

Virtual Observatory & LOFAR

Hands-on tutorial

Authors: Francisco Jiménez-Esteban, Spanish Virtual Observatory, CAB, Spain
Thomas Franzen & Vlad Kondratiev, ASTRON, The Netherlands
Hendrik Heinl, Centre de Données astronomiques de Strasbourg, France.

(6th LOFAR Data School, 22-26 March, Dwingeloo, The Netherlands)

In this tutorial we are going to work with three Virtual Observatory (VO) tools to explore and analyse data from two pulsars. If you have not installed **TOPCAT** and **Aladin** yet, you have to do before so starting the tutorial. **VOSA** is at a web server, so you do not need to install anything.

- **ALADIN:** Download the [Aladin.jar](#) file (Linux users only). MacOS and Windows users: download the suitable files [here](#). Aladin is compatible with Java releases from Java release 1.7 to the last one. More information [here](#).
- **TOPCAT:** Download the [topcat-full.jar](#) file (Linux and Windows users). MacOS users: download the suitable file [here](#). TOPCAT is written in the Java language using the Java 2 Standard Edition version 8, and should run on any Java SE 8 or more recent system. See the documentation [here](#).

1.- PSR B1508+55

For the radio part of the demo, we will use PSR B1508+55, a middle-aged, non-recycled pulsar which is bright in the radio but with no known higher-energy emission. Using VO tools, we propose to carry out the following steps:

- i) Check the flux scale and astrometry of LoTSS-PDR data in the vicinity of the pulsar.
- ii) Measure the radio SED of the pulsar by combining LoTSS-PDR data at 144 MHz with data from other major radio surveys between 74 and 1400 MHz.

The LoTSS-PDR catalogue (Shimwell et al. 2017) is available within the VO (see next section). The nice bit of using VO standards is that you can use your preferred client software to access the data (pretty much as you use your preferred browser or mail client). Here we will use TOPCAT (Tool for OPERations on Catalogues And Tables) to search for the LoTSS-PDR catalogue.

TOPCAT is one of the most useful VO tools, very powerful to handle tables and to explore the data using graphics. More information about TOPCAT can be found [here](#).

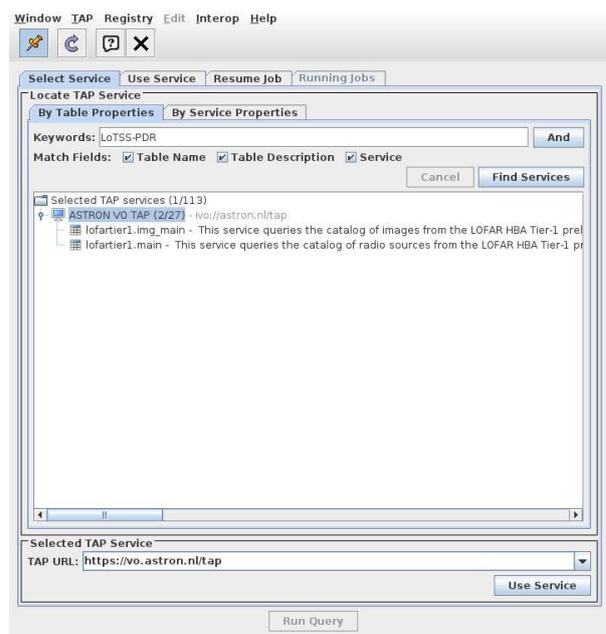
i) Flux scale and astrometry checks

1. Open a terminal and go to the directory where TOPCAT-full.jar was saved.
Type: `java -jar topcat-full.jar &` (On a Mac, click on the TOPCAT icon)
2. The LoTSS-PDR Cone Search is not in the registry (hence not directly findable “in the VO”), but there is a TAP service running which could be queried using TOPCAT and ADQL. The VO standards TAP and ADQL come as a package, you will always need the one with the other. ADQL is an extension to SQL to support queries which are specific to astronomy (e.g. selections on spherical data). For this tutorial you will not need to be fluent in ADQL, but certainly it’s helpful to get familiar with it.

In the main window of TOPCAT click on “VO” and select “Table Access Protocol (TAP) Query” from the menu. A new window will open and after a moment you will see a list of TAP Services.



3. If you knew which service you need to query, you could simply select it by double clicking. If you are still searching for the right service, you can use the field “Keywords” to find the catalogue you need. In our case there is only one result for LoTSS-PDR and it’s the service at ASTRON. Click on the small circle next to service to extend the information about the service. TOPCAT will show you the tables on service, which match our query.



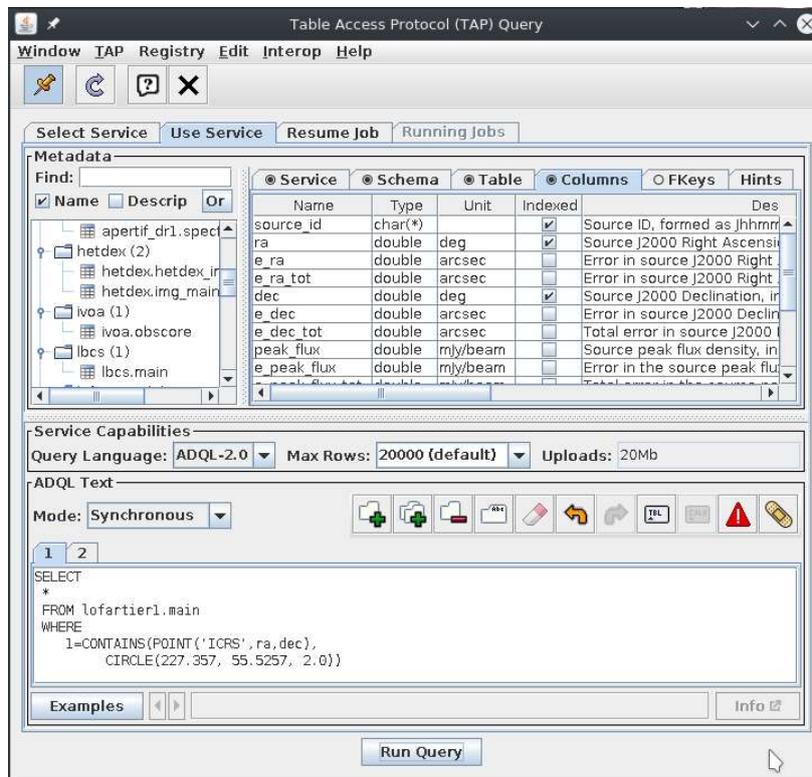
4. Select the service and click on “Use Service” at the bottom right to access the information of the Service at ASTRON. It may take a few seconds until the metadata of the service is loaded, but eventually you will see a table browser on the left, a metadata window on the right, and a field for the ADQL query on the bottom (see figure at the bottom of this page).

5. In our use case we want to make a selection on the table data of the lofartier1 catalogue on the ASTRON service. There are two tables. The one we need is called *lofartier1.main*. Click on the name of the table and information will appear at the right. We want to receive the data of all objects in the catalogue in 2 degrees cone around the position RA: 227.357, DEC: 55.5257

In ADQL such a cone selection looks like this (you can copy and paste this query):

```
SELECT
*
FROM lofartier1.main
WHERE
    1=CONTAINS(POINT('ICRS', ra, dec),
    CIRCLE('ICRS', 227.357, 55.5257, 2.0 ))
```

Click on “Run Query” and the resulting table should be downloaded within a few seconds. The table contains 555 sources with 16 catalogue fields. In the TOPCAT main window, click on Views/ Column Info to obtain information on the columns. These are the metadata.



To check the flux scale and the astrometry of LoTSS-PDR data, we use the TGSS ADR1 catalogue (Intema et al. 2017), which covers the whole sky north of -53 deg at a very similar frequency (150 MHz) to LoTSS-PDR.

1. The TGSS ADR1 catalogue is at Vizier. In the main window of TOPCAT click on VO/Multicone. A Multiple Cone Search window shows up. On this new window, write "Intema" in the Keywords box and click "Find Services". Select "The GMRT 150MHz all-sky radio survey" on the list. Select the lofartier1 table in the "Input Table". TOPCAT automatically identifies the RA and Dec columns (thanks to the metadata). Set the Search Radius to 10 arcsec and click "Go". After the query to TGSS ADR1 catalogue is finished, a new table with 119 matches is loaded. This table contains all columns from LoTSS-PDR and TGSS ADR1. Change the name of the table in the "Label" box of the TOPCAT main window. For example LoTSSxTGSS.

Another option is to use the CDS cross-match service ("VO/CDS Upload X-Match"), which is much faster. However, you need to know in advance the name of the table you want to cross-match.

A third option would be to use ADQL to combine the two tables on the Astron service with a single query:

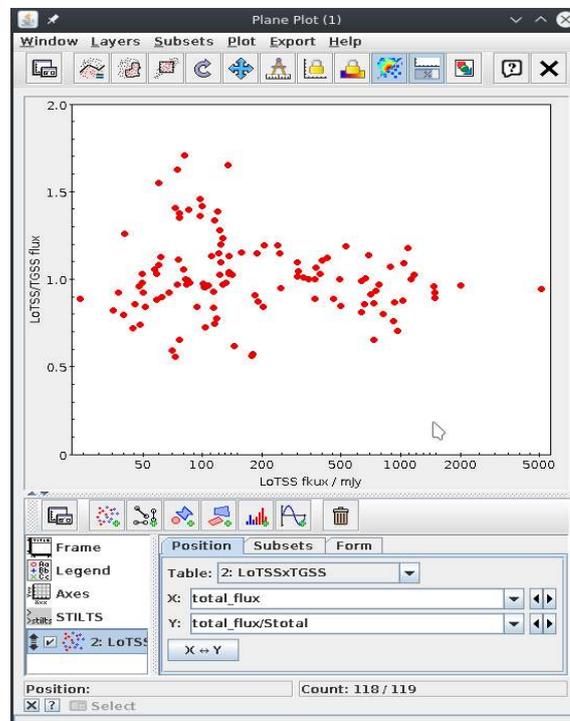
```
SELECT * FROM tgssadr.main AS tg
JOIN lofartier1.main AS lt
ON 1=CONTAINS(POINT ('ICRS', tg.ra, tg.dec),
              CIRCLE ('ICRS',lt.ra, lt.dec, 10./3600.))
AND 1=CONTAINS(POINT ('ICRS', lt.ra, lt.dec),
              CIRCLE ('ICRS', 227.357, 55.5257, 2.0))
```

As you can see, there is not **one single** solution to find and access the data, which is a good thing: what's the best solution may depend on your science case, the software you use, and of course your skills.

In the next tutorial steps we assume you performed the cross match with the Multi Cone Search on Vizier. You may try any of the mentioned alternative ways, but you may have to adjust column names in the following steps of this tutorial, so for your first way through this tutorial, we recommend using Vizier.

2. To check the LoTSS flux scale, plot the ratio of the LoTSS to TGSS integrated flux density (i.e. $\text{total_flux}/\text{Stotal}$) as a function of the LoTSS integrated flux density. In the flux comparison, it is best to use sources which are morphologically simple in both catalogues. Some filtering can be applied to the catalogues in TOPCAT to ensure this, but due to the limited time available for this tutorial, we have not included this step.

In the main TOPCAT window, click on “Graphics/Plane Plot”. A new window shows up. In this window, select the table result of the previous cross-match. Select “total_flux” for the X axis, and write “total_flux/Stotal” in the Y axis. Now it is possible to customize the plot. Click on “Axes” at the bottom-left box. Set the maximum Y = 2 and the minimum Y=0 at “Range”; X Log in “Coords”, and change the labels in “Labels”. Finally, you can save the plot clicking on “Export/Export plot to file”.



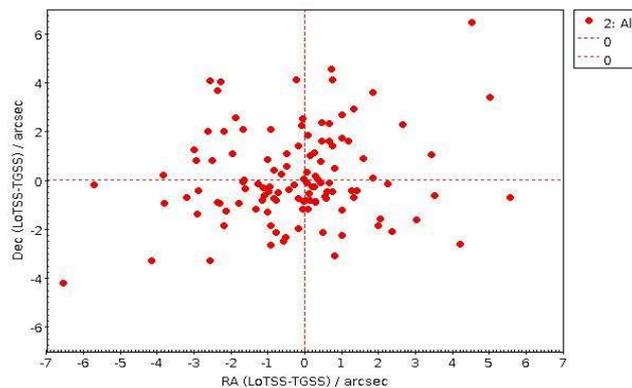
The overall flux scale of LoTSS-PDR appears to be in good agreement with TGSS. There is a relatively large scatter in the flux ratios especially at lower flux densities, but this is expected given the large difference in sensitivity and resolution of the two catalogues (LoTSS PDR has a resolution of ~ 5 arcsec while TGSS has a resolution of ~ 25 arcsec, and LoTSS PDR is more than 10 times deeper than TGSS).

3. To check the astrometry, calculate the RA and Dec offsets, in arcsec, as follows:
 - a. Open the table columns clicking on “Views/Column Info”. Table Columns shows up.
 - b. Click on “Columns/New Synthetic Column” to define a new column. In the new window write “RA separation” in “Name”, and in “Expression”:
 - c. $(RA-RAJ2000)*\cos(\text{degreesToRadians}(DEJ2000))*3600$
 - d. Repeat b but with the declination: “Dec separation” in “name”, and in “Expression”
 - e. $(DEC-DEJ2000)*3600$

where (RA, Dec) are the LoTSS-PDR coordinates and (RAJ2000, DEJ2000) are the TGSS coordinates, in deg.

Plot the RA and Dec offsets in a similar way than before, selecting the new created columns in the X and Y axes. To draw the lines, you need to add two more layers to the plot:

- a. In the Plane Plot window, select “Layers / Add Function Control”
- b. Set 0 in the “Function Expression” box
- c. Change the style of the line in the “Style” tag.
- d. Repeat the previous steps but set “Vertical” in the “Independent Axis” box, to draw the vertical line.



The astrometry could alternatively be checked by cross-matching LoTSS-PDR with FIRST at 1.4 GHz, which has a resolution of 5 arcsec.

4. With TOPCAT it is also possible to calculate some statistics. In the Table Columns, deselect all fields by clicking “Columns/Hide All Columns”, and select “Separation”, “RA separation”, and “Dec Separation” by clicking on the small square together the name of the column. “Separation” is the angular separation between the query position and the result position, and was calculated by the VO service during the cross-match. Now in the main window of TOPCAT click on “Views/Column Statistics”.

Name	Mean	SD	Minimum	Maximum	nGood
Separation	0.00063	0.000444	1.578273E-5	0.00219	119
RA separation	-0.30302	2.0409	-7.3486	5.96544	119
Dec separation	0.1477	1.83112	-4.18393	6.47937	119

Subset for calculations: All

ii) Radio SED

We use TOPCAT to estimate the spectral index of PSR B1508+55. For this we combine radio data from the following catalogues: VLSSr (74 MHz), LoTSS-PDR (144 MHz), TGSS (150 MHz), WENSS (325 MHz) and NVSS (1.4 GHz).

The table below gives the flux density of the pulsar at each frequency

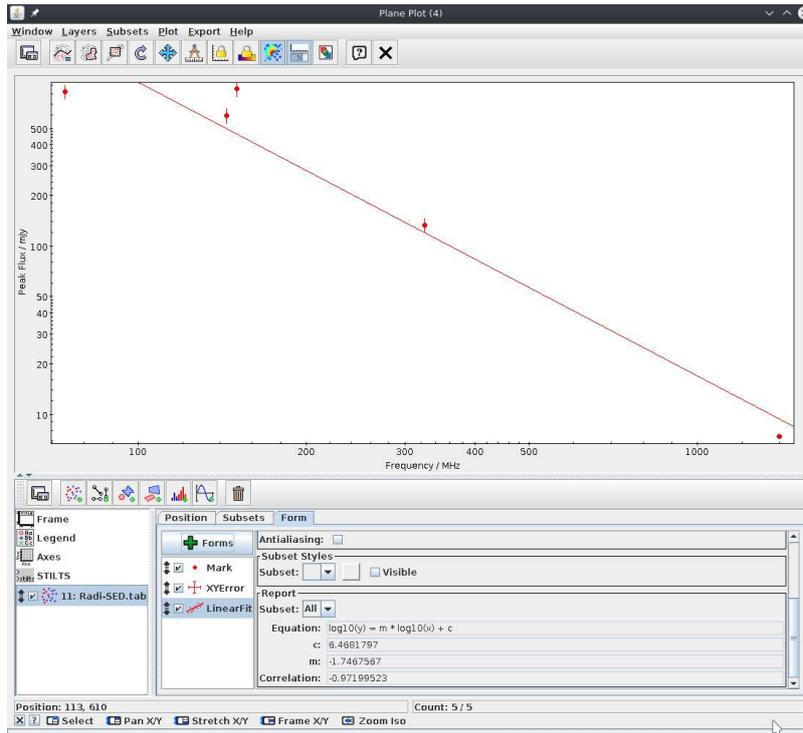
Survey	Frequency (MHz)	Peak flux (mJy/bm)
VLSSr	74	830 +/- 80
LoTSS-PDR	144	596 +/- 60
TGSS	150	859 +/- 86
WENSS	325	133 +/- 13
NVSS	1400	7.4 +/- 0.5

In the previous part of the tutorial you have already collected the data from LoTSS-PDR and TGSS. The data from the other catalogues is also available at VO and can be collected with TOPCAT. Due to the limited time we have, we left this as a challenge for the student (See Annex I). To continue with the tutorial, download the above table from the Slack channel #t11-vo-lofar, and upload it to TOPCAT. Note that the table is in ascii format.

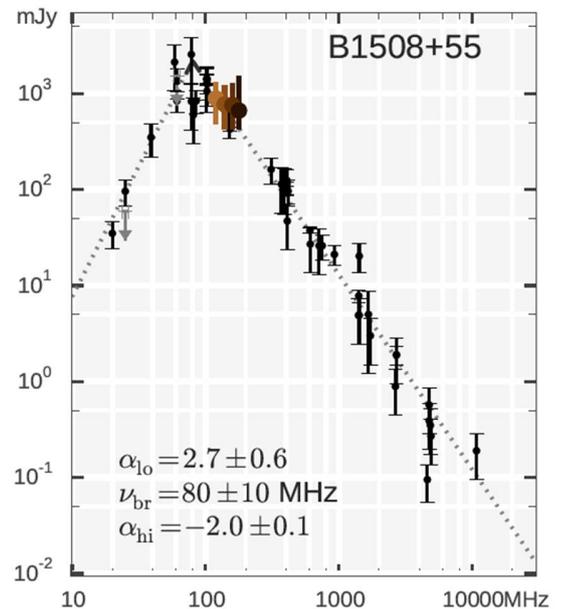
The LoTSS-PDR and TGSS fluxes are somewhat discrepant, but a number of years separate the measurements from the two surveys, and in principle variations of about ~30% are possible on timescales of weeks/months due to refractive scintillation.

Estimate the spectral index with TOPCAT:

1. Open a "Plane Plot" clicking on "Graphics/Plane Plot"
2. Select "Freq" and "Peak Flux" for the X and Y axis, respectively.
3. Set logarithmic scale in both axes (Axes/Coords at the left box).
4. Add error bars:
 - a. Click on the table name at the bottom-left box.
 - b. At the "Form" tag, click on the "Add Form" icon  and select "Add XYErrors". Set "er_flux" as the "Y Positive Error".
5. Perform a linear fit to the data:
 - a. At the "Form" tag, click on the "Add Form" icon  and select "Add LinearFit"
 - b. The result of the fit is shown at the box on the right. The slope of the line corresponds to the spectral index.



The red line shows a power-law fit, the spectral index is -1.75. [Bilous et al. \(2016\)](#) measured the radio SED of this pulsar between 20 MHz and 10 GHz, combining LOFAR flux densities with other measurements in the literature (figure reproduced below). There is a spectral break around 80 MHz. They measured a spectral index of -2.0 ± 0.1 above 80 MHz, which is similar to what we measure here. The VLSSr flux density is close to the spectral break which may explain why it is low compared with the power-law fit.



2.- PSR J1816+4510

We will use PSR J1816+4510 to explore non-radio catalogues. It is an energetic, eclipsing millisecond pulsar in a binary system with a white dwarf (WD) companion. The pulsar is detected at low radio frequency in LoTSS DR2, but the LoTSS DR2 data are not yet publicly available. Using VO tools, we propose to carry out the following analysis:

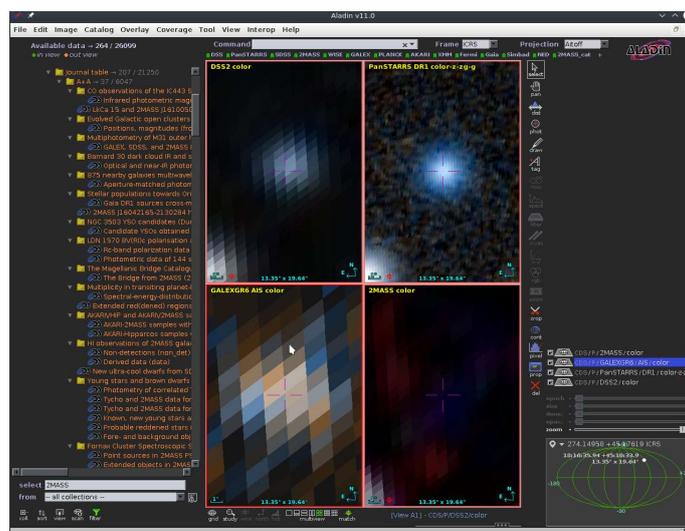
- Use Aladin to identify the UV and optical counterpart of the companion
- Use VOSA to construct the SED of the companion and to derive some physical parameters

The reference paper for this part of the demo is [Kaplan et al. \(2012\)](#).

i) Identify the optical and UV counterpart of the WD companion

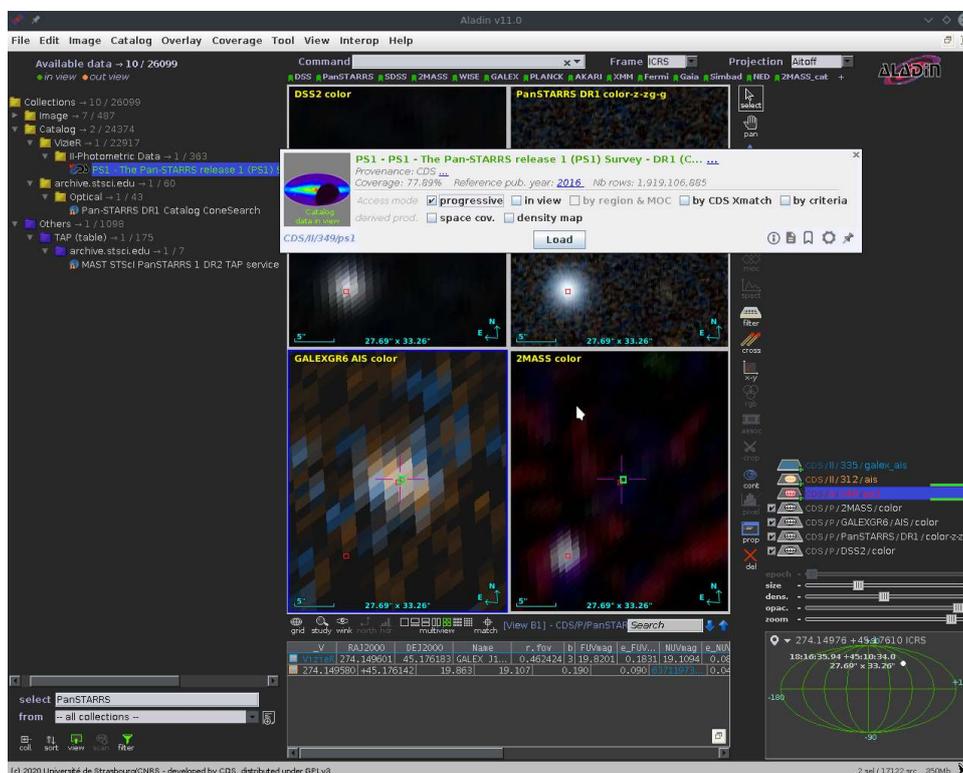
In this part we are going to use Aladin to explore the available VO-data for the WD. Aladin is an interactive sky atlas allowing the user to visualize digitized astronomical images or full surveys. More information about Aladin can be found [here](#).

1. Open a terminal and go to the directory where Aladin.jar was saved.
Type: `java -jar Aladin.jar &` (On a Mac, click on the Aladin icon)
2. Type the name of the object in the “Command” box at the top-center in Aladin and press intro. Aladin will resolve the coordinates of the objects using SESAME VO service. A Hierarchical Progressive Survey (HiPS) image from the DSS2 centred at the object’s coordinates is automatically loaded. Zoom in/out the images with the wheel of the mouse.
3. Select “multiview” (4 fields) mode in the icons at the bottom. Click on an empty field and select other surveys in the menu just above the images, for example GALEX (UV), PanSTARRS (optical), 2MASS (NIR). Match all images to show the same field of view clicking in the “match” icon at the bottom. The optical and UV counterpart is easily identified in the DSS2, PanSTARRS, and GALEX images. However, it is not visible in the NIR 2MASS image.



- Now we search for VO data from a multitude of catalogues. In the left side of the Aladin window there is a list of available data collections (>26.000). Of course, there is not data for our source in all of them. Clicking on the “view” icon at the bottom, Aladin will show only those collections with data in the field of view. Note that data in the field of view does not mean data of our source. To investigate the possible available data you can just unfold the collection list. To enclose the search you can put keywords in the “select” box at the bottom-left, for example “optical”, “PanSTARRS”, etc.

Upload white dwarf counterparts of the Gaia-EDR3, GALEX-DR5 AIS, and PanSTARRS-DR1 catalogues by clicking on the name of the catalogue. A new window shows up. Select “progressive” and click “load”. A new plane is loaded with the data from each catalogue. The counterparts are shown with different symbols in the images. Clicking on the symbols the data from the catalogues will be shown at the box below the images.



i) VU/Optical SED and some physical parameters.

In this part we are going to use another VO tool (VOSA) to build the SED (Spectral Energy Distribution) of the white dwarf companion, and obtain some physical parameters by fitting the observational data to a grid of hydrogen rich atmosphere models ([Koester 2010](#)).

VOSA (VO SED Analyzer) is a VO tool developed by the Spanish Virtual Observatory. This tool is able to explore a large number of photometric catalogues, combine the data from them to construct the SED from the UV to the far-IR, and fit the observational data to several collections of models. Users can also upload their own photometric data. VOSA can also explore the VO for parallaxes and extinctions, and use them in the determination of the source physical parameters. In addition, VOSA is able to work with thousands of sources at a time. More information about VOSA can be found [here](#).

1. Go to <http://svo2.cab.inta-csic.es/theory/vosa/>
2. To use VOSA you need to be registered. Click on “Register” and fill in the fields (email, name and password). This is necessary to recover the session in case you leave it without finishing the whole process.
3. At the top-right side, we create a single object data file by filling the name of the source, add a comment to identify this session in the future, and select the plot units ($\lambda \cdot F_\lambda$ vs λ). Click “Create” and “Continue”. If the file you have just created is not selected, select it.
4. VOSA needs the coordinates of the source to search for photometry in VO archives. Place the cursor in the Object tag and then click on Coordinates. Click on “Search for Obj. Coordinates”. VOSA finds the coordinates of the source at the Sesame service. Select these coordinates and save them by clicking in “Save Obj. Coordinates”.

The screenshot shows the VOSA web interface. At the top, there is a navigation bar with links for 'Files', 'Objects', 'Build SEDs', 'Analyse SEDs', 'HR Diag', 'Results', and 'Help'. The current file is 'LOFRA School'. The 'Object coordinates' section is active, showing instructions on how to use the Sesame VO service. A warning box states: 'You have used Sesame to try to resolve these objects names, but there are still objects in your file without final coordinates. Take into account that you will not be able to search the VO for those objects (either properties or photometry)'. Below this, there is a 'Delete VO data' button. The 'Actions for all the objects in the file' panel includes a dropdown for 'Do you prefer User or Sesame values?' (set to 'First User, then Sesame if User not available') and a 'Make all changes' button. The 'Actions only for objects in this page' panel includes 'Mark all: Sesame', 'Unmark all: Sesame', and 'Save Obj. Coordinates' buttons. At the bottom, a table displays the coordinates for the object PSR+J1816%-2B4510.

Object	Final		User Data		Sesame	
	RA (deg)	DEC (deg)	RA (deg)	DEC (deg)	RA (deg)	DEC (deg)
PSR+J1816%-2B4510	---	---	---	---	274.14971417	+45.17607333

- Place the cursor on the Build SEDs tag and then click VO photometry. Here we will be able to look for photometric information of our objects in different VO archives and services. As there is just one source, leave VOSA to search in all the catalogues but Gaia-DR2. So, untick Gaia-DR2, and click “Query selected services” at the bottom of the page. Once this is done, a summary table with the VO photometry (in flux density units) will appear.

VO SED Analyzer

This is VOSA 6.0

This project has received funding from the European Union's Seventh Framework Programme (FP7-SPACE-2013-1) for research, technological development and demonstration under grant agreement no. 606740

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

Stars and brown dwarfs (Change) File: LOFAR School (info) (Change)

VO Photometry SED edit/visualize

VO photometry

Delete this VO photometry

(Flux densities are given in erg/cm²/s/Å)

Object	GALEX/GALEX_FUV	GALEX/GALEX_NUV	PAN-STARRS/PS1_g	GAIA/GAIA3.Gbp	GAIA/GAIA2.Gbp	GAIA/GAIA3.G	PAN-STARRS/PS1_r	GAIA/GAIA3.G
PSR+J1816%2B4510	5.35e-16 ± 9.03e-17	4.65e-16 ± 3.82e-17	2.77e-16 ± 2.39e-17	2.21e-16 ± 3.31e-18	2.30e-16 ± 3.07e-18	1.32e-16 ± 4.16e-19	1.29e-16 ± 9.26e-19	1.31e-16

- Place the cursor on the Build SEDs tag and then click SED edit/visualize. This tag gives us the possibility of visualising/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. Upper limits are treated in a similar way. The user can manually override this selection of photometric points by ticking/unticking the appropriate boxes.

VO SED Analyzer

This is VOSA 6.0

This project has received funding from the European Union's Seventh Framework Programme (FP7-SPACE-2013-1) for research, technological development and demonstration under grant agreement no. 606740

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

Stars and brown dwarfs (Change) File: LOFAR School (info) (Change)

VO Photometry SED edit/visualize

Object data

See object: PSR+J1816%2B4510 excess See all

PSR+J1816%2B4510
Position: (274.14958333, 45.17608333) Distance: unknown
Data for this object:

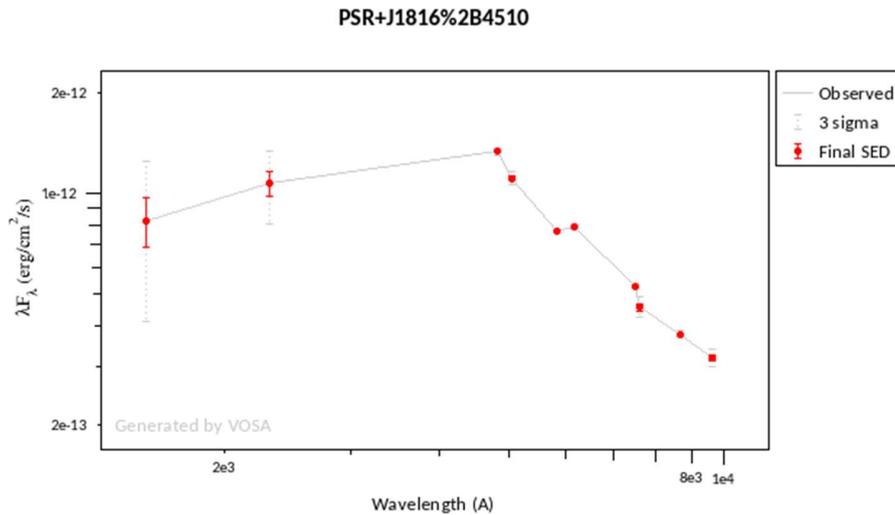
Send final SED to SAMP Hub

Filter	λ_{med}	Observed		Dereddened		In SED	Point Opts				Source	RA (VO)	DEC (VO)	
		Obs. Flux	Δ Obs. Flux	Flux	Δ Flux		NoFit	Uplim	Bad	Ignore				Delete
GALEX/GALEX_FUV	1549.02	5.354e-16	9.029e-17	5.354e-16	9.029e-17	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	GALEX	274.149601321871	45.1761831799647	0.3
GALEX/GALEX_NUV	2304.74	4.654e-16	3.822e-17	4.654e-16	3.822e-17	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	GALEX	274.149601321871	45.1761831799647	0.3
PAN-STARRS/PS1_g	4810.88	2.774e-16	2.389e-18	2.774e-16	2.389e-18	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Pan-Starrs PS1	274.14972627	45.176068	0.3
GAIA/GAIA3.Gbp	5035.75	2.207e-16	3.315e-18	2.207e-16	3.315e-18	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Gaia eDR3 (viz)	274.14972586259	+45.17606864562	0.3
GAIA/GAIA3.G	5822.39	1.320e-16	4.161e-19	1.320e-16	4.161e-19	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Gaia eDR3 (viz)	274.14972586259	+45.17606864562	0.3
PAN-STARRS/PS1_r	6156.36	1.291e-16	9.259e-19	1.291e-16	9.259e-19	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Pan-Starrs PS1	274.14972627	45.176068	0.3
PAN-STARRS/PS1_i	7503.68	6.998e-17	4.049e-19	6.998e-17	4.049e-19	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Pan-Starrs PS1	274.14972627	45.176068	0.3
GAIA/GAIA3.Gbp	7619.96	5.957e-17	1.392e-18	5.957e-17	1.392e-18	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Gaia eDR3 (viz)	274.14972586259	+45.17606864562	0.3
PAN-STARRS/PS1_z	8668.56	4.345e-17	3.972e-19	4.345e-17	3.972e-19	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Pan-Starrs PS1	274.14972627	45.176068	0.3
PAN-STARRS/PS1_y	9613.45	3.324e-17	6.607e-19	3.324e-17	6.607e-19	✓	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	Pan-Starrs PS1	274.14972627	45.176068	0.3

Apply changes

(Add a new point)

For this use case, do not make any change in the SED edit/visualize section.



- Place the cursor on the Analyse SEDs tag and then click Chi-square fit. Different grids of theoretical models covering different ranges of physical parameters are displayed. For this tutorial select only the “Koester WD models”. Click “Next: Select model params” at the bottom of the page. Do not change the parameter ranges and click “Next: Make the fit”.

We will see now a summary table with the best fit results ($T_{\text{eff}}=11750$ K; $\log g=6.5$). Click on “Show graphs” to have a look at the graphics.

Files	Objects	Build SEDs	Analyse SEDs	HR Diag.	Results
Stars and brown dwarfs (Change)			File: LOFAR School (info) (Change)		
Chi-square Fit		Template fit	Model Bayes Analysis	Template Bayes Analysis	

Model fit

Best fit results

Click in the object name to see the best fits for that object.

[Click here to configure what fields to show](#)

Object	RA	DEC	D (pc)	Model	A_V	T_{eff}	$\log g$	Meta.	more	χ^2	M_d	$F_{\text{obs}}/F_{\text{fit}}$
PSR+J1816%2B4510	274.14958333	45.17608333	10	Koester	0.0	11750	6.5	--	--	1.229e+1	2.284e-24	0.55

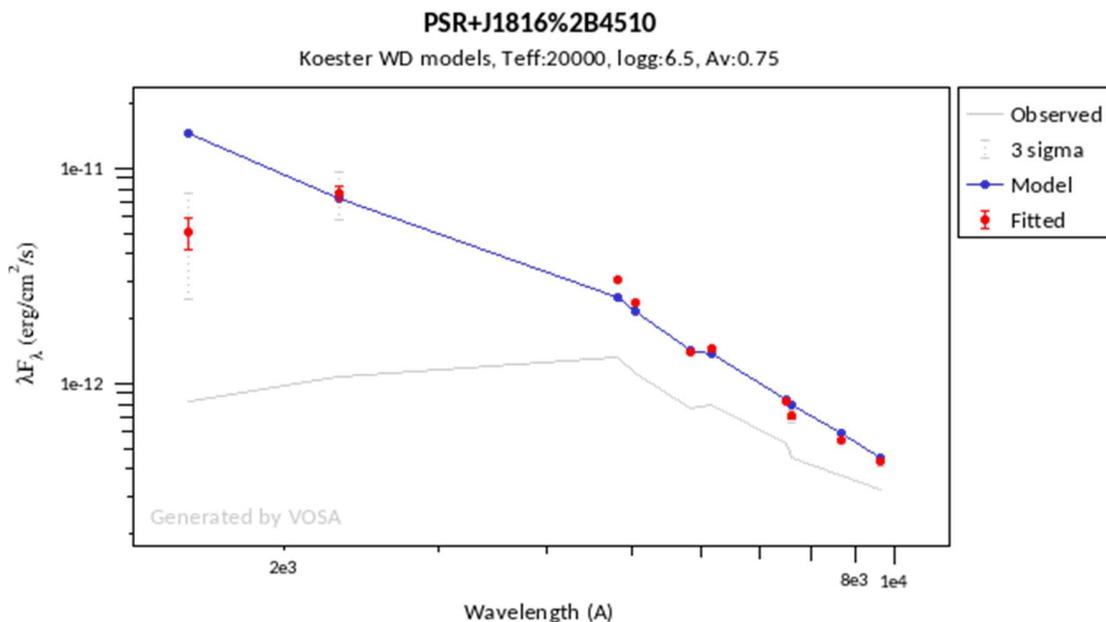
PSR+J1816%2B4510

Koester WD models, $T_{\text{eff}}:11750$, $\log g:6.5$, $A_V:0.0$

8. [Kaplan et al \(2012\)](#) estimated a higher T_{eff} for the WD companion of the pulsar. This is because they took into account the interstellar extinction. The extinction absorbs and scatters the object radiation, especially at shorter wavelengths which produces two effects in the observed SED: it seems fainter and redder than the real SED. VOSA is able to work with extinction, unreddening the observational photometry before the fit.

In the “Objects/Extinction” tag, users can search for extinction in a collection of catalogues available in the VO, or provide a value to be used by VOSA. In this case, there is not a value of the extinction in the VO catalogues so, following Kaplan et al. (2011) we adopted a value of $A_v = 0.75$ mag. Include this value at the bottom, in the “User/ A_v ” box, tick at the right of the box, and click “Save Extinction properties”.

Move back to the “Analyse SEDs/Chi-square Fit”. VOSA has detected that extinction value has changed and offers you to repeat the fit. Click on “Repeat the fit process”. The new result is $T_{\text{eff}}=20000$ K and $\log g=6.5$. This new estimation is more similar to the values obtained by [Kaplan et al \(2012\)](#).



In the figure the observed (grey) and the unreddened (red points) SEDs are shown. The fitted model (blue) is also shown. The new T_{eff} is higher, and also the luminosity estimated by VOSA from the observational data and the fitted model (see VOSA [help](#) for a more detailed explanation).

VOSA uses the distance to the object to calculate the luminosity. Since we have not specified a distance, VOSA uses 10 pc as default. However, VOSA can also search for distances in several VO catalogues. I left the student the exercise of searching for a distance to our WD (“Objects/Distances” tag).

Annex I

Construct of the Radio SED of PSR B1508+55

We use TOPCAT to compile and combine radio data from the following catalogues: VLSSr (74 MHz), LoTSS-PDR (144 MHz), TGSS (150 MHz), WENSS (325 MHz) and NVSS (1.4 GHz). Here I give some tips:

1. VLSSr, WENSS, and NVSS are in VizieR, with the following identifying: VIII/97, VIII/62, and VIII/65, respectively. Use the “VizieR catalogue Service” at VO menu to query them. Use the “By Keyword” option.
2. LoTSS-PDR and TGSS data were already obtained in the first part of the tutorial. You can extract the data for our source with a cross-match with any of the tables from the other catalogues. Use the “Pair Match” tool at the “Joins” menu.
3. Put all data together in a single table. Use “Joins/Concatenate Tables”. Before doing this select the columns you want to have in the resulting table.