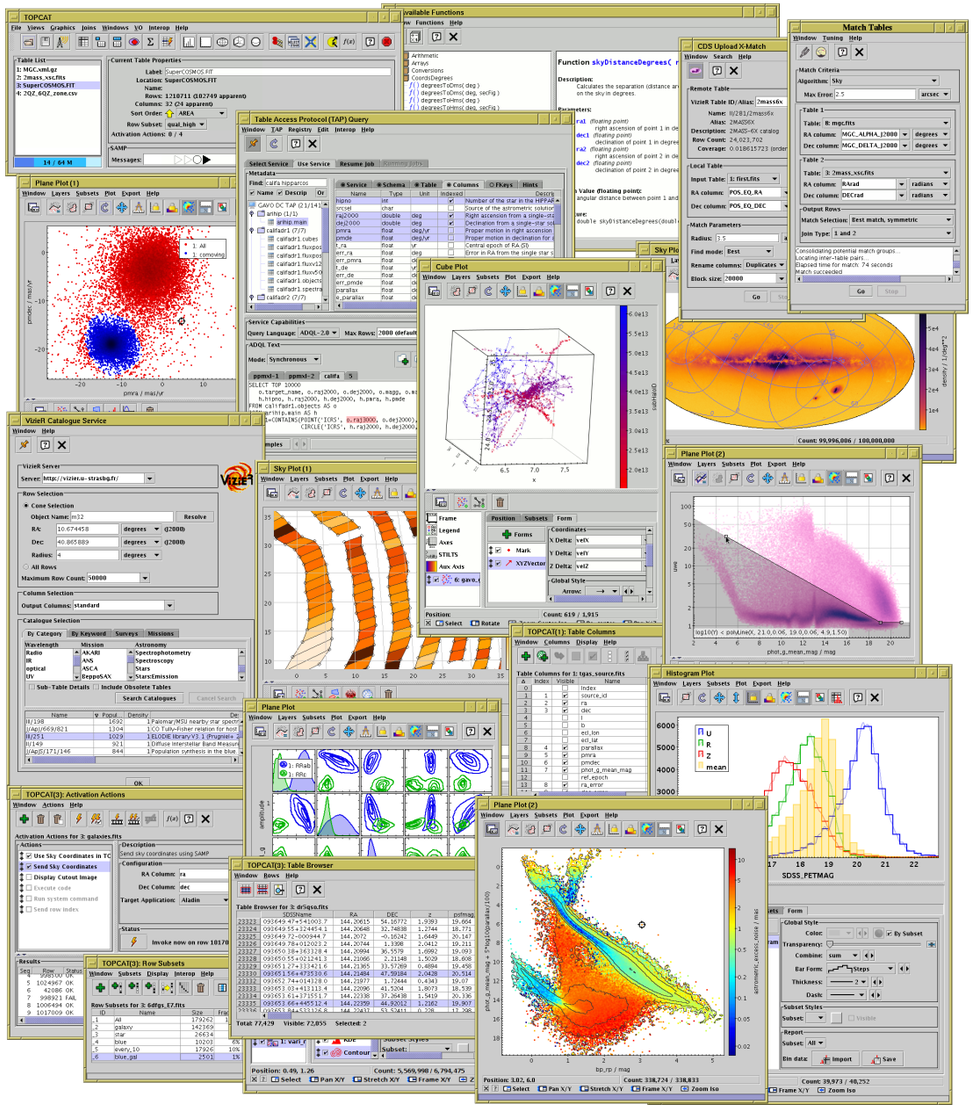
"Does what you want with tables"

Suitable for:

- Interactive exploration
- Quick look at unfamilar data
- In-depth analysis

Overall aim:

- Makes table manipulation easy,
  so users can concentrate on doing science



Characteristics

Aims:

- User-friendly
  - ▷ Easy to install and run (pure Java — one download file, no library issues)
  - ▷ Easy to get started
  - ▷ Simple things fairly obvious
  - ▷ Complicated things at least well-documented

    ... this does get harder as more functionality is added
- High Performance
  - ▷ Most things are fast
  - ▷ Handles quite large tables: millions of rows, hundreds of columns easily (can be much more)
  - ▷ ... even on modest hardware
  - ▷ Recent/upcoming versions: better use of multi-core machines
- Do the things that astronomers need
  - ▷ Development is led by community input (mailing list, personal emails, tutorials, feature requests, bug reports...)
  - ▷ Feedback always welcome!

Capabilities

It can do:

- Read/write tables in various formats (FITS, VOTable, CSV, ...)
- View data
- View metadata
- Calculations and simple statistics (expression language)
- Visualisation (many options, interactive)
- Make/combine/display row selections in various ways (linked views)
- Crossmatching (many options)
- Access external data services (VO and others)
- Talk to other astro tools (SAMP)
- Trigger some event when a row is selected

It can't do:

- Images, spectra (it's only for tables)
- Scripting (but see STILTS)
- *Very* large tables (but see STILTS)
- All possible file formats
- Do astronomy for you

Table Data and Metadata

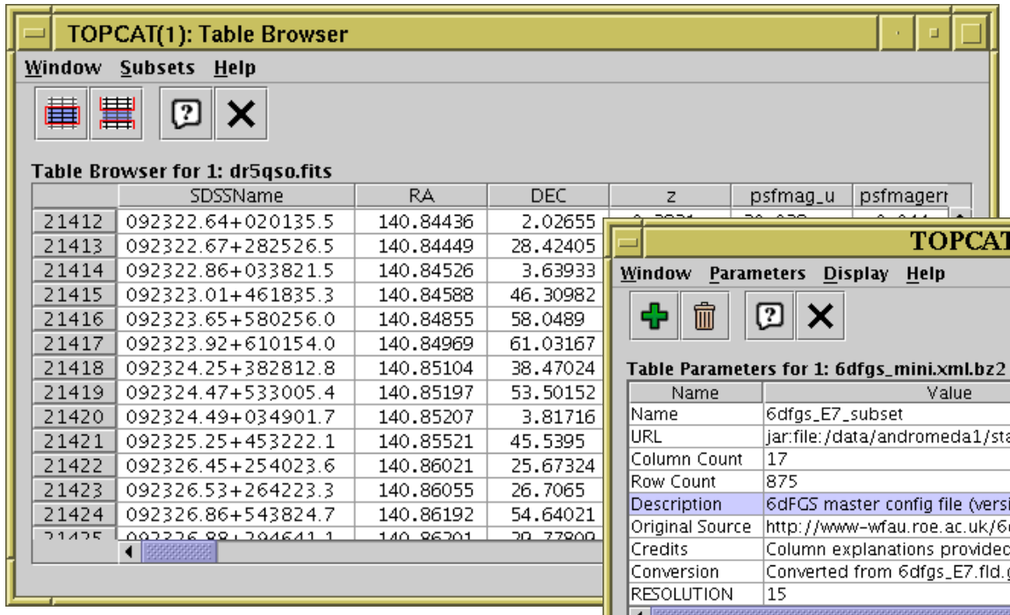


Table data view

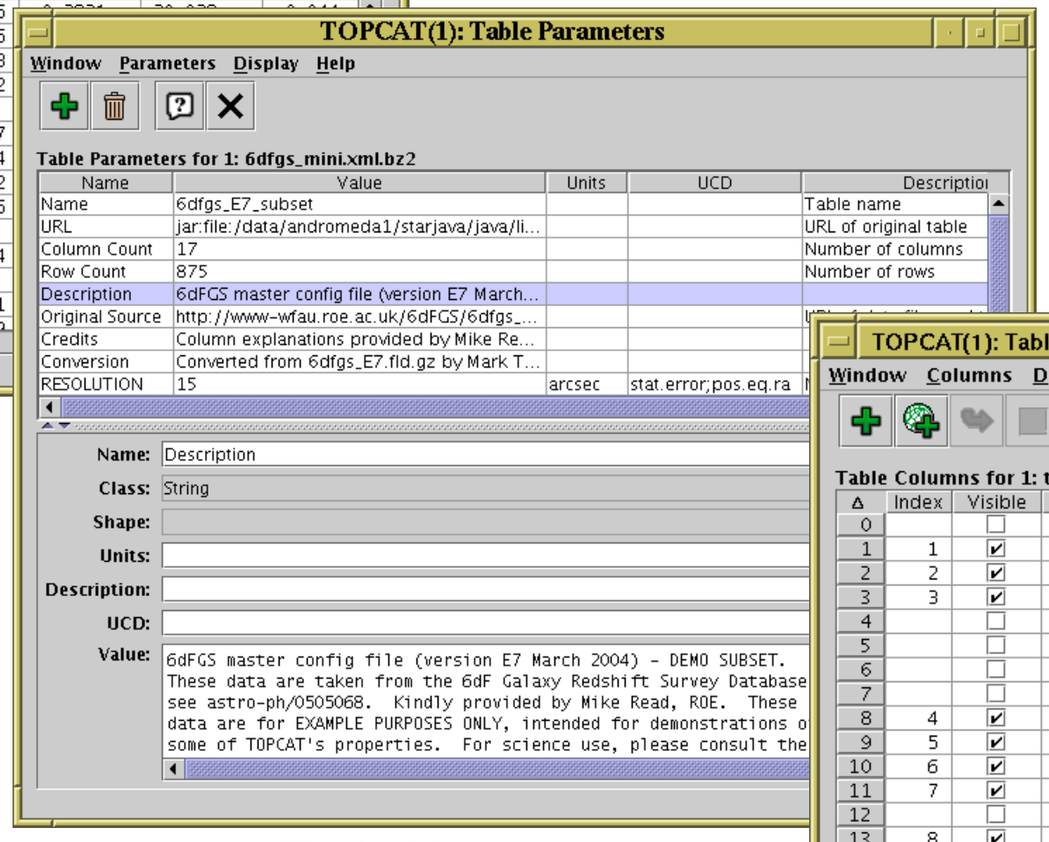
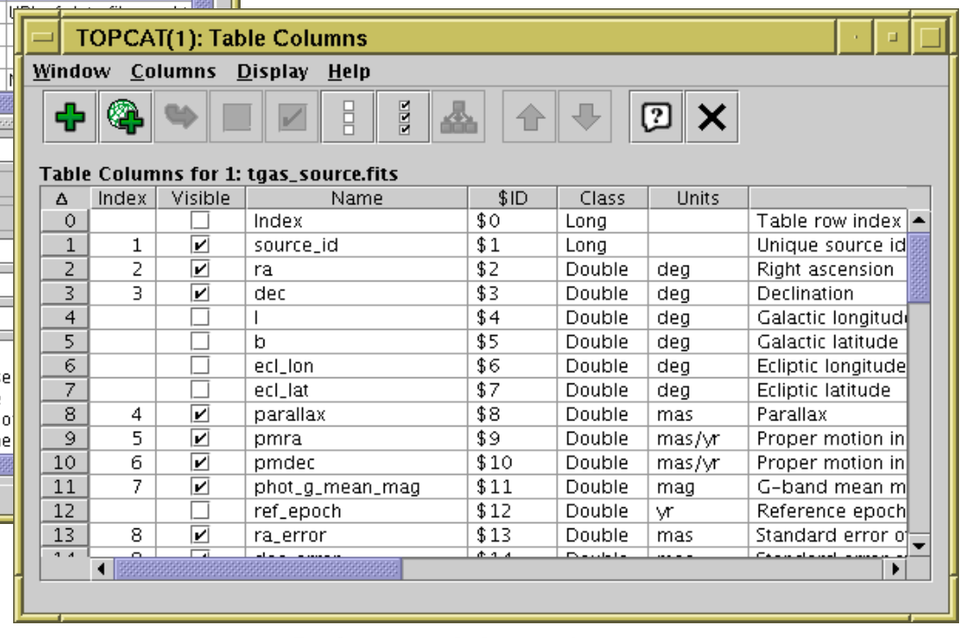


Table Metadata view



Column Metadata view

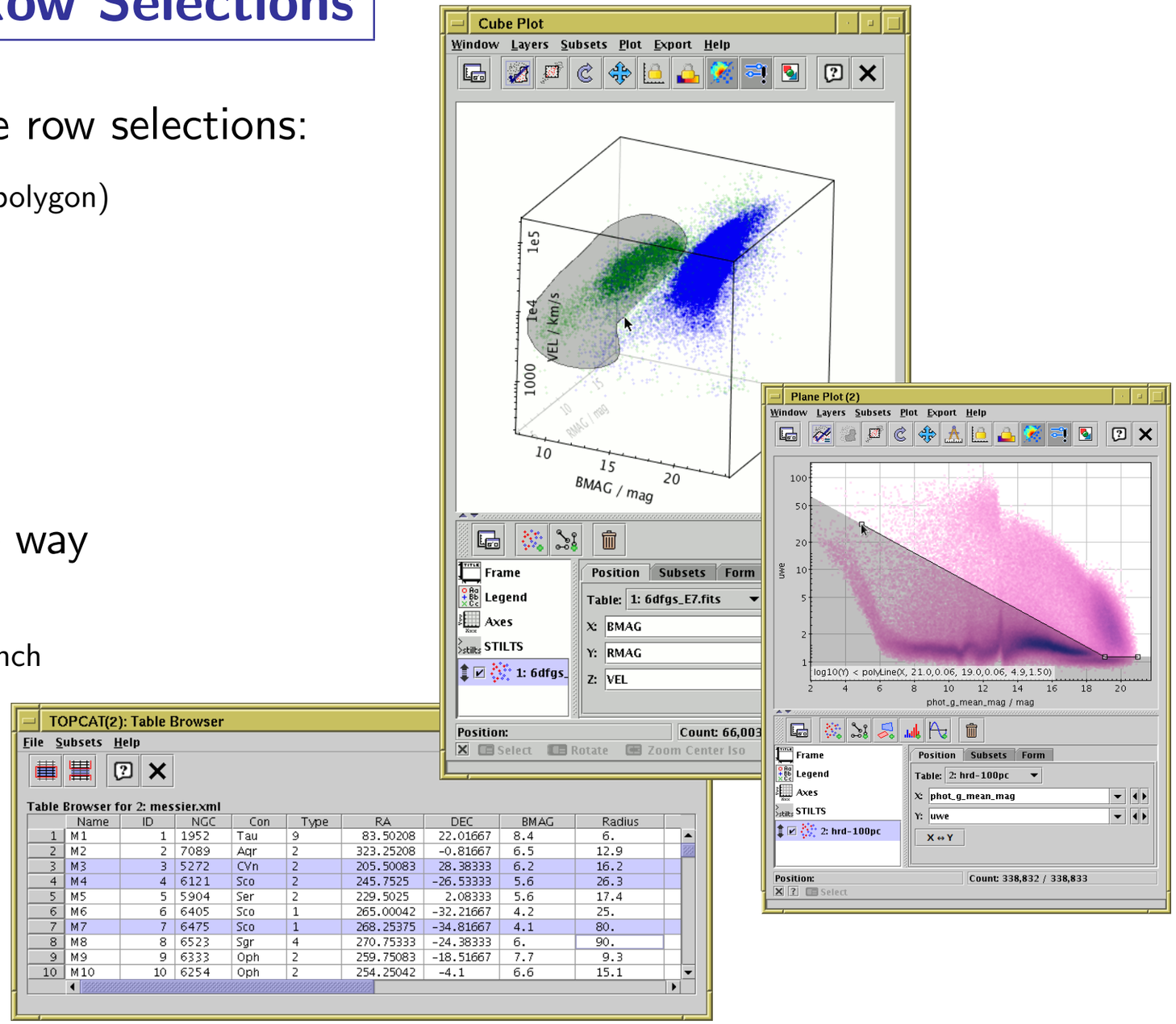
Row Selections

Different ways to make single or multiple row selections:

- Select points graphically from a plot (freehand or polygon)
- Select rows from the table view
- Use an algebraic expression
- Combine existing subsets
- Receive from an external application (SAMP)

Linked views mean a selection made one way is visible in other ways

- Perform crossmatch only on items in red giant branch
- Where on the sky is this colour cut?
- Spot outliers
- Identify objects on ds9 image display

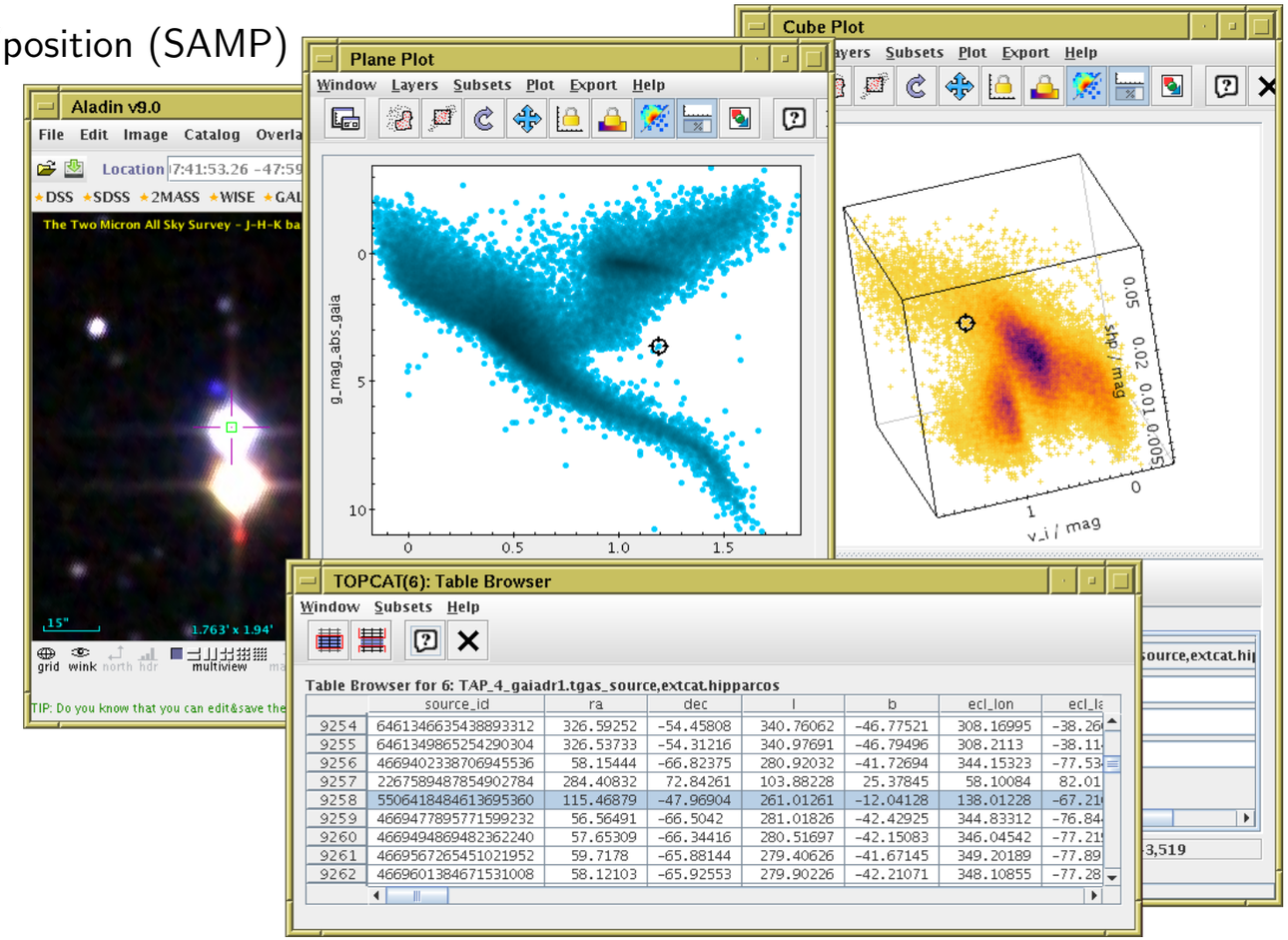


	Name	ID	NGC	Con	Type	RA	DEC	BMAG	Radius
1	M1	1	1952	Tau	9	83.50208	22.01667	8.4	6.
2	M2	2	7089	Aqr	2	323.25208	-0.81667	6.5	12.9
3	M3	3	5272	CVn	2	205.50083	28.38333	6.2	16.2
4	M4	4	6121	Sco	2	245.7525	-26.53333	5.6	26.3
5	M5	5	5904	Ser	2	229.5025	2.08333	5.6	17.4
6	M6	6	6405	Sco	1	265.00042	-32.21667	4.2	25.
7	M7	7	6475	Sco	1	268.25375	-34.81667	4.1	80.
8	M8	8	6523	Sgr	4	270.75333	-24.38333	6.	90.
9	M9	9	6333	Oph	2	259.75083	-18.51667	7.7	9.3
10	M10	10	6254	Oph	2	254.25042	-4.1	6.6	15.1

Row Highlighting

Row selection is coordinated between linked views:

- Click on row in table browser or plot
- Same row is highlighted in other plots & table browser
- Can configure external tools to highlight same object/position (SAMP)



Calculations

Expression language used for creating columns, defining selections, making plots etc:

- Straightforward arithmetic syntax (C-like)
- Use column names as variables
- Standard arithmetic operators (`+`, `-`, `/`, `*`)
- Standard mathematical functions (`abs`, `max`, `round`, `sin`, `cos`, `pow`, ...)
- Conditional expressions (`q?a:b`)
- Sky coordinates (degrees, sexagesimal, sky distances)
- Astrometry (epoch propagation with/without errors, ...)
- Cosmological distances (redshift, luminosity dist, lookback time, ...)
- Fluxes (Johnson AB Magnitudes, Jansky)
- Time conversions (ISO8601, MJD, Julian, Besselian)
- ... and more (and it's extensible)

Examples:

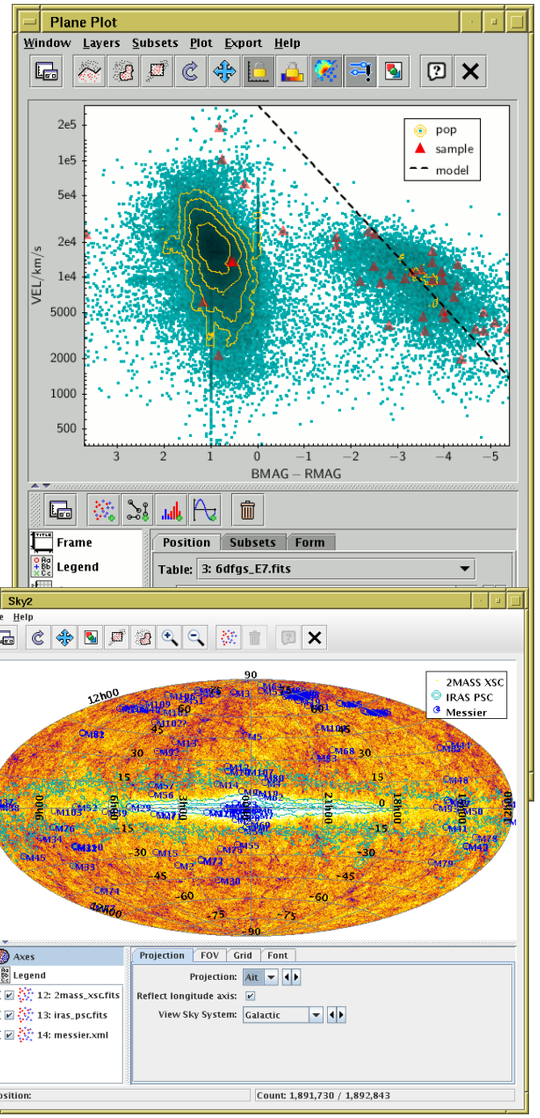
- `mag_u - mag_g` — *e.g. as quantity to plot*
- `janskyToAb(flux)` — *e.g. to define new column*
- `skyDistanceDegrees(ra, dec, 14.1, -72.9) < 1.2` — *e.g. to define row selection*

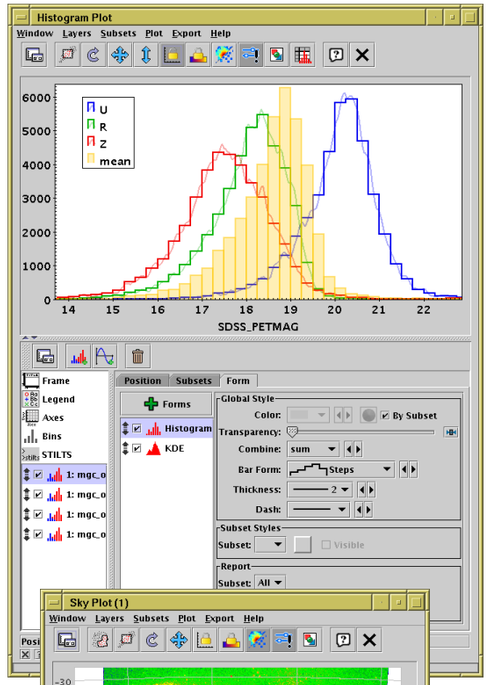
Visualisation

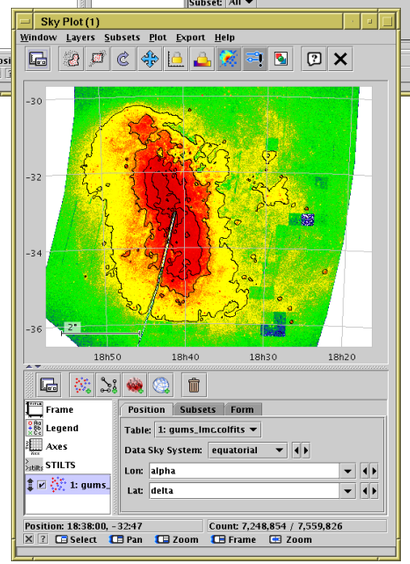
Very good for interactive exploration of large (or small) datasets:

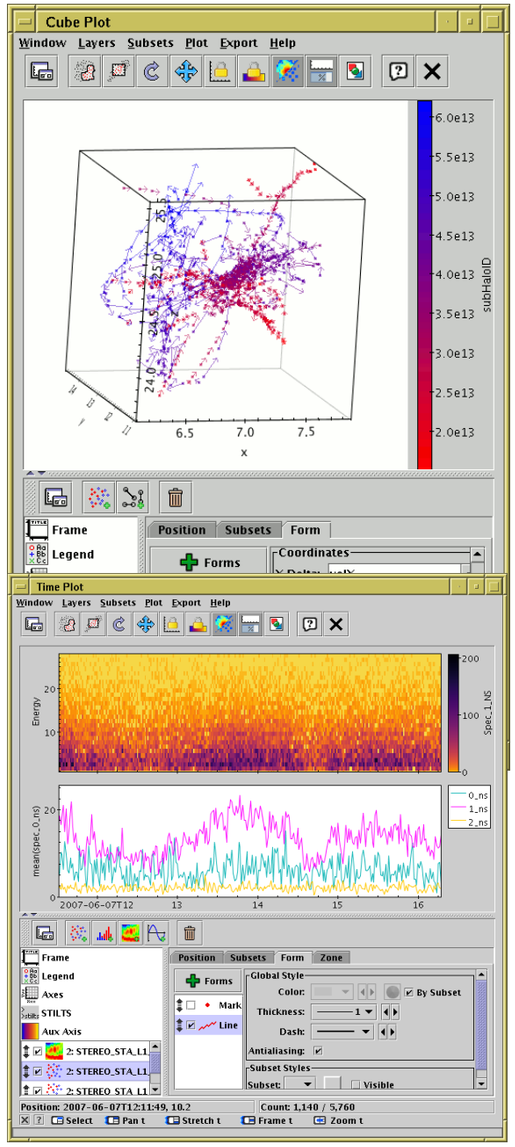
- Many plot types!
  - 2d/3d scatter plots, histograms, HEALPix, density maps, error bars/ellipses, vectors, lines, quantiles, text labels, contours, KDEs, analytic functions, spectrograms, ...
- Many options!
  - Colour, colour maps, shading mode, weighting, marker shape/size line style, sky projection, sky system, coordinate grid, axis labelling, smoothing, binning, ...
- Highly responsive
  - Interactive changes to options update plot immediately
- Special attention to large data sets
  - Plot arbitrarily large datasets in fixed memory
  - Represent very dense plots in comprehensible ways
  - Many options for high-dimensional visualisation
- Publication-quality output?
  - Export to PDF, EPS, PNG, SVG, ...
  - Optional LaTeX annotation
  - Script output (STILTS) for reproducibility
  - ... but not quite as good as Matplotlib/IDL/R

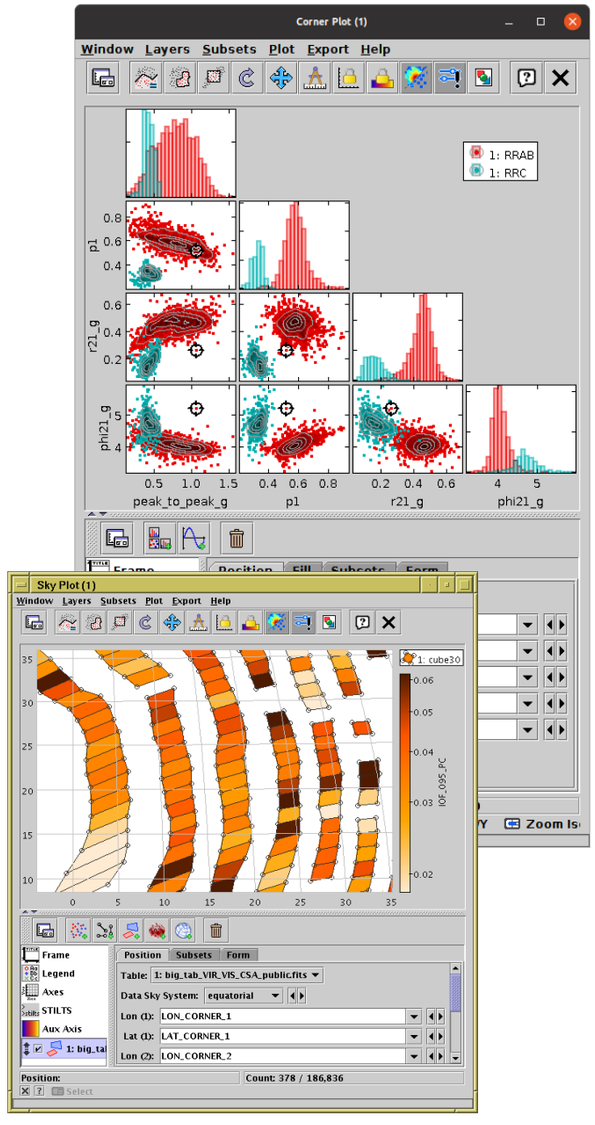
Visualisation: Plot Types



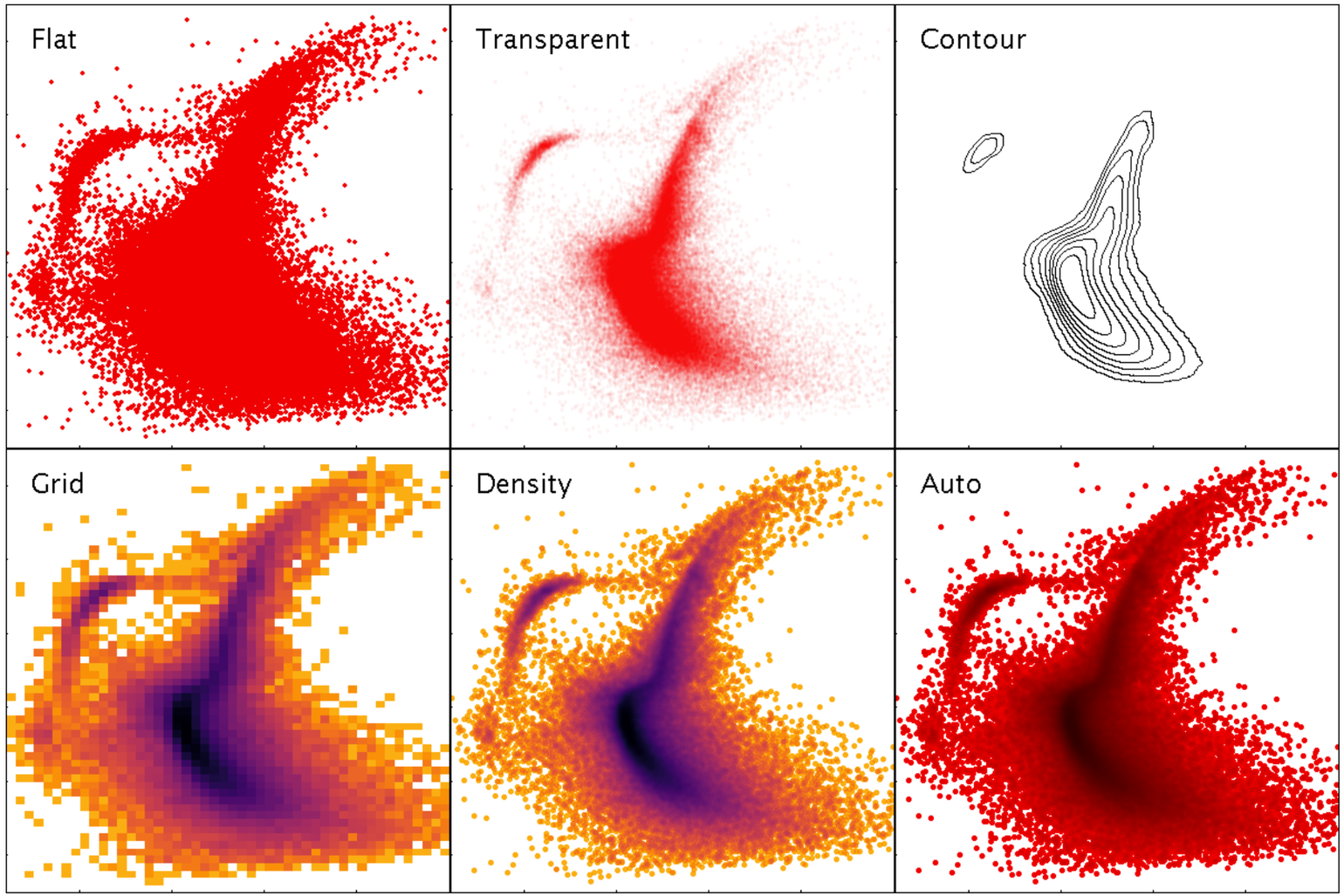








Visualisation: Dense plots



Different options for shading scatter-plot data.

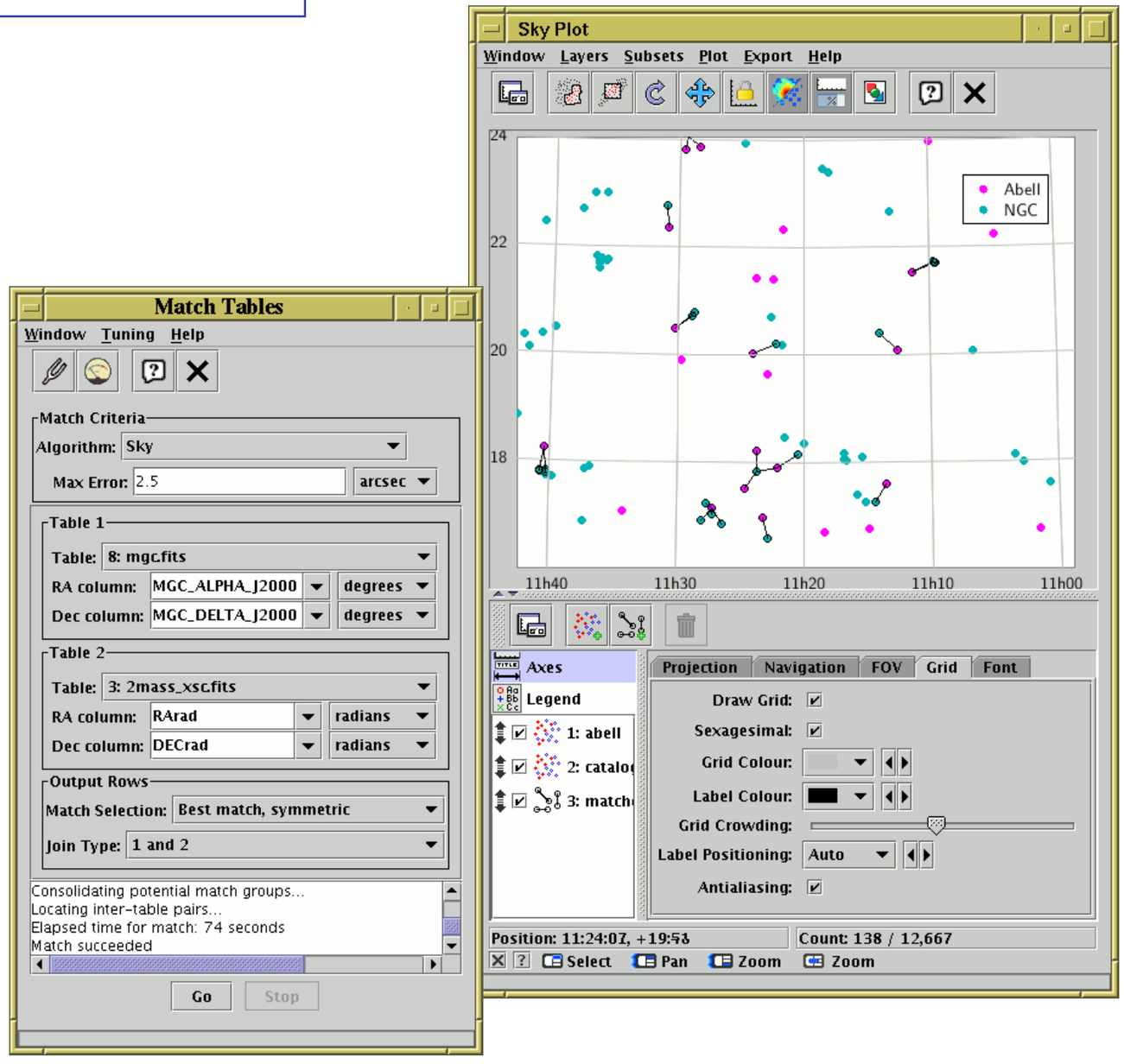
Crossmatching

Internal

- Both/all files loaded into TOPCAT
- Works well up to ∼1 million rows each
- Pretty fast (≤couple of minutes)
- Very flexible (sky, Cartesian, exact, 3D, ellipses, errors, combinations...)

External

- One or both tables too big to download
- Several options, with different pros and cons:
  - ▷ CDS X-Match
    (any VizieR table, sky match, fast, easy)
  - ▷ Multiple cone search
    (many tables available, sky match, slow)
  - ▷ TAP
    (few tables available, flexible, tricky)



Virtual Observatory

What is the Virtual Observatory (VO)?

- *"All astro archives in your computer"*
- A set of protocols that allows software clients to talk to external data services in a uniform way
- In most cases you (the software user) don't need to understand the details, but it's under the hood making data access work

External data access from TOPCAT:

- Cone Search: positional query of remote catalogue
- Table Access Protocol (TAP): SQL-like queries against remote databases
- Simple Image Access/Simple Spectral Access: positional query of image/spectrum archives
- CDS services: Simbad, VizieR cone/all-sky, X-Match, Hips2fits
- Registry: service discovery
- SAMP: communication with other desktop/web applications

STILTS

STIL Tool Set (STIL = Starlink Tables Infrastructure Library)

- Has pretty much the same capabilities as TOPCAT
- but works from the command line (also JyStilts from Jython)

TOPCAT 	**STILTS** 
GUI	Command line
Interactive	Scriptable
Easy to use	Reproducible
Good for data exploration	Good for batch/programmed use
Exploratory phase	Production phase
few$\times 10^6$ rows	Unlimited size (for most things)

Typical usage:

- start off with TOPCAT
- maybe move on to STILTS for more specialised requirements
- TOPCAT >stilts STILTS control helps constructing plot commands

Installation

Installation instructions on TOPCAT web page:

`http://www.starlink.ac.uk/topcat/#install`

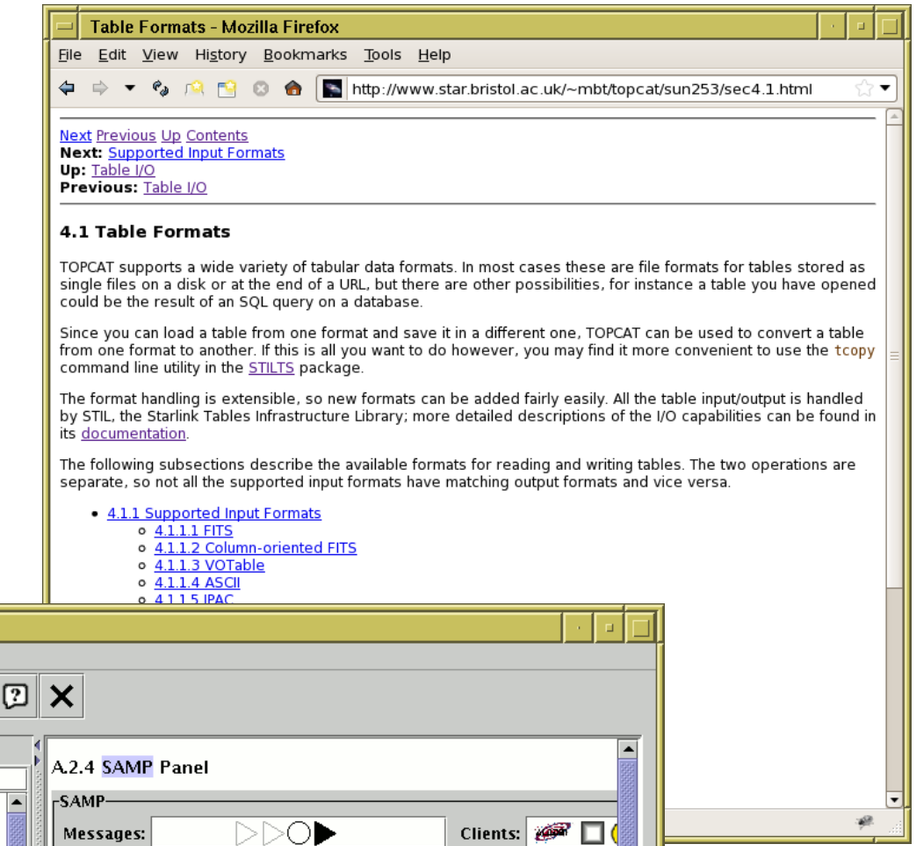
Quick summary:

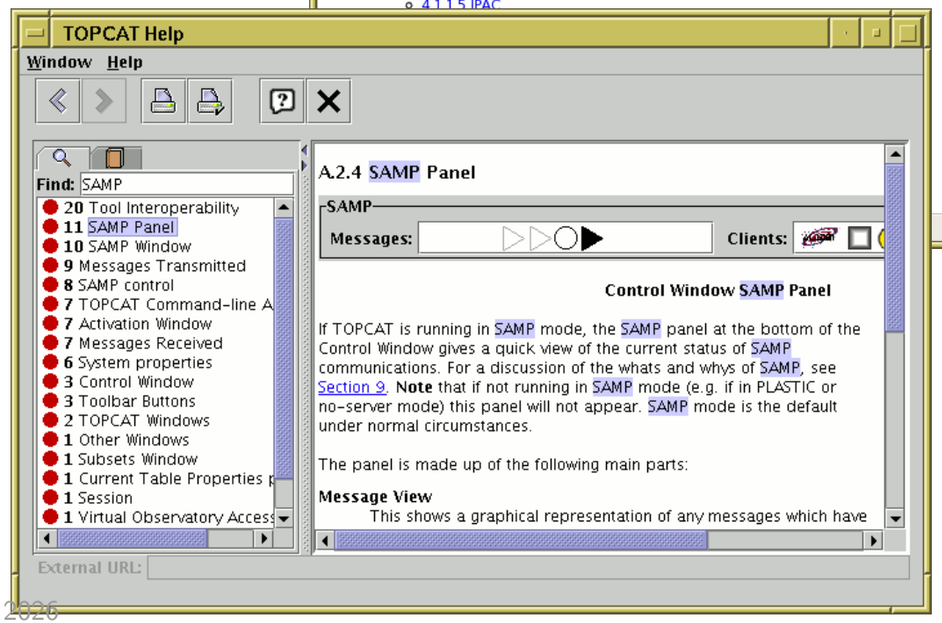
- Generic instructions:
  - Just need Java (JRE or JDK, any version ≥ 8) and `http://www.starlink.ac.uk/topcat/topcat-full.jar`
  - Then run `java -jar topcat-full.jar` (or maybe click on it)
- System-specific options:
  - MacOS with homebrew:
    - `brew install --cask topcat --no-quarantine`
  - MacOS without homebrew:
    - `curl -OL http://www.starlink.ac.uk/topcat/topcat-all.dmg`
  - Debian astro:
    - `sudo apt install topcat` (but this is a slighly old version, a couple of things in tutorial don't work)
  - Other Linux/Ubuntu problems:
    - Try `https://github.com/RedChaosWolf92/TOPCAT_RESOURCES`

Help and Documentation

Full tutorial and reference documentation:

- Full HTML manual on web page
- **Help for Window** button [?] on every window
- Help browser includes search tool
- More options in Help Menu (including **Help for Window in Browser** item [?])
- Or print out the 700-page PDF

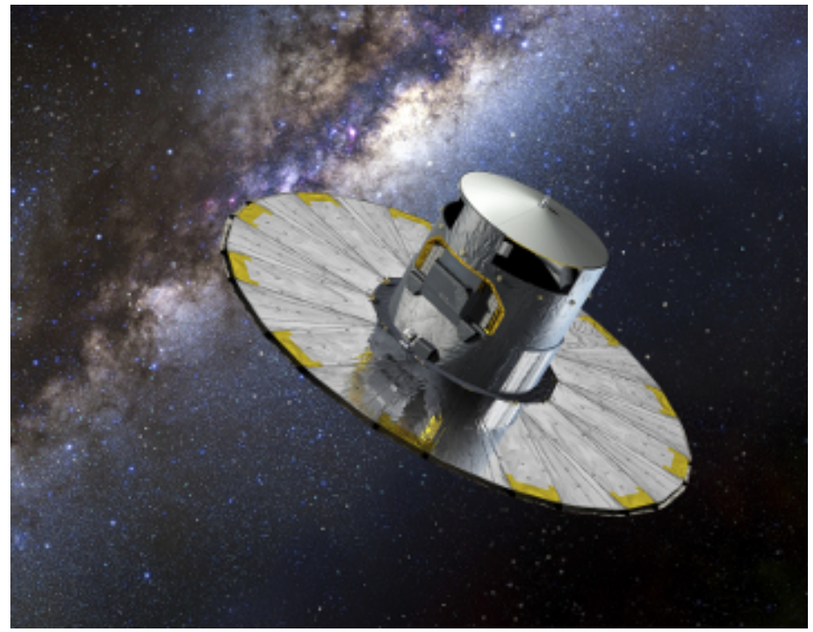




Gaia Mission

ESA astrometry satellite:

- Satellite at L2
- ∼10 year mission, 2013–2025



Aims

- Measure ∼2 billion point sources, complete to G≈20
  - ▷ mostly milky way stars, also galaxies, QSOs, SSOs, ...
  - ▷ each source observed multiple times
- Astrometry: positions, parallaxes, proper motions (10^1–$10^3\mu$as accuracy)
- Photometry: G, RP, BP bands (mmag accuracy)
- Spectrometry: radial velocities (1–15 km/s accuracy)
- Spectro-Photometry: low-res spectra in range 330–1050 nm

Highly successful

- Thousands of published papers, impacts on all areas of astronomy

Data Releases

- Data all public, released to everybody at the same time
- Most recent: DR3 (13 June 2022)
- Next: DR4 (expected December 2026)

Hands-On Exercises: Topics

- Cluster Identification #1: Messier 4 in proper motion space
  - Cone search, sky plot, subsets, histogram
- Cluster Identification #2: Hyades in 3-D velocity space
  - TAP, expression language, 3D plot, linked views
- Match Gaia and HST Observations for NGC346
  - VizieR download, CDS X-Match, multi-layer plots, pair match
- Local Herzsprung-Russell Diagram
  - Shading modes, polygon selection

Hands-On Exercises: Instructions

Exercise script:

https://github.com/mbtaylor/tctuto/releases/download/voschool-2025/tctuto.pdf

- We will probably do exercises #1, #2, #3 and #5

For each exercise:

- I will go through it with explanation
- You can have a few minutes to catch up or work through it;
  instructions in the script are quite detailed, especially for the earlier exercises
- If there are questions I can answer them
- It doesn't matter if you don't finish, you can go back after the session if you want

The main thing is to get a flavour of what can be done and how to do it

Exercise #1

Cluster identification #1: Messier 4 in proper motion space

- Locate Gaia EDR3 Cone Search service
- Query for sources in region of Messier 4
- Plot positions on sky
- Plot proper motions
- Create subset of comoving objects
- Create subset of background objects
- Plot proper motion vectors
- Histogram parallaxes of comoving and background objects
- Infer distance to Messier 4

Exercise #2

Cluster identification #2: Hyades in 3-D velocity space

- Locate Gaia TAP service
- Explore Gaia TAP service
- Run toy TAP query
- Run TAP query giving 6-d phase space information for nearby sources (cut'n'paste)
- Create new columns with 3-d Cartesian velocity components
- Plot sources in 3-d velocity space
- Create subset of comoving sources (Hyades)
- Examine Hyades *vs.* background sources on the sky
- Plot colour-magnitude diagram of Hyades *vs.* background sources

Exercise #3

Match Gaia and HST observations for NGC 346

- Download J/ApJS/166/549 catalogue from VizieR
- Crossmatch with Gaia EDR3 using CDS X-Match service
- Plot the crossmatch results
- Graphically find offset between HST and Gaia positions
- Use this to make sense of cross-match results
- Re-do crossmatch using TOPCAT internal match window

Exercise #5

Clean up local Gaia HR diagram following Lindgren et al., A&A, *616*, A2 (2018)

- Load local sources with small parallax and flux errors from Gaia TAP service
- Calculate absolute magnitudes from apparent mags and parallax
- Plot HR diagram
- Filter for good astrometry using weighted plot
- Filter for good photometry using algebraic subset definition
- Combine astrometric and photometric filters to get a clean HRD
- Examine HRD to see astrophysical detail

Well done!

Further Information

There are things I haven't mentioned!

Full tutorial and reference documentation:

- TOPCAT web page: `http://www.starlink.ac.uk/topcat/` (or google it)
  - ▷ TOPCAT manual: SUN/253
  - ▷ Script for examples: tctuto.pdf
- Don't forget the **Help for Window** button [?] on every window

Support:

- email me: m.b.taylor@bristol.ac.uk
- mailing list: `topcat-user@jiscmail.ac.uk`
- All feedback and questions welcome!