Transient characterization using the Virtual Observatory

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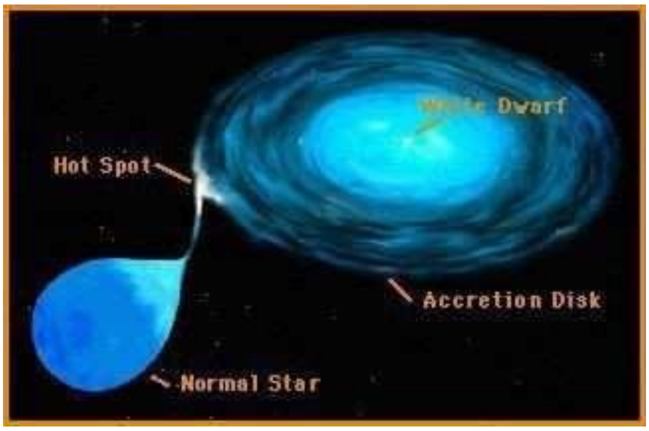
NOTE: The tutorial has been tested using Firefox v130.0.1 (64-bit).

- **Scientific background:** Transients can be defined as astrophysical phenomena whose duration is significantly lower than the typical timescale of the stellar and galactic evolution (from seconds to years in contrast to millions or billions of years). Supernovae, novae, gamma-ray burst..., are some examples of transient events. In most cases, a fast, multiwavelength characterization is required to properly understand the true nature of the transient. Follow-up observations made by both professional and amateur astronomers using ground- and space-based facilities are key to achieve this goal.

  Here we propose an alternative approach using the existing information in astronomical archives and benefiting from the advantages that the Virtual Observatory offers in terms of discovery, access and analysis of astronomical data. Using **TOPCAT**, **Vizier** and **SPLAT-VO**, and two services developed in the framework of the Spanish Virtual Observatory (**SVO Discovery Tool** and **VOSA**) we will validate and characterize a cataclysmic variable identified by the Gaia Science Alerts project. Cataclysmic variable stars (CVs) are interacting binary systems composed by a white dwarf that accretes material from a companion star. Because of its accreting nature, the system irregularly presents an important increase of brightness and then drop back down to a quiescent state.

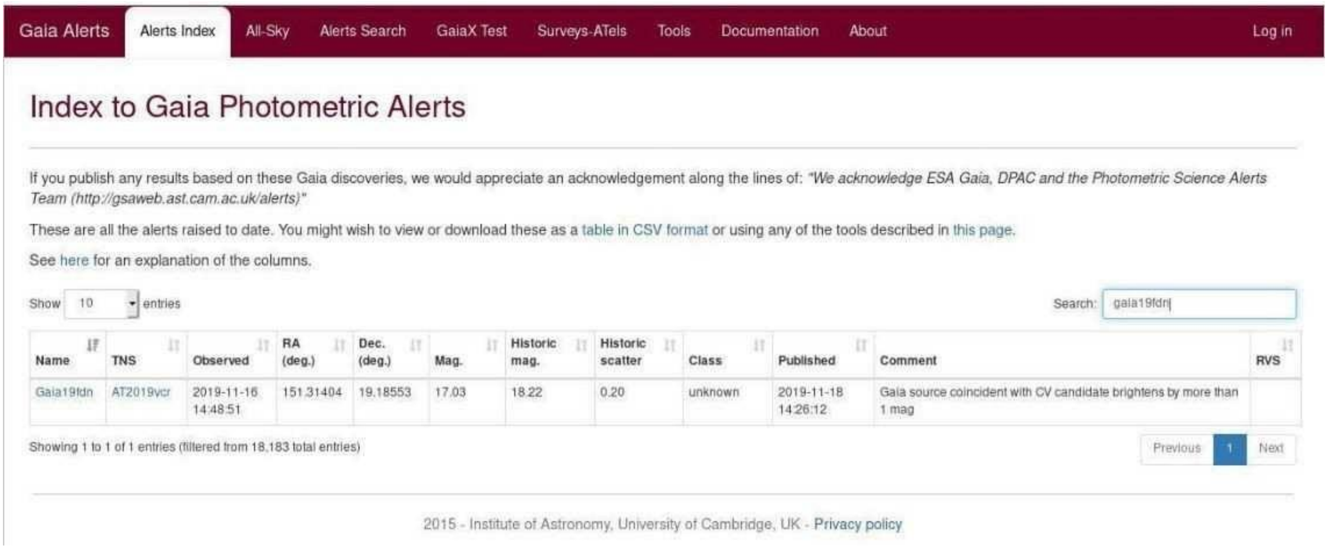


Cataclysmic variable (source: Wikipedia)

- **Workflow:**

1. Target selection. From the Gaia Science Alerts project we will select an object classified as "unknown" and suspect of being a cataclysmic variable:

   - Open your web browser and go to: http://gsaweb.ast.cam.ac.uk/alerts/alertsindex
   - In the search box (top right) type "Gaia19fdn". This object has been classified as unknown and has the following statement under the *Comment* column: "Gaia source coincident with CV candidate brightens by more than 1 mag".

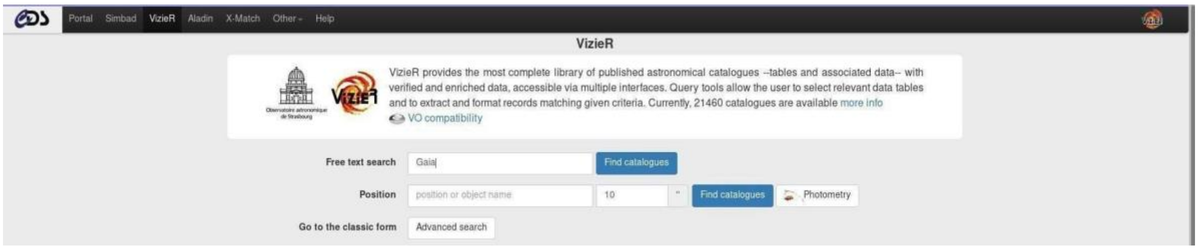


- Click on the name "gaia19fdn" (column "Name"). A new tab will open with a file card containing information like the coordinates and the magnitude variation over time.

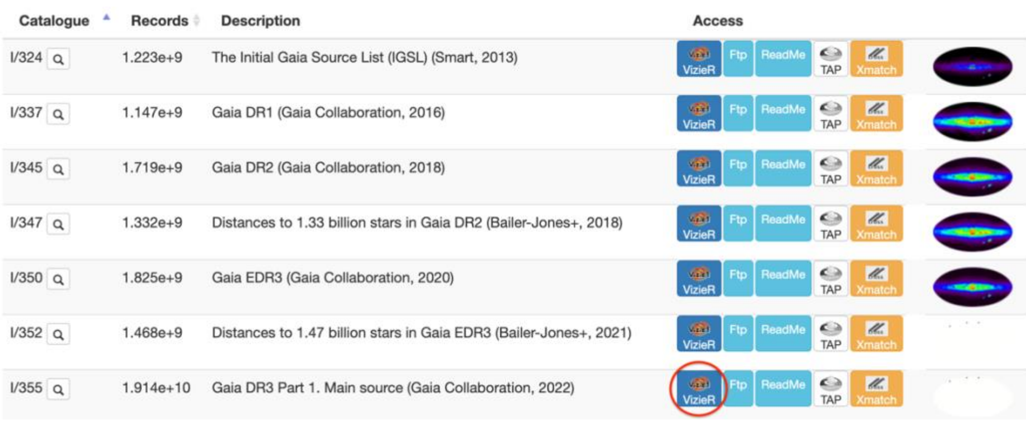
2. HR diagram. Cataclysmic variables occupy the intermediate region in the Hertzsprung-Russell diagram (HRD) between the main sequence and the white dwarf locus.

We will draw our target in a HRD diagram using TOPCAT and the VizieR service.

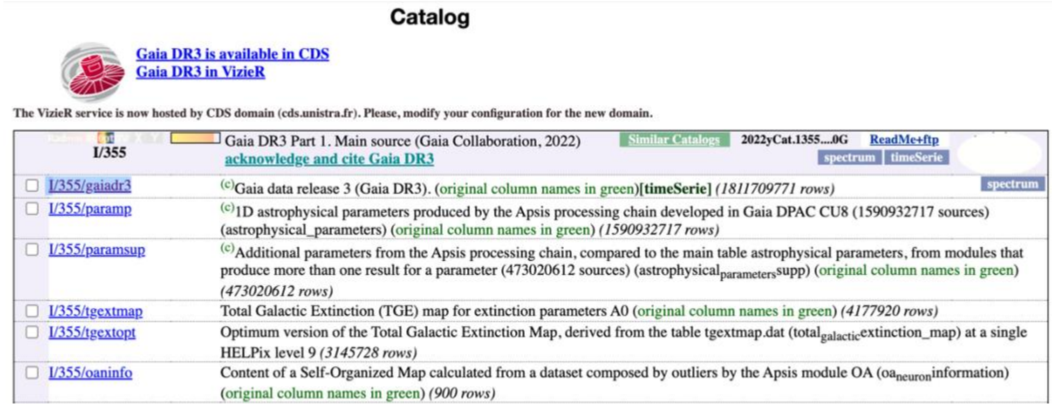
- **Obtaining the data**:
  - We will gather Gaia DR3 data from the VizieR service. Open your web browser and go to http://vizier.u-strasbg.fr/
  - Write "Gaia" in the **Free text search** and click on the *Find catalogues* button.



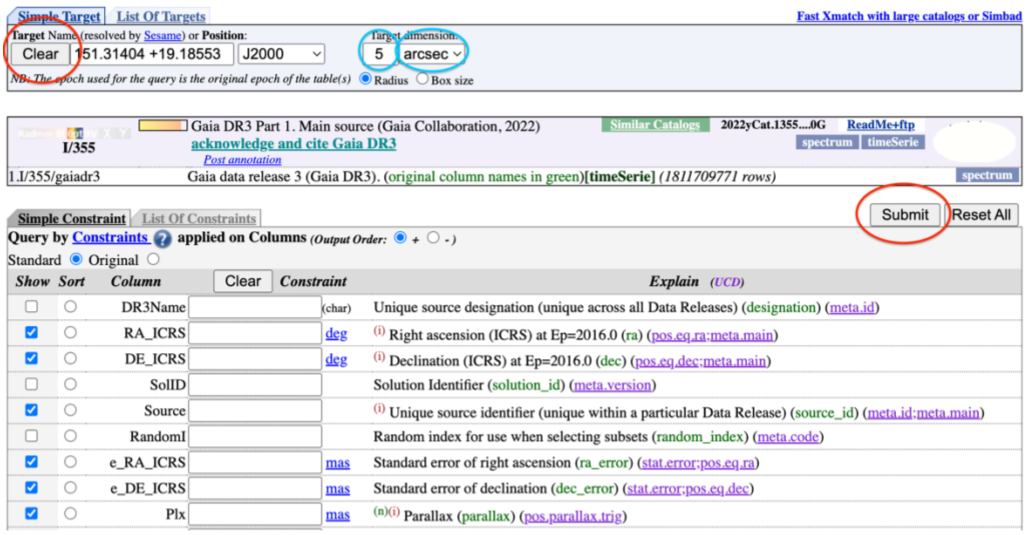
  - Look for "Gaia DR3 Part 1. Main source (Gaia Collaboration, 2022)" in the list of results and click on the VizieR button to query the VizieR table.



- The query returns several catalogues for Gaia DR3 Part 1. Click on the first one (I/355/gaiadr3).



- In the ***Target Name*** *(resolved by Sesame) or* ***Position*** *box* on top left, write the coordinates of the object: 151.31404 +19.18553. Then change the target dimension to 5 arcsec and click the *Submit* button.



- Launch TOPCAT: If you downloaded the Jar file, open a terminal and type: java - jar topcat-full.jar & ; if you have the MacOS installation, open the TOPCAT application.

- Back to VizieR, on the top right corner of the results' page, you will see the text **Send to VO tools**. Click on the antenna icon below the text. A SAMP Hub Security window will pop-up. Click on *Yes* to authorize the connection. Then click on *Broadcast* button near the antenna in the VizieR window. A table named "gaiadr3" will be loaded in TOPCAT.

- Download the file "[hrdiagram_dr3.xml]". It contains the astrometric solution for more than 46000 Gaia sources with good parallaxes and colours. We will use it as a reference for the HRD.

- **Exploring the data**:
  - In TOPCAT, load the file "hrdiagram_dr3.xml": *File → Load table → Filestore Browser.* Select the file and click *OK*. You will see the table loaded in the *Table List* box, to the left. By double clicking on it you can open the table to make a visual inspection of its content.

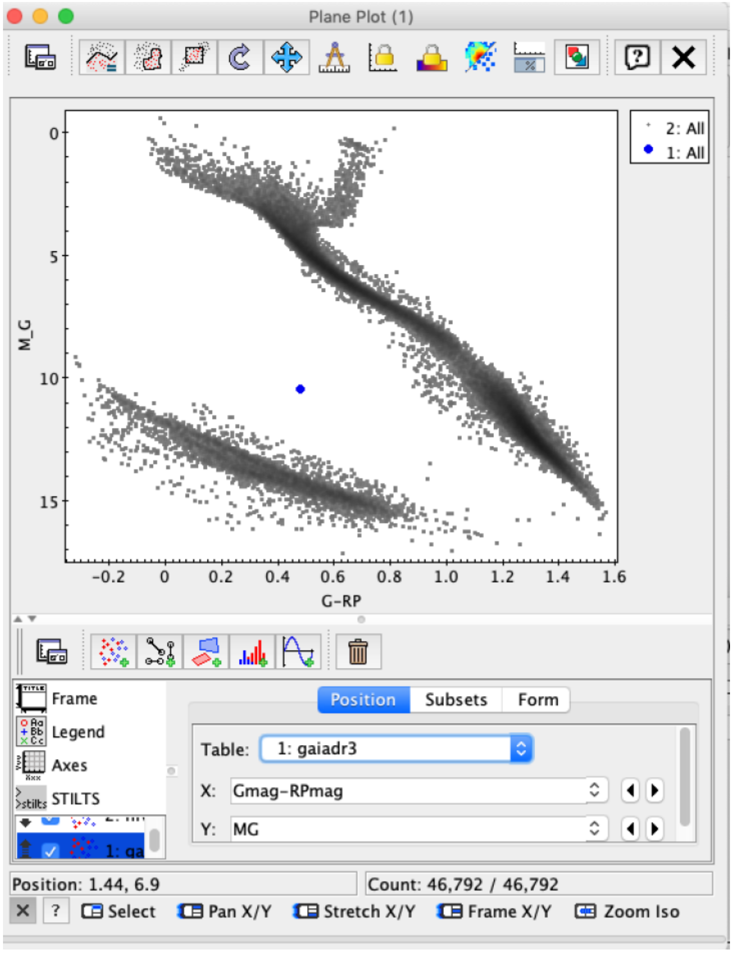
  - To plot the HRD: *Graphics → Plane Plot* (or click on the 11th icon starting from the left). A new window will pop up.
    - Select your table "hrdiagram_dr3.xml"
    - X axis will be (G-RP) (difference in magnitude in the Gaia G and RP bands)
    - Y axis: M_G (absolute magnitude in the G band).
  - On the left panel of this window, go to **Axes** → **Coords** and select *Y Flip.*

  - The color of the sources can be changed in the *Plane Plot* window by clicking on the name of the plane (hrdiagram_dr3.xml; it should be highlighted in blue), then click on ***Subsets*** (the tag in between *Position* and *Form)* and change the red color to, for instance, light gray.

  - In order to overplot in this HRD the gaiadr3 source we need first to create a new column with the absolute magnitude in the G band. For this, we will proceed as follows:
    - Click on *gaiaedr3* in the Table List box of the TOPCAT main window (it should be highlighted in blue).
    - *Views → Column info* (or click on the 6th icon starting from the left). A new window (Table columns) will pop up. Click on the first icon
      starting from the left (a green cross). A new window (define synthetic column) will pop up. Name it MG and write in the *Expression* box:

      Gmag-5*log10(1000./plx)+5
    - Click OK

  - In the same Plane Plot window: *Layers → Add Position Control.* A new line will appear below the left box. In the frame to the right, select the table "gaiadr3" and plot (Gmag-RPmag) on the X axis and MG on the Y axis. The source lies between the main sequence and the white dwarf locus, as expected for a cataclysmic variable star.

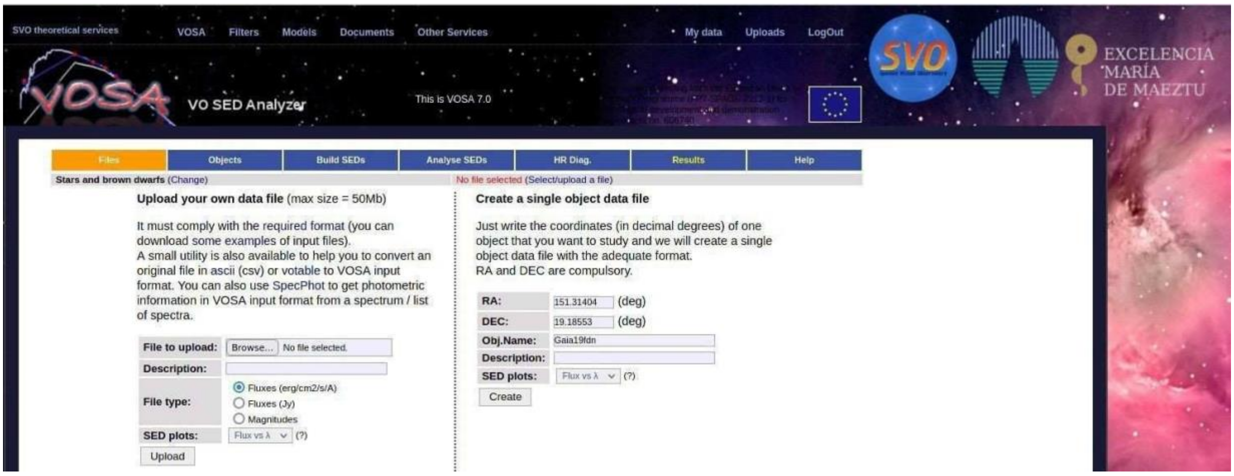


2. Spectral Energy Distribution (SED). Close binary stars of different effective temperature will present two differentiated distributions, one per each component in the system. We will now build the SED of our target using VOSA (VO SED Analyzer).

   - Open your web browser and go to: http://svo2.cab.inta-csic.es/theory/vosa Log in with your user and password if you already have an account. Complete the registration process, otherwise. To do that, click on *Register* and fill in the fields (e- mail address, name and password).

   - Create a single object data file typing the coordinates of the object in the RA and DEC boxes to the right. You can write the name of the object in the description box ("Gaia19fdn"). Click on the *Create* button.

     - RA: 151.31404
     - DEC: +19.18553



- Click the *Continue* link to keep going. You will be redirected to the initial page with this data file selected.

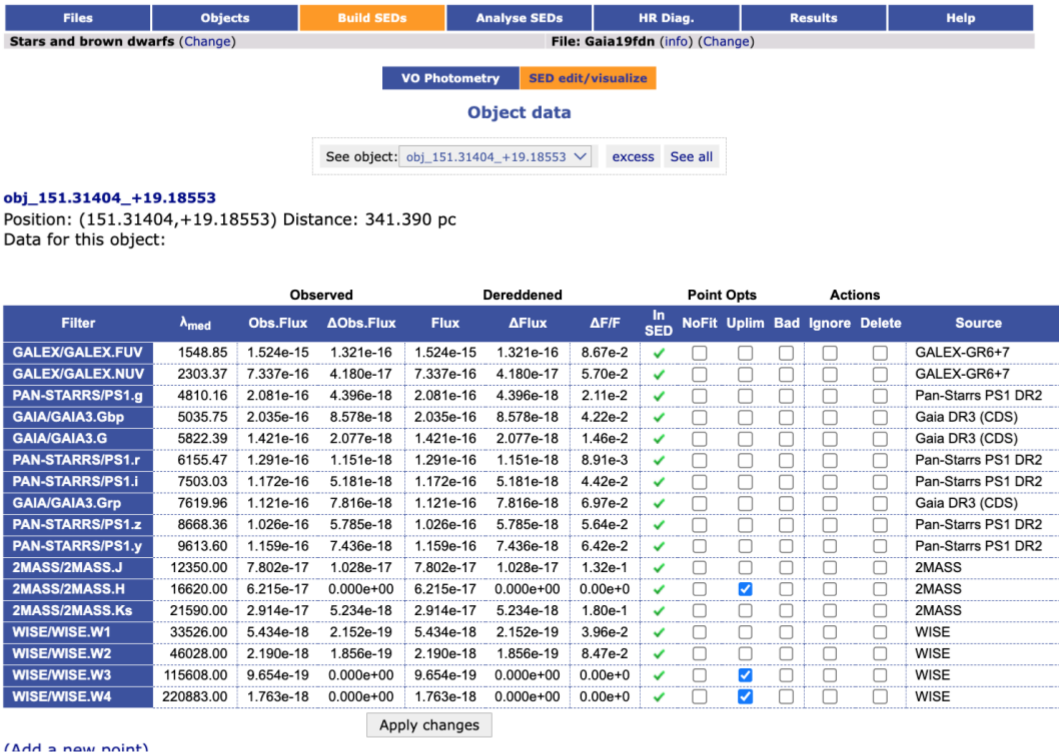
- Go to *Objects → Distances* tab to obtain the distance to the target. Keep the search radius at 5 arcsec. Click on *Search for Obj. Distances*. Distances from different catalogs will be shown. To make the Gaia DR3 distances the final ones, select them using the radio button on the right and click *Save Obj. Distances.* The distance and its error should appear boldfaced under the *Final* column.

GAIA DR3 (viz)

Δ (arcsec)	RA (deg)	DEC (deg)	Plx (mas)	ΔPlx (mas)	D (pc)	ΔDis (pc)	
0.0828	151.31405347582	+19.18551111348	2.9292	0.1693	341.390	19.731	○

- Move to *Build SEDs → VO photometry*. Here we will be able to look for photometric information of our objects in different VO archives and services. In order not to slow down too much the tutorial, click on *unmark All* and select only 2MASS, WISE, Gaia DR3 (CDS), Pan-Starrs PS1 DR2, and GALEX GR6+7. Then, click *Query selected services* at the bottom of the page. Once this is done, a summary table with the VO photometry (in flux units) will appear.

- Go to *Build SEDs → SED edit/visualize*. This tag gives us the possibility of visualizing/modifying the SED before the model fitting. VOSA gathers from VO services not only the photometric information but also different metadata of interest (Object name, observing date and information on quality). In particular, VOSA uses the information on quality to automatically identify bad photometric points and remove them from the fitting (see next step). Upper limits are treated in a similar way. The user can manually override this selection of photometric points by ticking/unticking the appropriate boxes. For this use case, do not make any change in the SED edit/visualize section.



Files | Objects | Build SEDs | Analyse SEDs | HR Diag. | Results | Help

Stars and brown dwarfs (Change) File: Gaia19fdn (info) (Change)

VO Photometry | SED edit/visualize

Object data

See object: obj_151.31404_+19.18553 excess See all

obj_151.31404_+19.18553
Position: (151.31404,+19.18553) Distance: 341.390 pc
Data for this object:

		Observed		Dereddened			Point Opts				Actions		
Filter	λ_{med}	Obs.Flux	ΔObs.Flux	Flux	ΔFlux	ΔF/F	In SED	NoFit	Uplim	Bad	Ignore	Delete	Source
GALEX/GALEX.FUV	1548.85	1.524e-15	1.321e-16	1.524e-15	1.321e-16	8.67e-2	✓	☐	☐	☐	☐	☐	GALEX-GR6+7
GALEX/GALEX.NUV	2303.37	7.337e-16	4.180e-17	7.337e-16	4.180e-17	5.70e-2	✓	☐	☐	☐	☐	☐	GALEX-GR6+7
PAN-STARRS/PS1.g	4810.16	2.081e-16	4.396e-18	2.081e-16	4.396e-18	2.11e-2	✓	☐	☐	☐	☐	☐	Pan-Starrs PS1 DR2
GAIA/GAIA3.Gbp	5035.75	2.035e-16	8.578e-18	2.035e-16	8.578e-18	4.22e-2	✓	☐	☐	☐	☐	☐	Gaia DR3 (CDS)
GAIA/GAIA3.G	5822.39	1.421e-16	2.077e-18	1.421e-16	2.077e-18	1.46e-2	✓	☐	☐	☐	☐	☐	Gaia DR3 (CDS)
PAN-STARRS/PS1.r	6155.47	1.291e-16	1.151e-18	1.291e-16	1.151e-18	8.91e-3	✓	☐	☐	☐	☐	☐	Pan-Starrs PS1 DR2
PAN-STARRS/PS1.i	7503.03	1.172e-16	5.181e-18	1.172e-16	5.181e-18	4.42e-2	✓	☐	☐	☐	☐	☐	Pan-Starrs PS1 DR2
GAIA/GAIA3.Grp	7619.96	1.121e-16	7.816e-18	1.121e-16	7.816e-18	6.97e-2	✓	☐	☐	☐	☐	☐	Gaia DR3 (CDS)
PAN-STARRS/PS1.z	8668.36	1.026e-16	5.785e-18	1.026e-16	5.785e-18	5.64e-2	✓	☐	☐	☐	☐	☐	Pan-Starrs PS1 DR2
PAN-STARRS/PS1.y	9613.60	1.159e-16	7.436e-18	1.159e-16	7.436e-18	6.42e-2	✓	☐	☐	☐	☐	☐	Pan-Starrs PS1 DR2
2MASS/2MASS.J	12350.00	7.802e-17	1.028e-17	7.802e-17	1.028e-17	1.32e-1	✓	☐	☐	☐	☐	☐	2MASS
2MASS/2MASS.H	16620.00	6.215e-17	0.000e+00	6.215e-17	0.000e+00	0.00e+0	✓	☐	☑	☐	☐	☐	2MASS
2MASS/2MASS.Ks	21590.00	2.914e-17	5.234e-18	2.914e-17	5.234e-18	1.80e-1	✓	☐	☐	☐	☐	☐	2MASS
WISE/WISE.W1	33526.00	5.434e-18	2.152e-19	5.434e-18	2.152e-19	3.96e-2	✓	☐	☐	☐	☐	☐	WISE
WISE/WISE.W2	46028.00	2.190e-18	1.856e-19	2.190e-18	1.856e-19	8.47e-2	✓	☐	☐	☐	☐	☐	WISE
WISE/WISE.W3	115608.00	9.654e-19	0.000e+00	9.654e-19	0.000e+00	0.00e+0	✓	☐	☑	☐	☐	☐	WISE
WISE/WISE.W4	220883.00	1.763e-18	0.000e+00	1.763e-18	0.000e+00	0.00e+0	✓	☐	☑	☐	☐	☐	WISE

Apply changes

(Add a new point)

- Move to *Analise SEDs → Binary Fit*. Different grids of theoretical models covering different ranges of physical parameters are displayed. For this tutorial select the "Koester WD models" and "BT-Settl (CIFIST)" for fitting the white dwarf and the main sequence components of the system, respectively.

  At the bottom of the page, in **Options for this fit,** select "*Include model spectrum in fit plots? (The fit process will be slower, because getting the spectra from the VO can take some time)".* Click on *Next: Select model params* at the bottom of the page.

- To save time, for BT-Settl set the logg range to 4.5 – 5.5. For Koester set the temperatures range to 5000 – 15000 K. Click on *Next: Make the fit.*

  A summary table will appear. Click on the *Show graphs* button above the table to see the SEDs plot.

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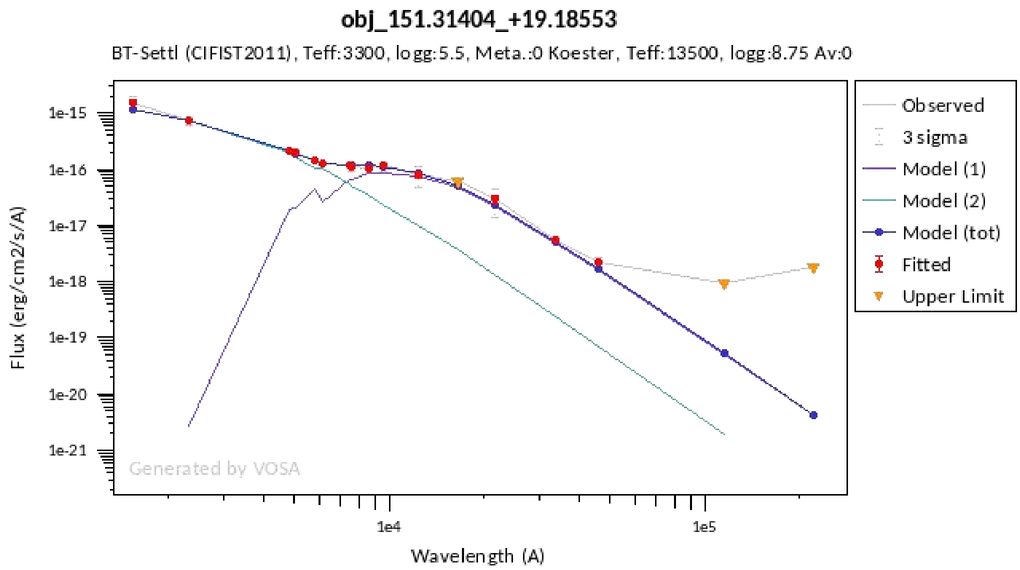

Both components of the systems have been fitted with temperatures of 1350 K and 3300 K for the white dwarf and the low-mass star secondary, respectively.

- To see the importance of the binary fitting, try yourself by fitting only the white dwarf component. For this, move to the tab *Analise SEDs → Chi- square Fit* instead and select the "Koester WD models" with the same parameter restrictions. The observational SED shows an infrared excess compared to the models due to the presence of the cool component and the estimated effective temperature (6750 K) comes from a poor SED fitting and does not represent the real temperature of the white dwarf.

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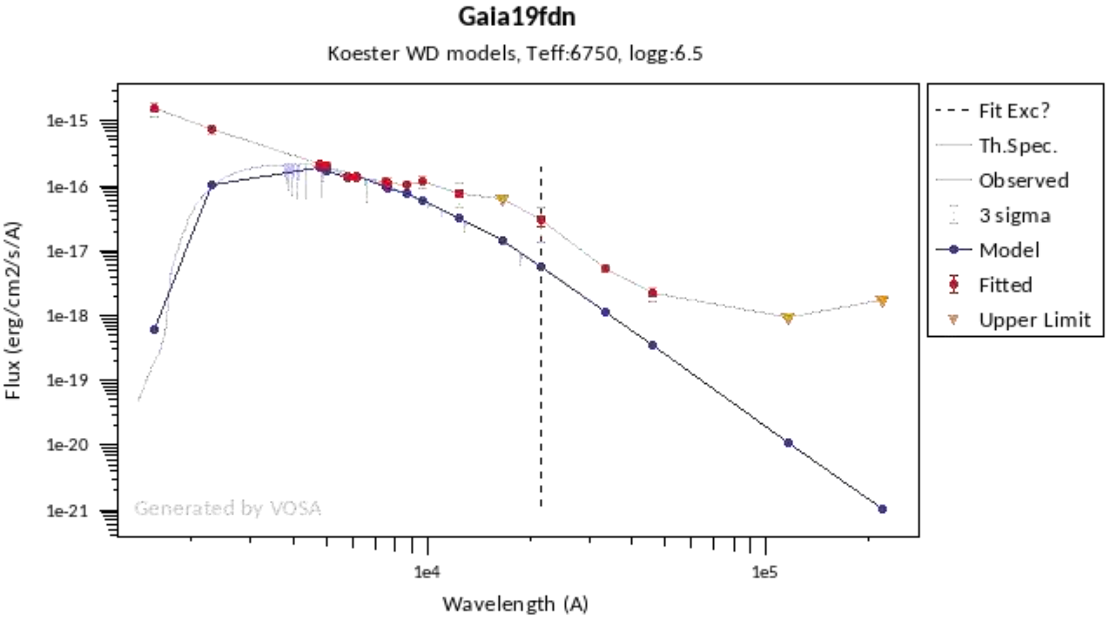


3. Search for spectroscopic information. Cataclysmic variables show Halpha emission due to accretion. Let's look for spectra of our source in VO archives to see if this feature is present.

- Open your web browser and go to: http://sdc.cab.inta-csic.es/SVODiscoveryTool/ The SVO Discovery Tool will help you getting basic information like physical parameters and photometry in the VizieR service, as well as images and spectra in all the Virtual Observatory.

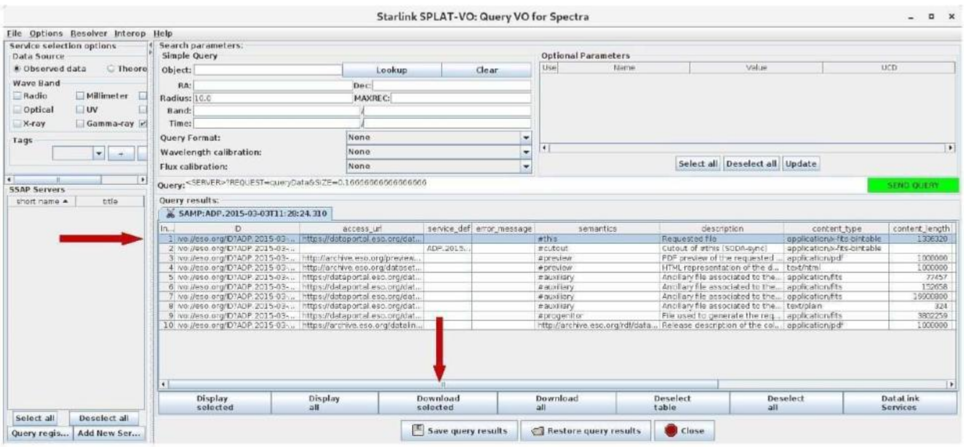
- Copy the coordinates of the object in the *List of object coordinates* box: 151.3140 +19.18553. Select the *Spectra* mark box under **VO Services** to obtain all available spectra of the target. Click on *Submit Query* at the bottom. A summary table shows that there are 27 spectra from the ESO spectra service and 95 from Hubble SSAP ESA service. On the bottom table, click on the number *27* to list the spectra. They were taken with the X-Shooter instrument. You can download them by ticking them and clicking on *Download selected*. They will be saved in a zip file. But you can also keep the window open and launch SPLAT-VO.

- Launch SPLAT-VO: Open a terminal and type ./splat-vo/bin/splat/splat & (or the corresponding path in your local installation).

IMPORTANT NOTE: The latest version of SPLAT-VO (v3.15.1) was compiled with java 8 (Java SE 8 [1.8.0_221]). Higher java versions may lead installation errors and/or malfunctioning of the application. Check your java version (*"java - version"*) and, if necessary, change it to java 8.

- Go back to the SVO Discovery Tool and locate the spectrum named "ADP.2015-03-03T11:28:24.310" provided by the ESO spectra service (do not use the ESO SSAP service). Click on *Send to SAMP Hub* to the right. A SAMP Hub Security window will pop-up. Click on *Yes* to authorize the connection. A new window will pop up in SPLAT-VO with the query of the spectrum. Note that, if other VO tools (TOPCAT, Aladin,…) are open, the spectrum will also send to them. It does not matter.

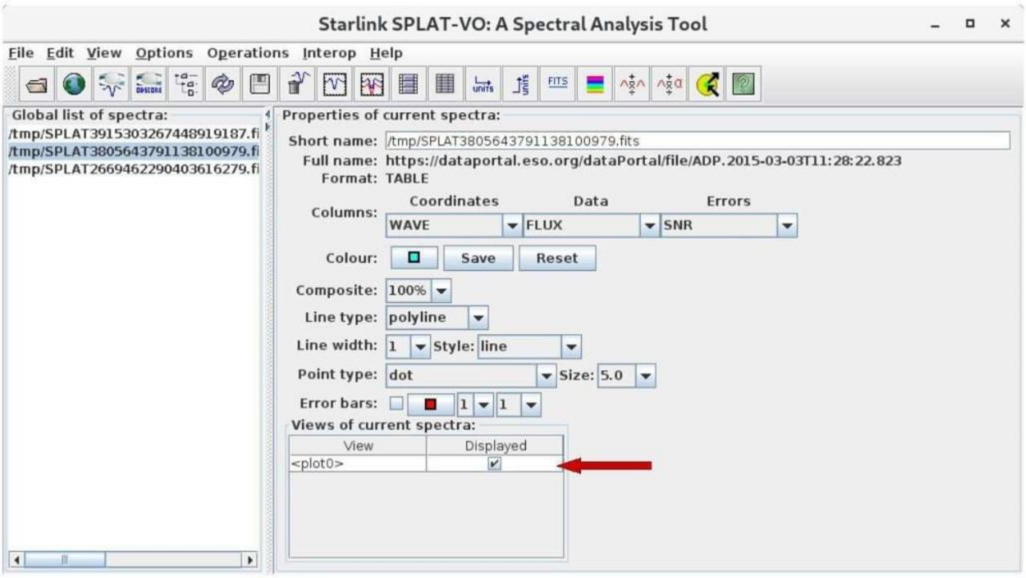
- Select the first line, which is the science spectrum (see the *eso_category* column) and click on *Download selected*. The spectrum will be loaded and listed in the *Global list of spectra* panel on the SPLAT-VO main window.



- Repeat the same steps to load these two spectra: ADP.2015-03-03T11:28:22.823 and ADP.2015-03-03T11:28:24.993. When you are done, if you wish, you can close the auxiliary window “Starlink SPLAT-VO: Query for VO spectra”.

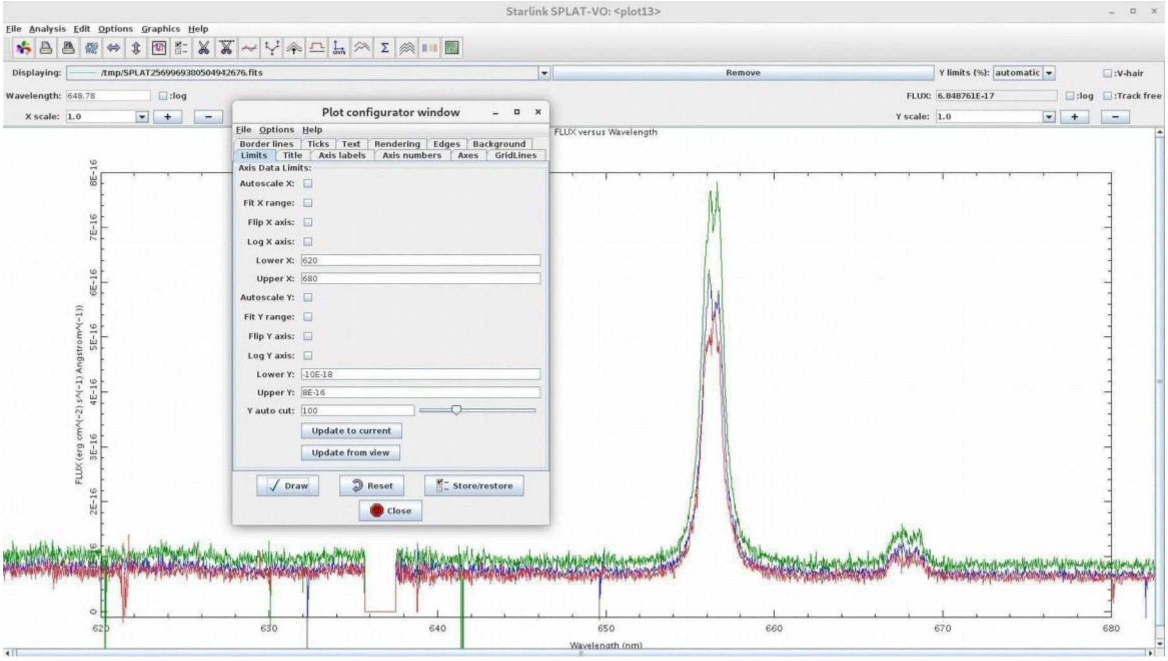
- In the SPLAT-VO main window, select the first spectrum and open it: *View →Display in new plots* (or double click on the name of the spectrum). A new window will pop-up with the spectrum.

- Again in the SPLAT-VO main window, select the second spectrum. In the right side of the window, at the bottom, you will see a table that lists the active plots. Tick the box under *Displayed* to display it together with the previous spectrum. Do the same with the third spectrum. You can change the colour of the displayed spectrum in this same panel, under the selection of columns to be displayed.



- Go to the plot window. Go to *File → Configure* (or click on the 8th icon from the left). A new window will pop-up. Untick the *Autoscale X* and *Autoscale Y* boxes and change the wavelength and flux ranges. Then click on the *Draw* button.

    - Lower X = 620
    - Upper X = 680
    - Lower Y = -10E-18
    - Upper Y = 8E-16



This is the Halpha emission line at 656.28 nm, which shows strong variability associated to the accreting process typical of cataclysmic variables.