Abell 1656: the Coma Cluster of Galaxies

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created in Curvenote

This tutorial shows how to examine the Coma cluster of galaxies using data and tools of the Virtual Observatory. It is based on the EURO-VO tutorial (http://www.euro-vo.org/?q=science/scientific-tutorials) by Massimo Ramella & Giulia Iafrate (INAF - Osservatorio Astronomico di Trieste), later updated by Caroline Bot, Thomas Boch, Jenny G. Sorce and Katharina A. Lutz (all CDS, CNRS, Observatoire astronomique de Strasbourg). This version is updated for the 5th Cosmology school in July 2022 and includes state-of-the-art software and data.

Contents

1 Introduction

Goals:

- Examine the Coma cluster of galaxies (Abell 1656) using VO data and tools in order to perform a quick evaluation of the mean redshift and velocity dispersion of the cluster.
- Use redshifts and photometry (r magnitude) of the SDSS survey and then add redshifts of the CAIRNS survey (Rines et al. 2003) in order to improve the completeness of the redshift sample.
- Look for hydrogen lines in HST spectra in the direction of this cluster and check whether the lines are consistent with foreground or with galaxy velocities.

Software:

- Aladin (https://aladin.cds.unistra.fr/)
- TOPCAT (http://www.star.bris.ac.uk/{~}mbt/topcat/)

2 Display the region of Abell 1656 in Aladin

- Launch Aladin: Open a terminal and type: `~/Aladin/Aladin &`
- In Aladin, enter 'A1656' (Coma Cluster) in the **Command**[1] box at the top of the main window.
- Zoom/unzoom to work with galaxies in a region of about 40 by 40 arcmin around the Coma cluster. At the distance of Coma (z=0.0234), 40 arcmin corresponds to 1.2 Mpc (with *Planck2018* H_0=67 km s^{-1} Mpc^{-1}, Ω_Λ=0.69 and Ω_m=0.31), a region large enough for our purposes. Tip: The cyan/blue numbers at the bottom of the main window and in the overview panel in the bottom right corner of Aladin indicate the area shown in the main window (Figure 1). As a second option draw a 40' long arrow with the **dist**[2] button.

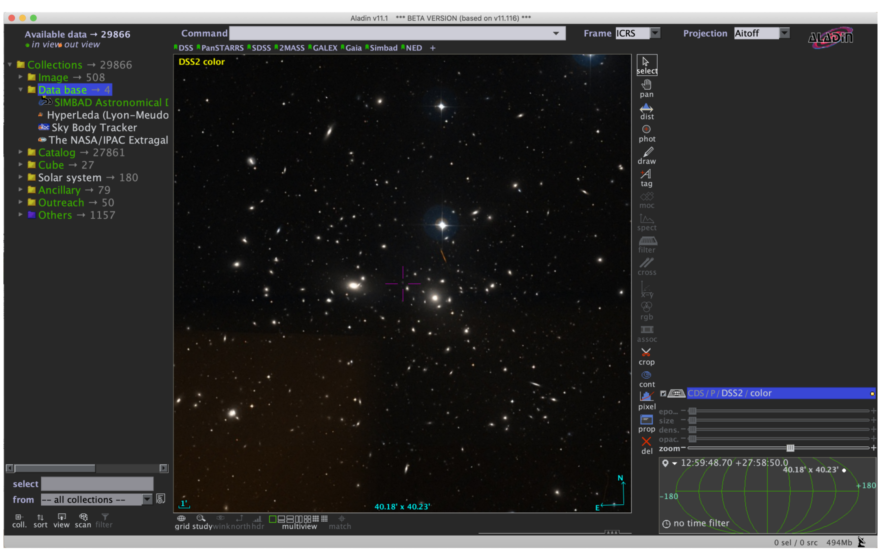


Figure 1: Abell 1656 (Coma Cluster) in Aladin

3 Load the SDSS-DR16 catalogue and select galaxies

- Load the SDSS-DR16 catalogue through the DATA TREE: Type "SDSS" in the **Select**[3] line below the DATA TREE. You can further narrow down your search by restricting the collection of data sets: **from**[4] "Large catalogs". Under "Catalog" → "VizieR" → "V-Combined Data" click on SDSS-DR16, make sure that the **in view** box is ticked and click **Load** (Figure 2).

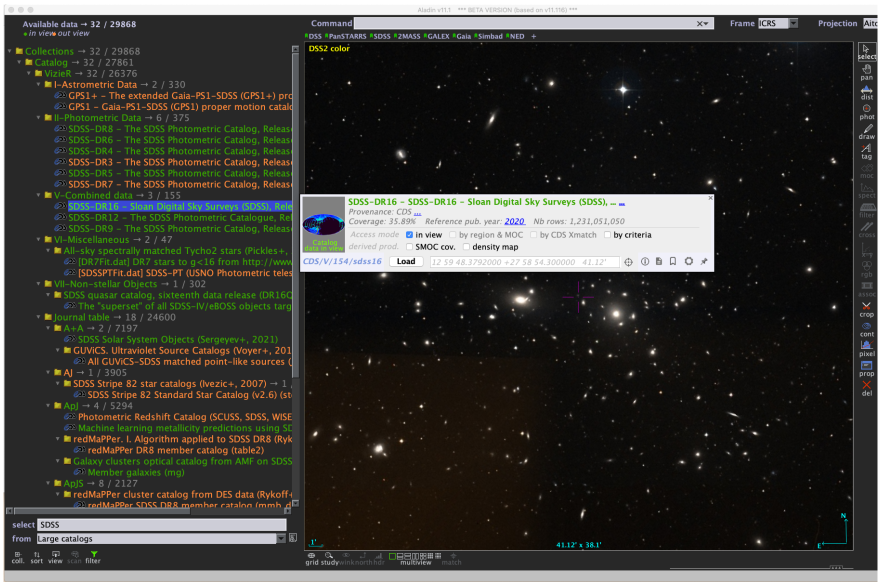


Figure 2: The Aladin DATA TREE when filtered to "SDSS" resources in "large catalogues". Green resources have entries in the area of the sky that is currently shown in the main viewing window, while orange ones do not. The grey pop-up window allows you to load the data in different ways, e. g. load all data within the field of view or filter the catalogue by MOC.

- Catalogue data of approximately 50,000 sources have now been loaded. To limit this sample to galaxies (class=3) that are also SDSS primary sources (mode=1) we continue as follows (Figure 3):
  - In the *Current view* stack on the right, select the catalogue plane, click on the **Filter**[5] button and write the following syntax in the **Advanced mode** tab: `${class}=3&&${mode}=1{draw}`
    Clicking **Apply** ensures that our sample is selected according to our selection criteria and that only sources that adhere to these criteria are shown in the main viewing window.
  - Still in the filter window, clicking **Export** will build a new plane with only filtered sources included.
  - Note that the **Pick** line above the free syntax field is helpful to create other filters.

- Rename this new plane SDSSgalaxies using the **Properties**[6] button in the toolbar. Depending on your field of view the new filtered catalogue includes around 30000 sources.

- Broadcast the filtered catalogue to TOPCAT Figure 4. You can do so by right-clicking on the catalogue plane and selecting **Broadcast selected tables to...>topcat**. Beware that TOPCAT must be launched for this function to be enabled.

- In TOPCAT, **display column metadata**[1]. In the new window, deselect all rows[2]

  and then select only the four necessary columns: RA_ICRS ($5), DE_ICRS ($6), zsp ($22) and rmag ($14).

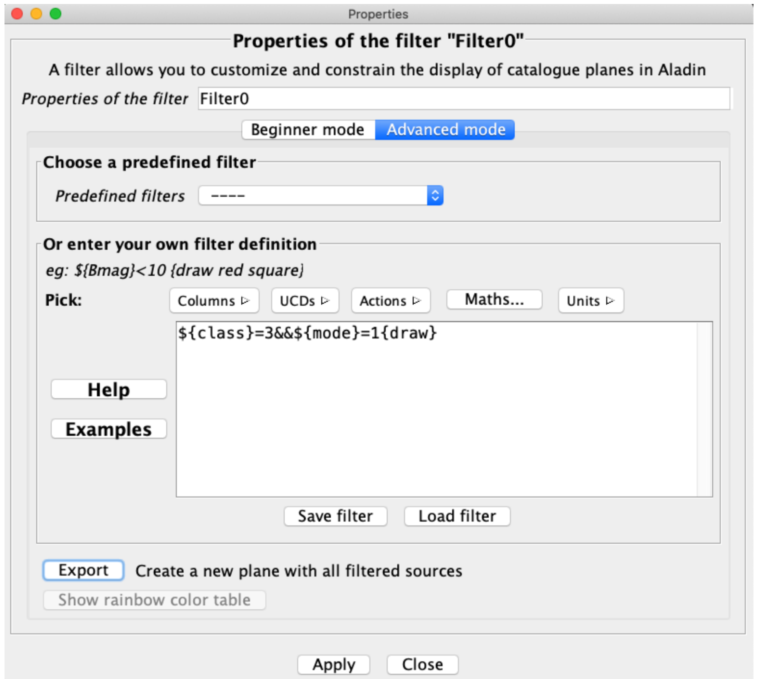


Figure 3: Filtering with Aladin

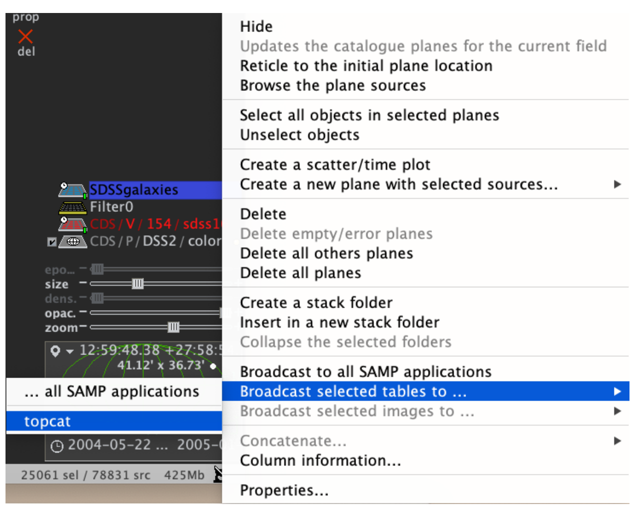


Figure 4: Broadcasting the filtered catalogue to TOPCAT.

4 Identify the brightest sources as being stars contaminating the sample

- In the main TOPCAT window, open the **subset**[3] window and build a subset of the brightest sources (with magnitudes rmag<11.5):
  - In the subset window, click on the **plus**[4] sign to define a new row subset.
  - **Subset name**: 'stars'.
  - **Expression**: `$14<11.5` or `rmag<11.5` (Note: TOPCAT expressions do not differentiate small/capital letters. Depending on the column names of the table you might have to use $ID of the column rather than its name. $ID can be found with **Views** → **Column Info** or in the column metadata[1]).
- There are two options to check that each source in the star subsample is indeed a star, using Aladin:
  1. In the main TOPCAT window, select **Row Subset**[5]: 'stars', and **broadcast**[6] it to Aladin (**Interop** → **Send table to** → **Aladin.** Switch to Aladin and look through the sources by clicking on their entry in the table. Zoom/unzoom as necessary.
  2. In TOPCAT go to **Views** → **Activation Action** or click on the **action**[7] symbol. In the newly opened window, select **Send Sky Coordinates**. Upon selection, you can edit the settings for this activation action. See Figure 5 for the options chosen for our case. If you now display the table cell data[8], you can click on any table entry and the corresponding source will be displayed in Aladin (Figure 6). Again zoom/unzoom as necessary.

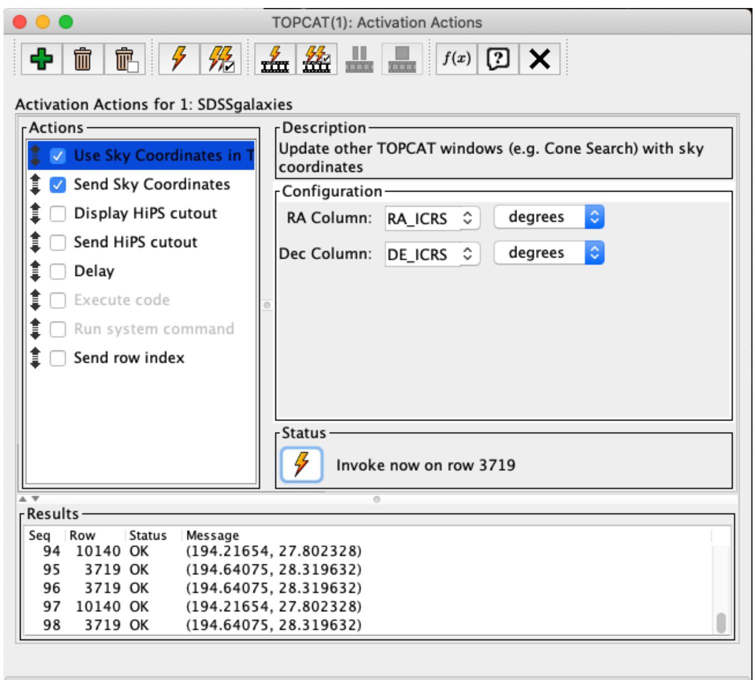


Figure 5: Setting up activation actions in TOPCAT.

5 Build a subset of SDSS galaxies with spectroscopic redshift

- In the main TOPCAT window, open the **subset**[3] window again and build a subset of galaxies (no stars, i.e. rmag>11.5) with a magnitude rmag brighter than 17.7 mag (completeness limit of the SDSS spectroscopic sample) and redshift information. This can be done with the subset expression: `zsp>0 && rmag<=17.7 && rmag>11.5`. Call this subset 'zsp17'.
- In the main window of TOPCAT select the subset 'zsp17' and duplicate the table (**File** → **Duplicate Table**).

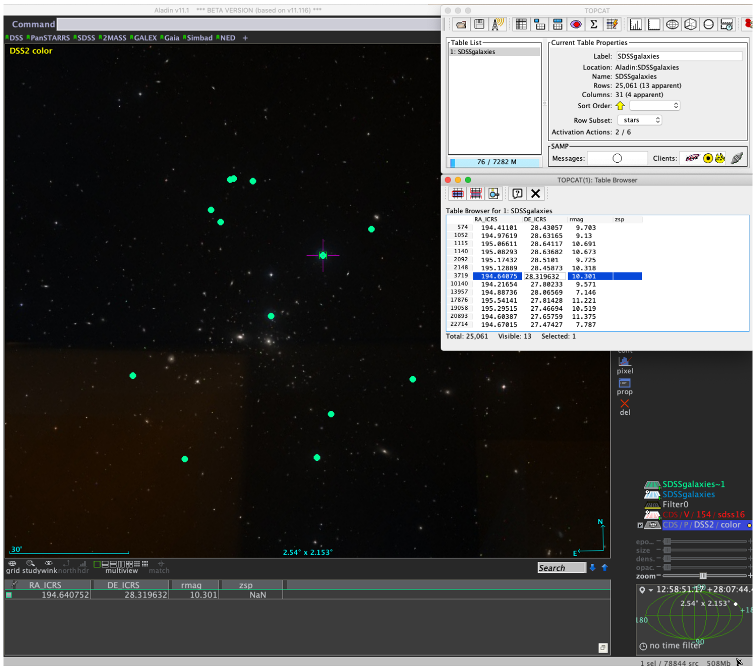


Figure 6: Aladin - TOPCAT Interoperability

- Rename the new table to ‘zsp17’.

6 Improve the completeness with other sources of redshifts in VizieR

- In TOPCAT, build the subset ‘nozsp17’ that contains galaxies with the same magnitude selection as before but no redshifts (use `!(zsp>0)` instead of zsp>0 in the above expression). Depending on your field of view, the new subset contains about 200 entries.
- Select the subset ‘nozsp17’ in TOPCAT main window, duplicate the table and rename the new table ‘nozsp17’.

In TOPCAT main window, search optical catalogues with redshifts (Figure 7):

- Go to **VO** → **VizieR catalogue service**.
- Select **Cone selection**: **Object name**=‘A1656’, click on **resolve**, **radius**=‘40’ arcmin. Then select **All Rows**.
- In the **catalogue selection** section: select the **by Keywords** tab and enter ‘Rines’, load the **Rines+2003** catalogue. Two tables are loaded. Delete the cluster catalogue to keep only the galaxy one (**File** → **Discard Table(s)**).
- Find redshifts in Rines+ catalogue for galaxies without redshift in nozsp17:
  - X-match the ‘nozsp17’ and the Rines catalogue (**Joins** → **pair match** click on the **matching**[9] symbol)
  - Use **sky** algorithm with ‘5 arcsec’ max error and choose **Best match, symmetric**. See Figure 8 for more details.

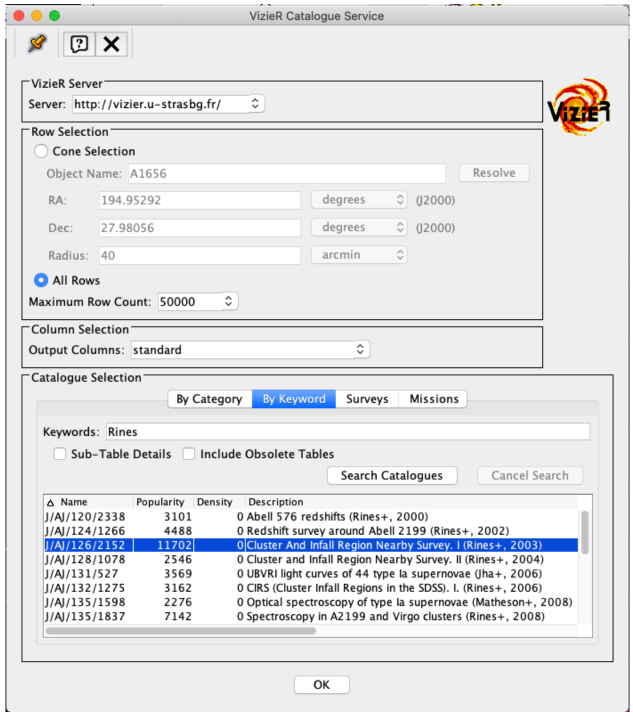


Figure 7: Loading a catalogue from VizieR with TOPCAT.

7 Build the final catalogue

- Add a new column to 'zsp17' catalogue to get the apparent radial velocity cz:
  - Click **Table Columns**[1], then do **Columns** → **New Synthetic Column** or click on the **plus** sign.
  - **Name**: 'czsp'
  - **Expression**: `toInteger(zsp*300000)`
- Concatenate 'zsp17' and match tables (**Joins** → **Concatenate Tables**). Fill in the **Base Table** and **Appended Table** tabs (Figure 9).

8 Determine the cz distribution

- View the **histogram**[10] of 'czsp' values.
- Isolate the main peak of Coma in the histogram by selecting the appropriate region by scrolling your mouse or playing with **Axes** (**Range** tab) and **Bins** (**Bin size**) (see Figure 10 for an example).
- Build a new subset named 'Coma' using the range of cz observed in the histogram (proceed as before to build new subsets or, more conveniently, once having zoomed in on the Coma peak use the button marked in the figure above).
- Select this Coma subset in the main window of TOPCAT and open the **Row Statistics**[11] window. You will find something like ∼7000 km s^{-1} and SD∼1000 km s^{-1}, both in good agreement with more refined analyses (Figure 11).

9 Look for HST spectra in the Coma cluster

- Go back to the Aladin window. Adjust the main viewing window such that it is centred on "A1656" and has a field of view of approximately 40 × 40 arcmin.

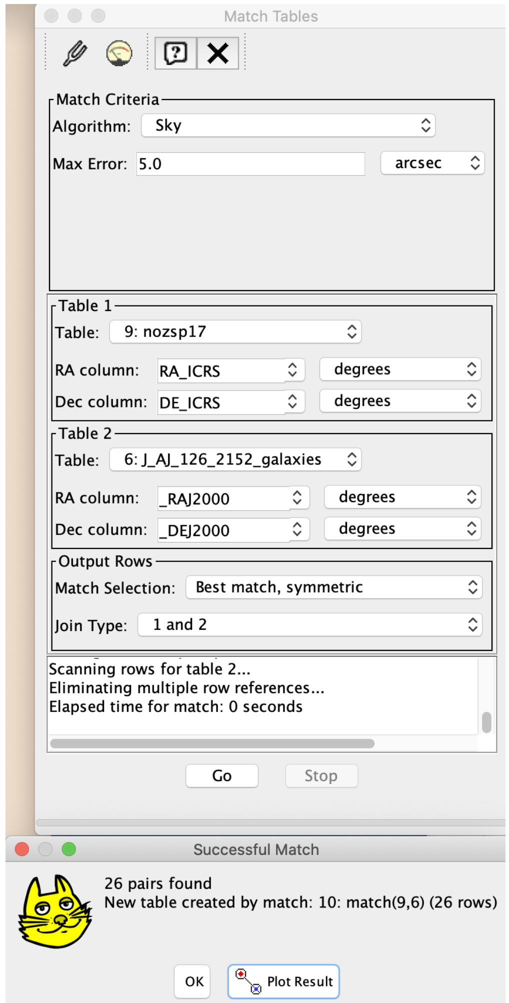


Figure 8: X-matching with TOPCAT.

- Type “HST” in the **Select** line and set **from** to “– all collections –”. Narrow down the search in the Data discovery Tree filter window[7] by ticking the box of **SSA** (for Simple Spectral Access) in the **Technical** tab.
  Select **Others** → **SSA** → **mast.stsci** → **Hubble Space Telescope Spectra**, tick **in view** and then **Load** the table.
- The table entry for each source contains the link to the URL where we can obtain the spectrum for further analysis.

10 Scripting in a Jupyter notebook [optional]

The tasks in this tutorial can also be carried out using a Jupyter notebook.

You can go to

https://mybinder.org/v2/gh/cds-astro/tutorials/master?filepath=Notebooks

and wait a moment for everything to load. You should then see list of files. Click on the link to

Abel1656 The Coma Cluster of Galaxies.ipynb

and follow the instructions there.

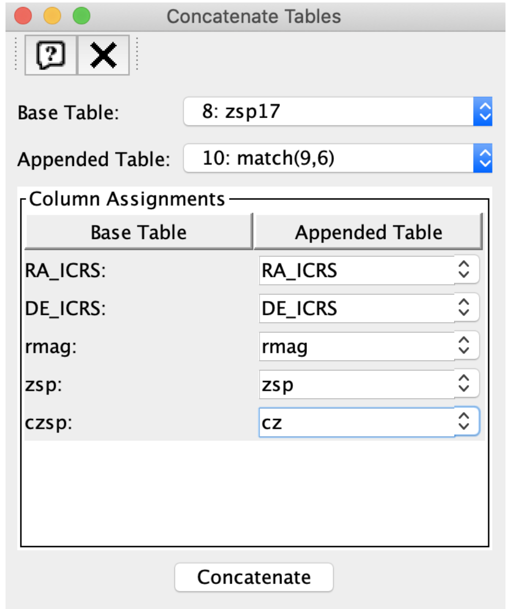


Figure 9: Concatenating tables with TOPCAT.

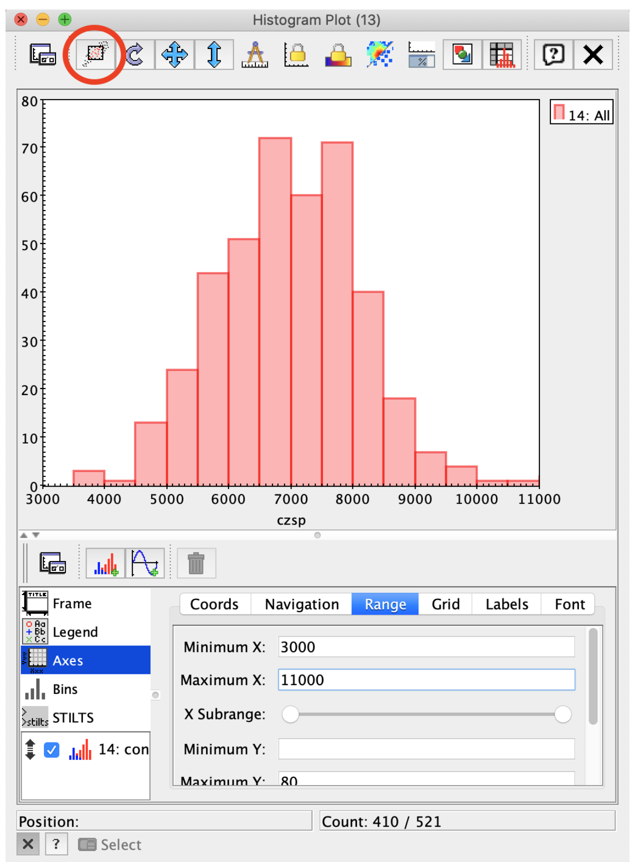
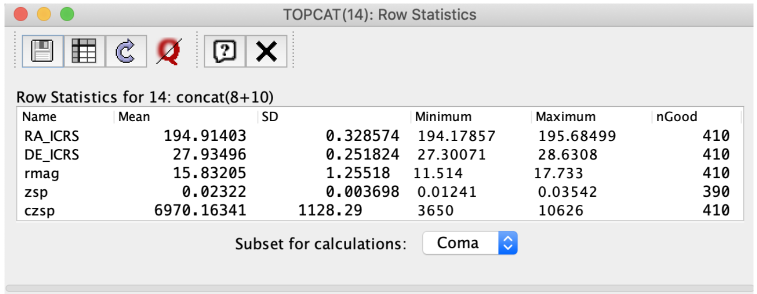


Figure 10: The main peak of the Coma cluster.



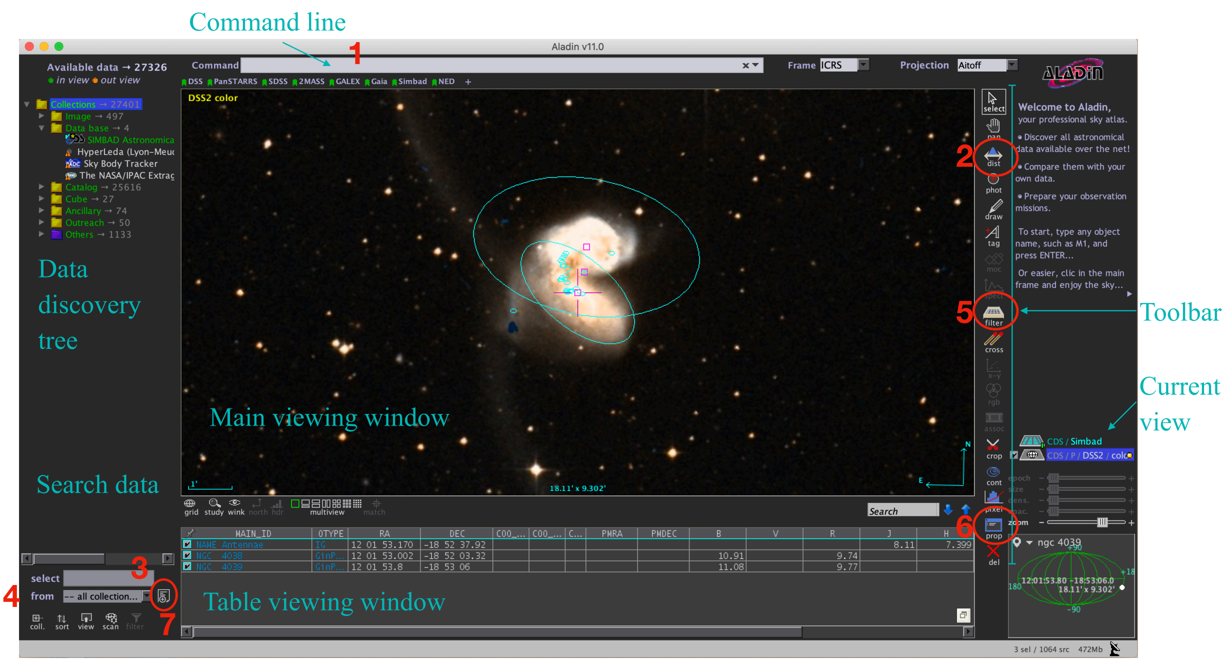
Name	Mean	SD	Minimum	Maximum	nGood
RA_ICRS	194.91403	0.328574	194.17857	195.68499	410
DE_ICRS	27.93496	0.251824	27.30071	28.6308	410
rmag	15.83205	1.25518	11.514	17.733	410
zsp	0.02322	0.003698	0.01241	0.03542	390
czsp	6970.16341	1128.29	3650	10626	410

Figure 11: Statistics with TOPCAT.

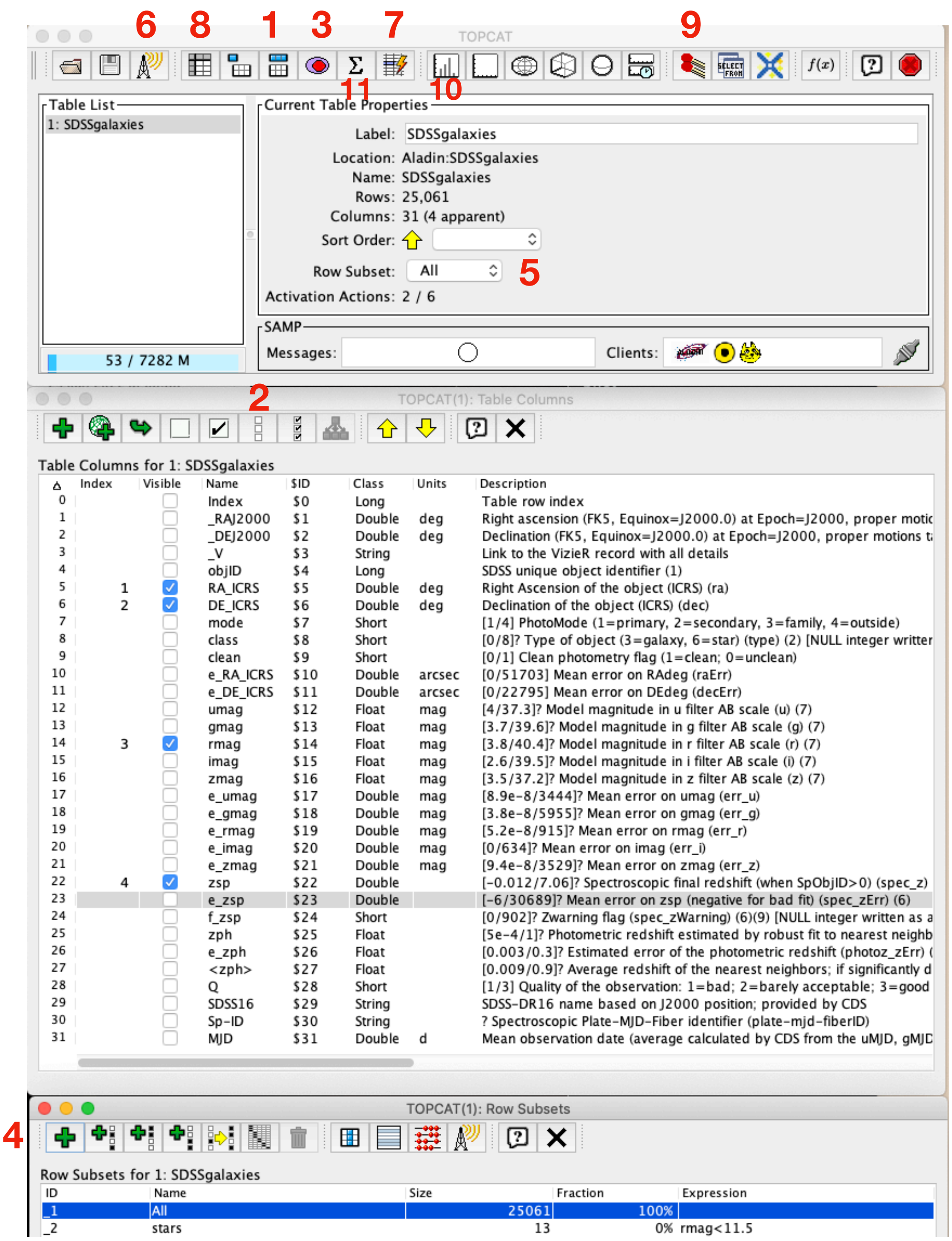
Acknowledgements

We acknowledge the support of ESCAPE (European Science Cluster of Astronomy and Particle Physics ESFRI Research Infrastructures) funded by the EU Horizon 2020 research and innovation program under the Grant Agreement n.824064.

A Aladin


Command line
1
2
5
6
3
4
7
Data discovery tree
Main viewing window
Search data
Table viewing window
Toolbar
Current view

B TOPCAT


6 8 1 3 7 9 11 10
TOPCAT
Table List
1: SDSSgalaxies
Current Table Properties
Label: SDSSgalaxies
Location: Aladin:SDSSgalaxies
Name: SDSSgalaxies
Rows: 25,061
Columns: 31 (4 apparent)
Sort Order:
Row Subset: All
5
Activation Actions: 2 / 6
SAMP
Messages:
Clients:
53 / 7282 M
2
TOPCAT(1): Table Columns
Table Columns for 1: SDSSgalaxies
Index Visible Name $ID Class Units Description
0 Index $0 Long Table row index
1 _RAJ2000 $1 Double deg Right ascension (FK5, Equinox=J2000.0) at Epoch=J2000, proper motic
2 _DEJ2000 $2 Double deg Declination (FK5, Equinox=J2000.0) at Epoch=J2000, proper motions t
3 _V $3 String Link to the VizieR record with all details
4 objID $4 Long SDSS unique object identifier (1)
5 1 RA_ICRS $5 Double deg Right Ascension of the object (ICRS) (ra)
6 2 DE_ICRS $6 Double deg Declination of the object (ICRS) (dec)
7 mode $7 Short [1/4] PhotoMode (1=primary, 2=secondary, 3=family, 4=outside)
8 class $8 Short [0/8]? Type of object (3=galaxy, 6=star) (type) (2) [NULL integer writter
9 clean $9 Short [0/1] Clean photometry flag (1=clean; 0=unclean)
10 e_RA_ICRS $10 Double arcsec [0/51703] Mean error on RAdeg (raErr)
11 e_DE_ICRS $11 Double arcsec [0/22795] Mean error on DEdeg (decErr)
12 umag $12 Float mag [4/37.3]? Model magnitude in u filter AB scale (u) (7)
13 gmag $13 Float mag [3.7/39.6]? Model magnitude in g filter AB scale (g) (7)
14 3 rmag $14 Float mag [3.8/40.4]? Model magnitude in r filter AB scale (r) (7)
15 imag $15 Float mag [2.6/39.5]? Model magnitude in i filter AB scale (i) (7)
16 zmag $16 Float mag [3.5/37.2]? Model magnitude in z filter AB scale (z) (7)
17 e_umag $17 Double mag [8.9e-8/3444]? Mean error on umag (err_u)
18 e_gmag $18 Double mag [3.8e-8/5955]? Mean error on gmag (err_g)
19 e_rmag $19 Double mag [5.2e-8/915]? Mean error on rmag (err_r)
20 e_imag $20 Double mag [0/634]? Mean error on imag (err_i)
21 e_zmag $21 Double mag [9.4e-8/3529]? Mean error on zmag (err_z)
22 4 zsp $22 Double [-0.012/7.06]? Spectroscopic final redshift (when SpObjID>0) (spec_z)
23 e_zsp $23 Double [-6/30689]? Mean error on zsp (negative for bad fit) (spec_zErr) (6)
24 f_zsp $24 Short [0/902]? Zwarning flag (spec_zWarning) (6)(9) [NULL integer written as a
25 zph $25 Float [5e-4/1]? Photometric redshift estimated by robust fit to nearest neighb
26 e_zph $26 Float [0.003/0.3]? Estimated error of the photometric redshift (photoz_zErr) (
27 <zph> $27 Float [0.009/0.9]? Average redshift of the nearest neighbors; if significantly d
28 Q $28 Short [1/3] Quality of the observation: 1=bad; 2=barely acceptable; 3=good
29 SDSS16 $29 String SDSS-DR16 name based on J2000 position; provided by CDS
30 Sp-ID $30 String ? Spectroscopic Plate-MJD-Fiber identifier (plate-mjd-fiberID)
31 MJD $31 Double d Mean observation date (average calculated by CDS from the uMJD, gMJD
TOPCAT(1): Row Subsets
4
Row Subsets for 1: SDSSgalaxies
ID Name Size Fraction Expression
1 All 25061 100%
2 stars 13 0% rmag<11.5

C Use CASSIS to visualise and analyse the HST spectrum [optional]

- Launch CASSIS (see instructions at http://cassis.irap.omp.eu/)
- In Aladin, find the table entry for source 1257-2840 and (left-) click on the link in the URL of the spectrum (in the first column). This will open a menu and allow you to broadcast the spectrum to CASSIS (see Figure 12).

Figure 12: Broadcast the spectrum of 1257-2840 to CASSIS.

- Once the spectrum is transferred to CASSIS, the **Spectrum Manager** appears. Select **Display Spectrum** . The spectrum is now displayed in the CASSIS main window. Two lines are clearly visible: one around 1250 Ångström and one around 1350 Ångström (see Figure 13).

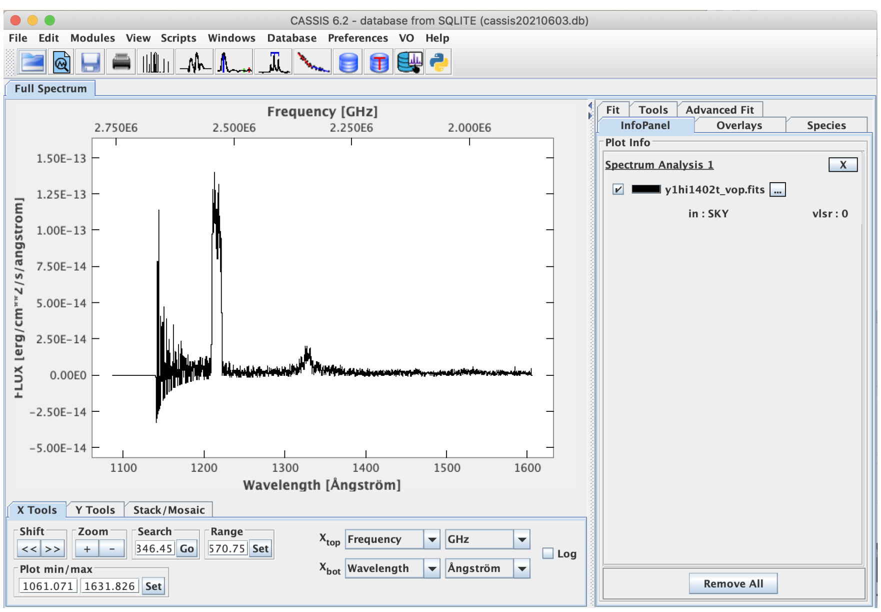


Figure 13: Visualisation of the spectrum with CASSIS.

- To check that these are hydrogen lines (Lyα), one at the local velocity, the other at the velocity of the Coma cluster (Figure 13):
  - Select the **Species** tab. Choose the **Full NIST** or the **Full XASD** database in the **Template** section.
  - Unselect all species by clicking on the **Sel.** column.

- Select the sole **HI** line by ticking only this line.
- The maximum **Eup threshold** is by default too low for our case. Remove the '150.0K' and replace it with ' * ' to get all the HI transitions without any threshold in energy.
- Tick **show signal** and click **Display** at the bottom of the window (Figure 14). A green tick appears below the largest of the two lines. This confirms that this line is a Hydrogen line at zero velocity. Clicking on the green tick gives more information on the line parameters. A right click allows you to edit the overlay.

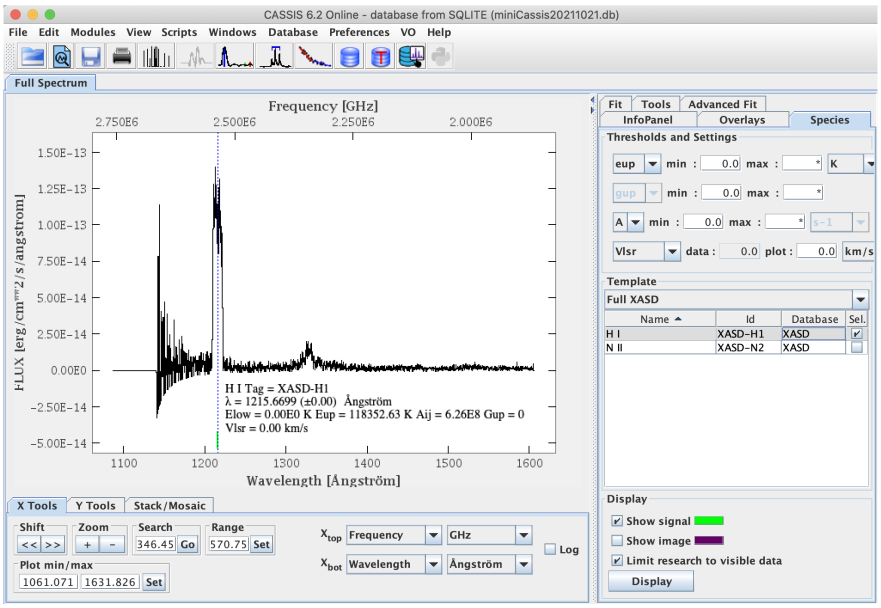


Figure 14: Spectrum with CASSIS. The dotted line and the green dash mark the location of the Lyα line at a line of sight velocity of 0.0 km s^{-1}.

- To look for the LSR velocity of the galaxy in SIMBAD:
  - Go back to the Aladin window and centre the image on the pointing centre of the HST spectral observations by double-clicking on the table row of the source 1257-2840. Zoom in or out as necessary.
  - Make sure that the **Simbad Pointer** is activated (a tick next to **Tool** $\rightarrow$ **Simbad pointer**).
  - Hover over the pointing centre of the HST spectral observations until a small window appears (Figure 15).
  - Clicking on the name of this galaxy (NAME X COMAE GALAXY) opens a web browser with all the SIMBAD information for this object.
  - The radial velocity of this galaxy is 27332.1 km s^{-1}.
  - Note that this galaxy is not part of the Coma cluster since the velocity of the Coma cluster is 6845 km s^{-1}. This value can be found with SIMBAD looking for A1656. The hierarchical link "**parents**" on NAME X COMAE GALAXY in SIMBAD confirms that the probability of this galaxy to belong to Coma is 0%.
- Go back to CASSIS and change the **Vlsr plot** field from 0 to 2.7e4 km s^{-1} (Figure 16). As soon as you click **Display** again, the green tick corresponding to the HI line moves right under the second fainter line in the HST spectrum. This confirms that this line is associated to this Seyfert 1 galaxy.

C.1 Fit a Gaussian and a continuum to the hydrogen line [optional]

Focus on a small portion of the spectrum, centred on the HI line of the Seyfert 1 galaxy and fit the line with a Gaussian profile and a continuum:

Figure 15: How to enable and operate the SIMBAD pointer in Aladin.

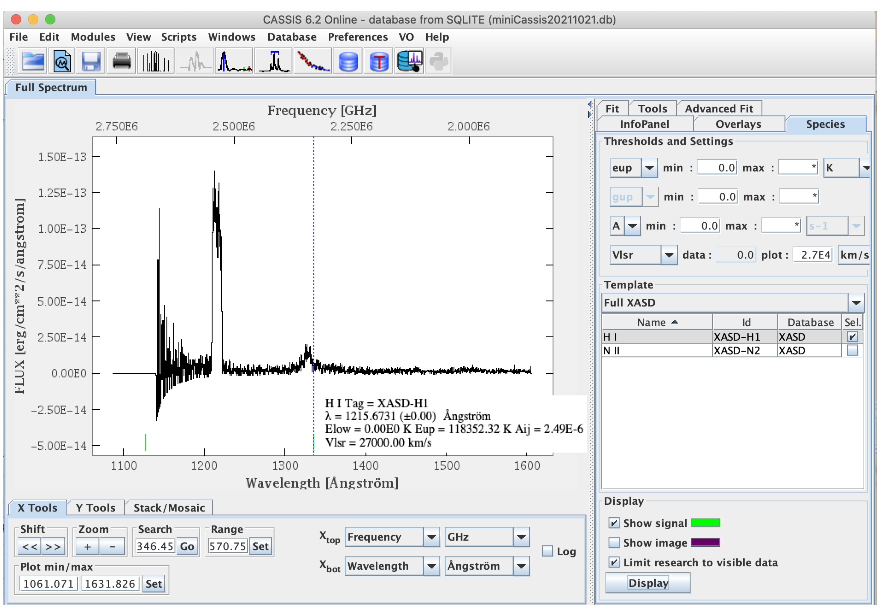


Figure 16: HI line of the Seyfert 1 galaxy.

- In the **spectrum analysis** window, reduce the wavelength range: 1300 to 1375 Ångström and click **Display**.
- In the CASSIS main window, select the **Fit** tab and add two components using the **Manage Components** menu: a polynomial baseline and a Gaussian line.
- Change the **degree** of the polynomial to ' 0 ' in order to fit a constant baseline.
- For the Gaussian component, the purple/blue fields should be filled with initial values in order to start the fitting procedure. They can be filled by hand but a useful way of filling them in is: use the middle button of your mouse to click and drag the region of the line or alternatively with a trackpad press both ctrl+alt and click and drag to draw the region. Beware that the Gaussian parameters should stay violet/blue (do not click on any of them) if you want them to fill in automatically. The position of the peak (**xo**), its height (**Io**) and the width of the line (**FWHM**) are estimated automatically from the selection. This selection, visible in purple/blue in Figure 16, can be erased using the **reset** buttons in **Selections [with middle-click-and-drag]**.
- Click on **Fit current** to perform a fit of the line+baseline. The different components of the fit can be selected or deselected in the **InfoPanel**.
- Go back to the **Fit** panel and note the central wavelength of this line as inferred from the best fit: 1327 Å.

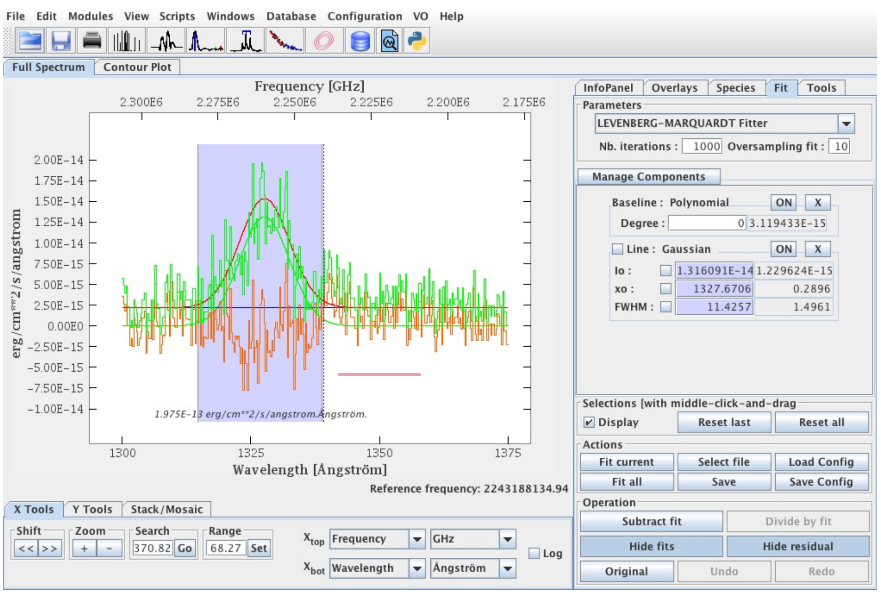


Figure 17: Fit of the spectrum.

- Given that the rest wavelength for the Lyman α line is 1215.67 Å, the velocity of the galaxy is $v = c \times \Delta\lambda / \lambda 0$ = 27,420 km s^{-1} or in redshift, z=v/c=0.0914.
- This value can be compared to the value given in SIMBAD.