VOSA tutorial

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VO-Tools: VOSA (v7.0)

1-. **Science case I: Determination of masses and radii of star hosting planets**

Scientific background:

This science case comes from a paper published in Stassun et al. (2017). The paper is focused on the determination of radii and masses of extrasolar planets (also known as exoplanets) in an empirical way (i.e. in a model-independent way).

Estimates of masses and radii can provide important insights into the physics of planetary atmospheres, their interiors as well as on planetary formation and evolution theories. For instance, the origin of "inflated hot Jupiters" (planets in the range 0.1-2.0 Jupiter masses, whose radii are much larger than that predicted from models) is still a matter of debate. It is widely accepted that the intense radiation received from the star, combined with internal heating, help to inflate the exoplanet's atmosphere. This effect is not so significant in more massive planets because the gravity is strong enough to keep the planet at roughly the Jupiter's size. Having a good determination of the planet radius will allow looking into other correlations with physical parameters like age, magnetic fields or winds.

Accurate radius can also provide constraints on the heavy element content and, therefore, on the existence of a solid core, which would favour the core accretion theory versus the gravitational instability scenario.

As we can deduce from the following equations (1) and (2), an accurate knowledge of the radius and mass of an exoplanet requires a very good determination of the mass and radius of the hosting star:

$$M_p = \frac{K_{\rm RV}\sqrt{1-e^2}}{\sin\, i}\left(\frac{P}{2\pi G}\right)^{1/3} M_\star^{2/3} \qquad (1)$$

$$\Delta \mathrm{F} = \left(\frac{R_{planet}}{R_{star}}\right)^2 \qquad (2)$$

where K_{RV} is the radial velocity semi-amplitude and *P*, *e*, and *i* are the period, eccentricity, and orbital inclination of the planet's orbit, respectively. M_p is the mass of the planet and M_* the mass of the star.

A key aspect in the methodology used in this paper is that radii and masses are empirically determined. And this is possible because most of the flux comes from photometry covering a large wavelength range, limiting the flux contribution from models just to the edges of the Spectral Energy Distribution (SED) where the flux is not significant. Knowing the empirical bolometric flux it is possible to compute luminosities using distances in a largely empirical manner.

Workflow:

Open VOSA

– *Step 1* – Go to http://svo2.cab.inta-csic.es/theory/vosa/

– *Step 2* – To use VOSA you need to be registered. Click on “Register” and fill in the fields (email, name and password).

– *Step 3* – Copy to your laptop the file “vosa_usecase_final.txt” available at the school webpage (link here).

Tag “Files”

– *Step 4* – Upload the file in VOSA (*File to upload / Browse*). Give a description (free text). And then, click ***Upload*** (do not bother about the File type). The message “*your-file-name has been successfully uploaded!”* will appear. Click ***Continue***. If the message does not appear, go to ***Your files*** section and click ***Select***.

Note: Here, you can know more about the required VOSA input file format.

Tag “Objects”

– *Step 5* – Place the cursor on the ***Objects*** tag and then click ***Coordinates***. The message *“There are objects in your file without coordinates. Please, try to find them using Sesame”*, will appear. Click ***Search for Obj. Coordinates***.

Note: More information about the CDS Sesame Name Resolver can be found here.

– *Step 6* – Once Sesame has been used to find the coordinates of our objects we have to make them the “final” coordinates. To do so, we have to click ***Make all changes*** in the left panel (the one labelled as *Actions for all the objects in the file*). The Sesame coordinates will appear in bold in the *Final* column.

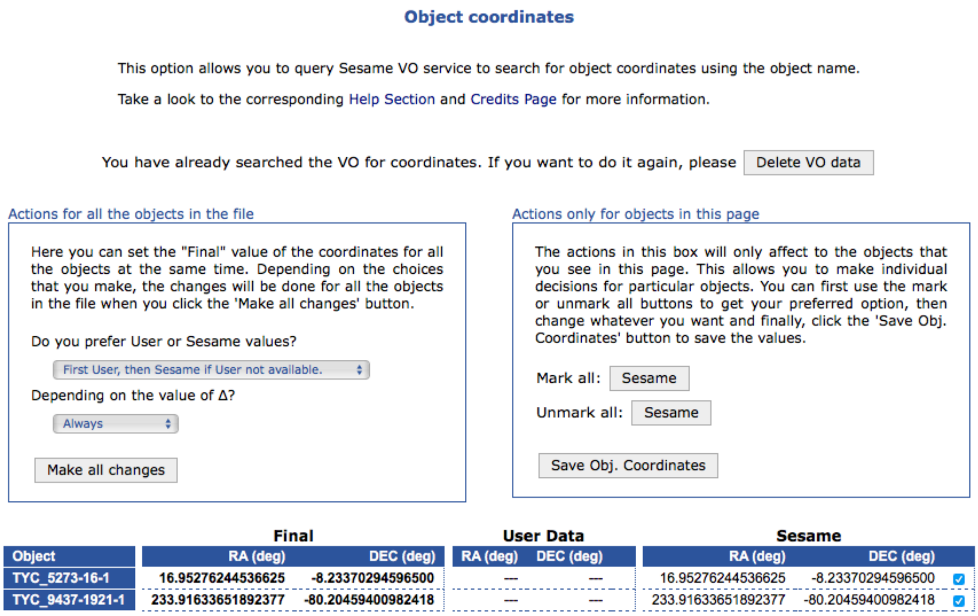
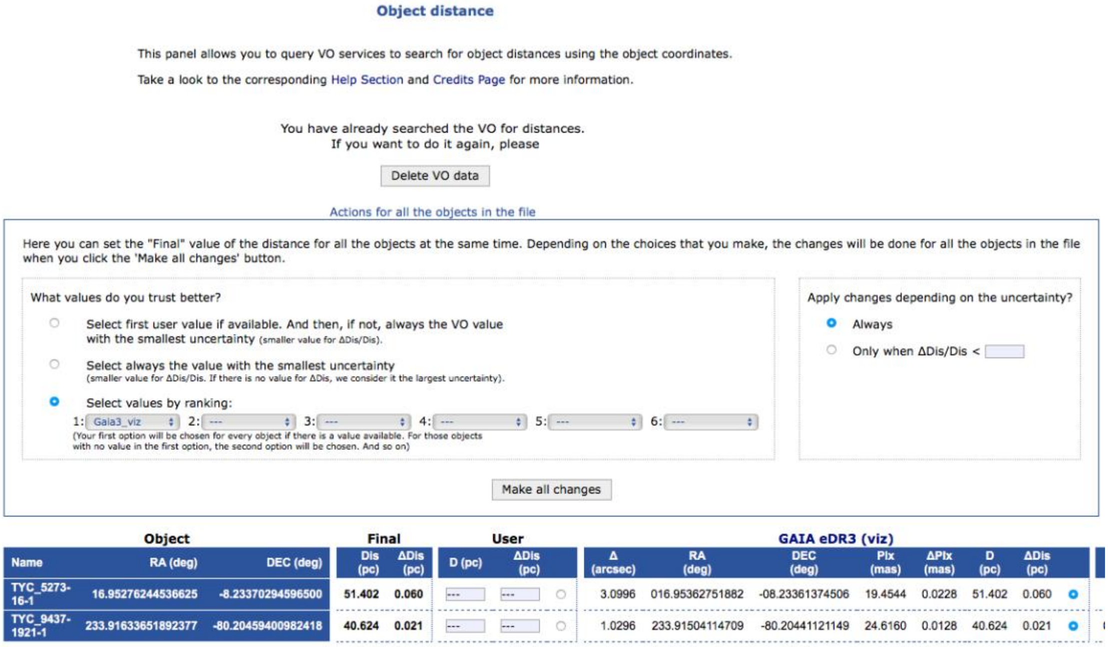


Figure 1. Coordinates obtained from Sesame.

– *Step 7* – Place the cursor on the ***Objects*** tag and then click ***Distances.*** Click ***Search for Obj. Distances***. To make the Gaia eDR3 distances the “final” distances, do the following: Go to the “*Actions for all the objects in the file”* panel, tick ***Select values by ranking*** and choose “Gaia3_viz” in the first place. Click ***Make all changes***. The Gaia eDR3 (viz) coordinates will appear in bold in the *Final* column.



Object distance

This panel allows you to query VO services to search for object distances using the object coordinates.

Take a look to the corresponding Help Section and Credits Page for more information.

You have already searched the VO for distances.
If you want to do it again, please

Delete VO data

Actions for all the objects in the file

Here you can set the "Final" value of the distance for all the objects at the same time. Depending on the choices that you make, the changes will be done for all the objects in the file when you click the 'Make all changes' button.

What values do you trust better?

Select first user value if available. And then, if not, always the VO value with the smallest uncertainty (smaller value for ΔDis/Dis).

Select always the value with the smallest uncertainty (smaller value for ΔDis/Dis. If there is no value for ΔDis, we consider it the largest uncertainty).

Select values by ranking:
1: Gaia3_viz 2: --- 3: --- 4: --- 5: --- 6: ---
(Your first option will be chosen for every object if there is a value available. For those objects with no value in the first option, the second option will be chosen. And so on)

Apply changes depending on the uncertainty?
Always
Only when ΔDis/Dis <

Make all changes

Object			Final		User		GAIA eDR3 (viz)						
Name	RA (deg)	DEC (deg)	Dis (pc)	ΔDis (pc)	D (pc)	ΔDis (pc)	Δ (arcsec)	RA (deg)	DEC (deg)	Plx (mas)	ΔPlx (mas)	D (pc)	ΔDis (pc)
TYC_5273-16-1	16.95276244536625	-8.23370294596500	51.402	0.060	---	---	3.0996	016.95362751882	-08.23361374506	19.4544	0.0228	51.402	0.060
TYC_9437-1921-1	233.91633651892377	-80.20459400982418	40.624	0.021	---	---	1.0296	233.91504114709	-80.20441121149	24.6160	0.0128	40.624	0.021

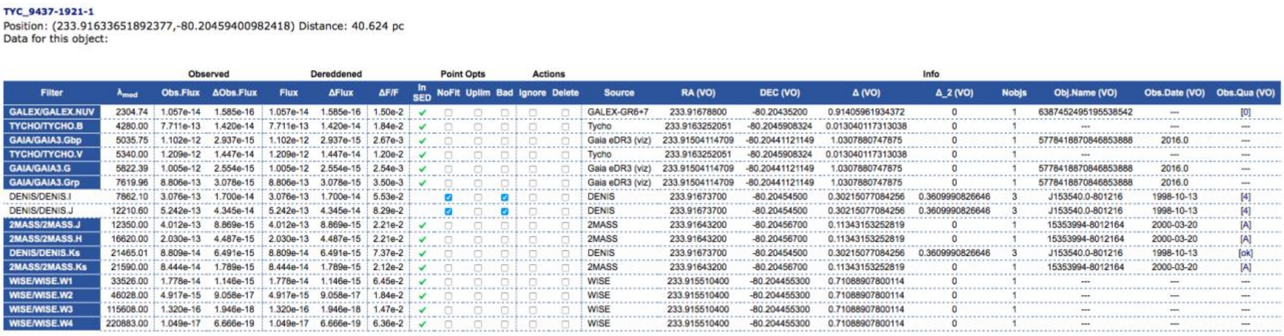
Figure 2. Distances obtained from Gaia eDR3.

Tag "Build SEDs"

– *Step 8* – 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. In order not to slow down too much the tutorial, click ***unmark All*** and select only 2MASS, DENIS, WISE, Tycho-2, Gaia eDR3 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 density units) will appear.

– *Step 9* – 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.

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



TYC_9437-1921-1
Position: (233.91633651892377,-80.20459400982418) Distance: 40.624 pc
Data for this object:

		Observed		Dereddened			Point Opts			Actions		Info								
Filter	λ_{med}	Obs.Flux	ΔObs.Flux	Flux	ΔFlux	ΔF/F	In SED	NoFit	Uplim	Bad	Ignore	Delete	Source	RA (VO)	DEC (VO)	Δ (VO)	Δ_2 (VO)	Nobjs	Obj.Name (VO)	Obs.Date (VO)	Obs.Qua (VO)
GALEX/GALEX.NUV	2304.74	1.057e-14	1.585e-16	1.057e-14	1.585e-16	1.50e-2	✓	☐	☐	☐	☐	☐	GALEX-GR6+7	233.91678800	-80.20435200	0.91405961934372	0	1	6387452495195538542	---	[0]
TYCHO/TYCHO.B	4280.00	7.711e-13	1.420e-14	7.711e-13	1.420e-14	1.84e-2	✓	☐	☐	☐	☐	☐	Tycho	233.9163252051	-80.2045908324	0.013040117313038	0	1	---	---	---
GAIA/GAIA3.Gbp	5035.75	1.102e-12	2.937e-15	1.102e-12	2.937e-15	2.67e-3	✓	☐	☐	☐	☐	☐	Gaia eDR3 (viz)	233.91504114709	-80.20441121149	1.0307880747875	0	1	5778418870846853888	2016.0	---
TYCHO/TYCHO.V	5340.00	1.209e-12	1.447e-14	1.209e-12	1.447e-14	1.20e-2	✓	☐	☐	☐	☐	☐	Tycho	233.9163252051	-80.2045908324	0.013040117313038	0	1	---	---	---
GAIA/GAIA3.G	5822.39	1.005e-12	2.554e-15	1.005e-12	2.554e-15	2.54e-3	✓	☐	☐	☐	☐	☐	Gaia eDR3 (viz)	233.91504114709	-80.20441121149	1.0307880747875	0	1	5778418870846853888	2016.0	---
GAIA/GAIA3.Grp	7619.96	8.806e-13	3.078e-15	8.806e-13	3.078e-15	3.50e-3	✓	☐	☐	☐	☐	☐	Gaia eDR3 (viz)	233.91504114709	-80.20441121149	1.0307880747875	0	1	5778418870846853888	2016.0	---
DENIS/DENIS.I	7862.10	3.076e-13	1.700e-14	3.076e-13	1.700e-14	5.53e-2		☑	☐	☑	☐	☐	DENIS	233.91673700	-80.20454500	0.30215077084256	0.3609990826646	3	J153540.0-801216	1998-10-13	[4]
DENIS/DENIS.J	12210.60	5.242e-13	4.345e-14	5.242e-13	4.345e-14	8.29e-2		☑	☐	☑	☐	☐	DENIS	233.91673700	-80.20454500	0.30215077084256	0.3609990826646	3	J153540.0-801216	1998-10-13	[4]
2MASS/2MASS.J	12350.00	4.012e-13	8.869e-15	4.012e-13	8.869e-15	2.21e-2	✓	☐	☐	☐	☐	☐	2MASS	233.91643200	-80.20456700	0.11343153252819	0	1	15353994-8012164	2000-03-20	[A]
2MASS/2MASS.H	16620.00	2.030e-13	4.487e-15	2.030e-13	4.487e-15	2.21e-2	✓	☐	☐	☐	☐	☐	2MASS	233.91643200	-80.20456700	0.11343153252819	0	1	15353994-8012164	2000-03-20	[A]
DENIS/DENIS.Ks	21465.01	8.809e-14	6.491e-15	8.809e-14	6.491e-15	7.37e-2	✓	☐	☐	☐	☐	☐	DENIS	233.91673700	-80.20454500	0.30215077084256	0.3609990826646	3	J153540.0-801216	1998-10-13	[ok]
2MASS/2MASS.Ks	21590.00	8.444e-14	1.789e-15	8.444e-14	1.789e-15	2.12e-2	✓	☐	☐	☐	☐	☐	2MASS	233.91643200	-80.20456700	0.11343153252819	0	1	15353994-8012164	2000-03-20	[A]
WISE/WISE.W1	33526.00	1.778e-14	1.146e-15	1.778e-14	1.146e-15	6.45e-2	✓	☐	☐	☐	☐	☐	WISE	233.915510400	-80.204455300	0.71088907800114	0	1	---	---	---
WISE/WISE.W2	46028.00	4.917e-15	9.058e-17	4.917e-15	9.058e-17	1.84e-2	✓	☐	☐	☐	☐	☐	WISE	233.915510400	-80.204455300	0.71088907800114	0	1	---	---	---
WISE/WISE.W3	115608.00	1.320e-16	1.946e-18	1.320e-16	1.946e-18	1.47e-2	✓	☐	☐	☐	☐	☐	WISE	233.915510400	-80.204455300	0.71088907800114	0	1	---	---	---
WISE/WISE.W4	220883.00	1.049e-17	6.666e-19	1.049e-17	6.666e-19	6.36e-2	✓	☐	☐	☐	☐	☐	WISE	233.915510400	-80.204455300	0.71088907800114	0	1	---	---	---

Figure 3. Example of the table showing the gathered photometry for TYC_9437 to illustrate how VOSA uses the information on quality to automatically identify bad photometric points and remove them from the fitting.

Tag “Analyse SEDs”

– *Step 10* – 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 “BT-Settl (CIFIST)”. Click ***Next: Select model params***.

– *Step 11* – In this window, we can limit the range of physical parameters that will be used for the fit. To save time we will make the following assumptions:

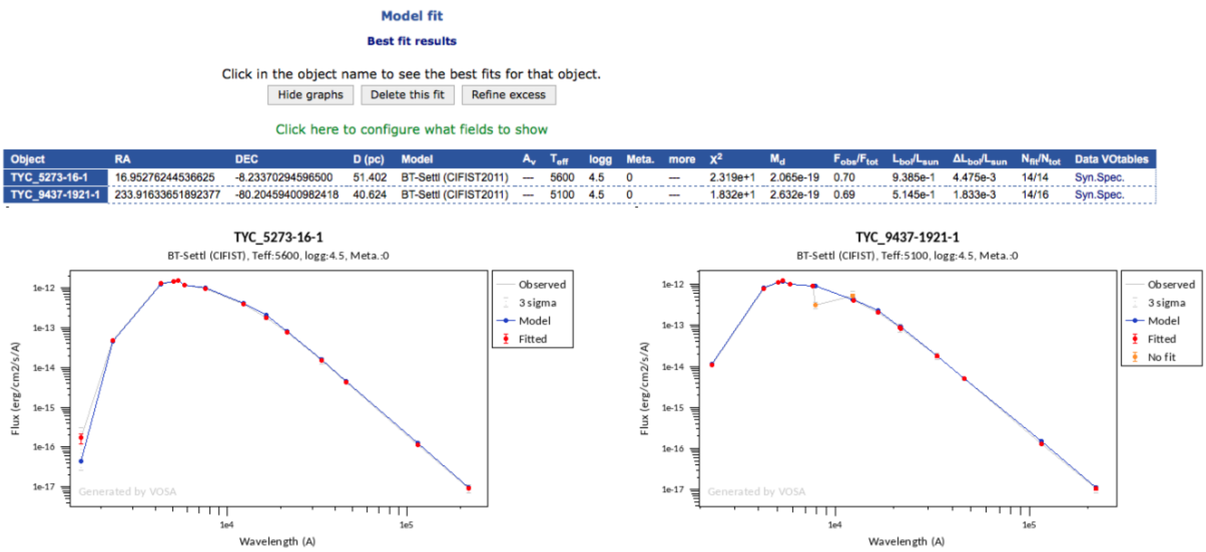
T_{eff}: 4000 – 7000 K

log g: 4.5 – 4.5 dex.

Then, click ***Make the fit.***

– *Step 12* – We will see now a summary table with the best fit results. Click on ***Show graphs*** to have a look at the graphics. The effective temperatures obtained after the fitting are:

TYC_5273: Teff= 5600 K
TYC_9437 Teff= 5100 K



Object	RA	DEC	D (pc)	Model	A_v	T_{eff}	logg	Meta.	more	χ^2	M_d	F_{obs}/F_{tot}	L_{bol}/L_{sun}	$\Delta L_{bol}/L_{sun}$	N_{fit}/N_{tot}	Data VOtables
TYC_5273-16-1	16.95276244536625	-8.23370294596500	51.402	BT-Settl (CIFIST2011)	—	5600	4.5	0	—	2.319e+1	2.065e-19	0.70	9.385e-1	4.475e-3	14/14	Syn.Spec.
TYC_9437-1921-1	233.91633651892377	-80.20459400982418	40.624	BT-Settl (CIFIST2011)	—	5100	4.5	0	—	1.832e+1	2.632e-19	0.69	5.145e-1	1.833e-3	14/16	Syn.Spec.

Figure 4. VOSA SED fitting

To get information on the radii and masses derived from VOSA, click ***Click here to configure what fields to show*** and tick all the parameters in the *Masses and radiuses* section. Click ***Save config.*** Radii and masses obtained using two different approaches will now appear in the summary table.

Note: Here you can find more information on how VOSA calculates masses and radii.

Tag “HR Diag.”

– *Step 13* – This tag allows the estimation of masses and ages using theoretical models. Click on “***HR Diag.”*** *tag*. The BHAC15 collection of isochrones and evolutionary tracks will be selected. Click ***Continue***. Do not modify the range of masses/ages. Click ***Make the HR diagram***. A table including the luminosities, masses and ages as well as the HR diagram will be shown.

HR Diagram

Delete this HR Diagram

Objects

Object	Model	T_{eff}		LogL		Age		Mass		
TYC_5273-16-1	BHAC15	5600	(5550,5650)	-0.0276	(-0.0297,-0.0255)	7.8979	..(0.0300,7.9356)	1.1484	(1.0053,1.1487)	[1]
TYC_9437-1921-1	BHAC15	5100	(5050,5150)	-0.2886	(-0.2902,-0.2871)	0.0337	..(0.0305,0.0382)	0.9570	(0.9325,0.9773)	[1]

[1] The distance to one of the closer curves has been estimated as the one to the closest point in the curve

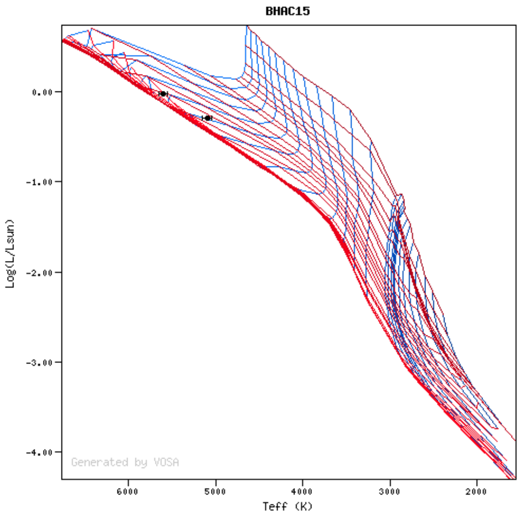


Figure 5. HR diagram

Summary

- TYC_5273-6-1
  - VOSA Radius (SED fitting): 1.04 Rsun / 1.03 Rsun
  - VOSA Mass (SED fitting): 1.24 Msun / 1.22 Msun
  - VOSA (HR diagram): 1.15 Msun
  - Stassun Radius: 0.95 Rsun
  - Stassun Mass: 1.08 Msun

- TYC_9437-1921-1
  - VOSA Radius (SED fitting): 0.92 Rsun / 0.92 Rsun
  - VOSA Mass (SED fitting): 0.99 Msun / 0.97 Msun
  - VOSA (HR diagram): 0.96 Msun
  - Stassun Radius: 0.88 Rsun
  - Stassun Mass: 0.68 Msun

Good agreement for TYC_5273 while for TYC_9437-1921-1 there are some discrepancies in the derived masses that should be looked into more in detail.

Tag "Results"

– *Step 14* – Place the cursor on the ***Results*** tag and then click ***Activity Log***. You will find here a summary of all steps executed during the workflow.

– *Step 15* – Place the cursor on the ***Results*** tag and then click ***Download Results***. You can save here different types of results (plots, VO photometry, HR diagram,...) in different formats. Click Retrieve (do not tick anything). A new window showing the message ***"Tar file successfully created"*** will appear. Click "Download your results". In the tar file (folder *"info"*) you will get a couple of files (*"refs.bibtex.bib"* and *"refs.dat"*) including the bibliographic references of all the resources you have made use of (VO services, theoretical models,...).

2. Science case II: VOSA and the infrared excess

Goal of the science case: Identification and management of infrared excess in the SED fitting.

An **infrared excess** appears in the spectral energy distribution of a star when it shows an infrared flux larger than that expected by assuming the star is a blackbody radiator. Infrared excesses are often the result of circumstellar dust heated by starlight and reemitted at longer wavelengths. They are common in young stellar objects and evolved stars on the asymptotic giant branch or older.

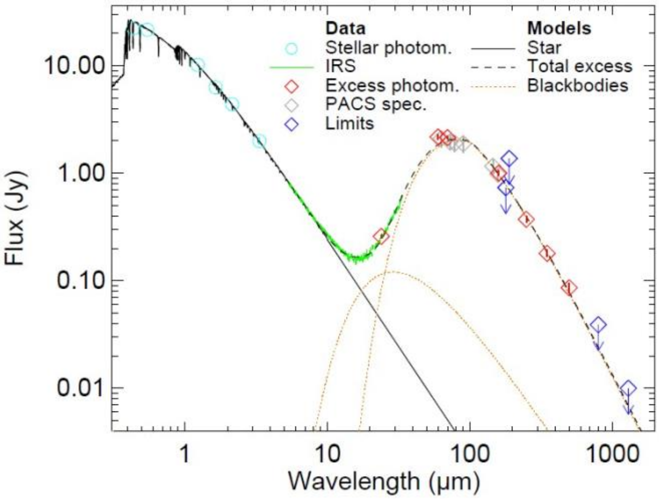


Figure 6. Example of a star+protoplanetary disk SED.

Workflow:

Open VOSA

– *Step 1* – If you have closed the application, then, go to VOSA. If the application is still open, then, move to the “Files” tag.

– *Step 2* – Copy to your laptop the file “vosa_excess.txt” available at the school webpage (link here).

Tag “Files”

– *Step 3* – Upload the file in VOSA (*File to upload / Browse*). Give a description (free text). **DO NOT FORGET TO SELECT “MAGNITUDES” AS FILE TYPE**. Then, click ***Upload***. The message *“your-file-name” has been successfully uploaded!”* will appear. Click ***Continue***. If this is not the case, look for your file in the ***Your files*** section and click ***Select****.*

Tag “Build SEDs”

– *Step 4* – Skip the ***Objects*** tag. In the next tag (***Build SEDs***) we can complement our “user photometry” with photometry found in VO services. Click on ***VO Photometry.*** For this use case, click ***unmark All*** and select only WISE. Then, 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.

– *Step 5* – Place the cursor on the ***Build SEDs*** tag and then click ***SED edit/visualize***. VOSA implements an algorithm based on the SED slope to detect a potential excess in the infrared. If this is the case, the affected photometric points are drawn in black and not considered in the fitting process (Figure 7). The user can manually override it and specify a new limit in the *Excess* panel.

Veiling can also be taken into account: photometric points bluewards than the wavelength included in the *Apply UV/blue excess up to* box will not be included in the fit.

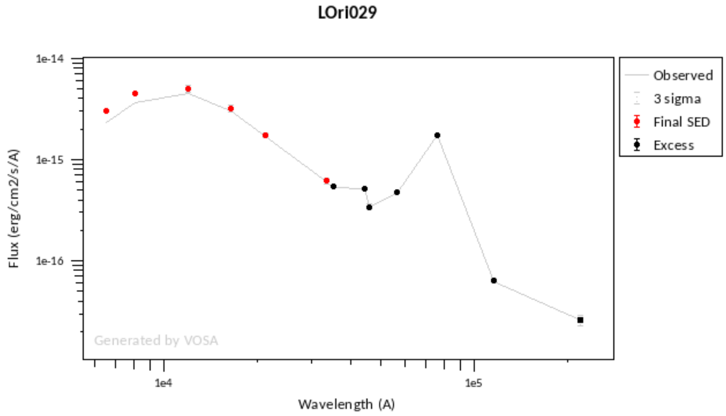


Figure 7. Plot of the photometric data, obtained in *Step 5*, showing the photometric points affected by infrared excess (black dots).

Tag "Analyse SEDs"

– *Step 6* – 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 "BT-Settl (CIFIST)". Click ***Next: Select model params****.*

– *Step 7* – In this window, we can limit the range of physical parameters that will be used for the fit. To save time we will make the following assumptions:

log g: 4.5 – 4.5 dex.

Then, click ***Make the fit.***

– *Step 8* – We will see now a summary table with the best fit results. Click on ***Show graphs*** to have a look at the graphic. Black points are affected by IR excess and they are not considered in the fit. Click ***Refine excess*** if you want to refine the excess estimation made by VOSA using just the slope of the SED.

– *Step 9* – A detailed description of how VOSA calculates the excess can be found here.

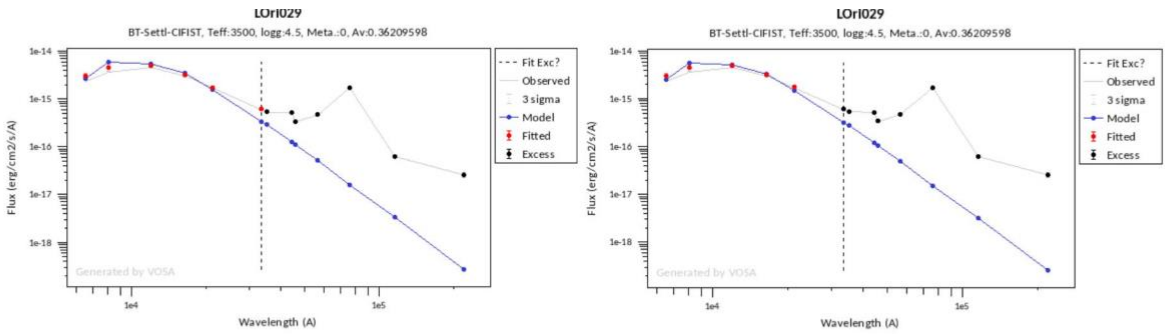
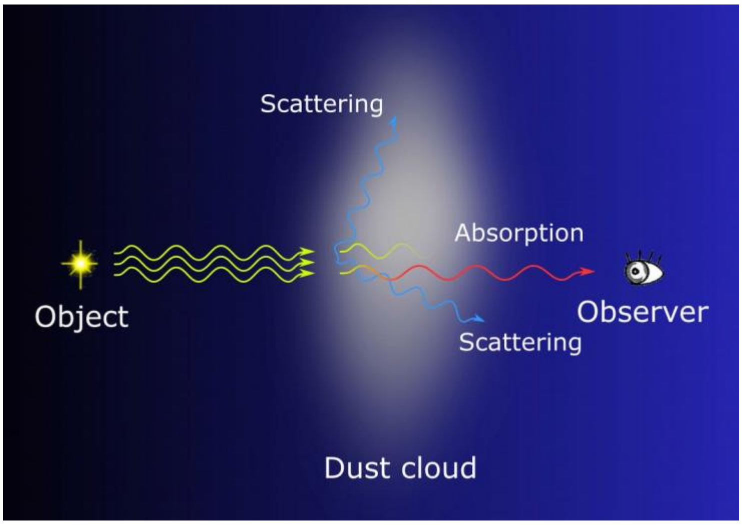


Figure 8. Plot of the SED fitting before and after refining the infrared excess (*Step 8*).

3. Science case III: The impact of extinction on the physical parameters obtained from SED fitting

Goal of the tutorial: Visualization of the effects of interstellar extinction in the SED fitting.

Extinction can be defined as the absorption and scattering of electromagnetic radiation by dust and gas existing between an emitting astronomical object and the observer.



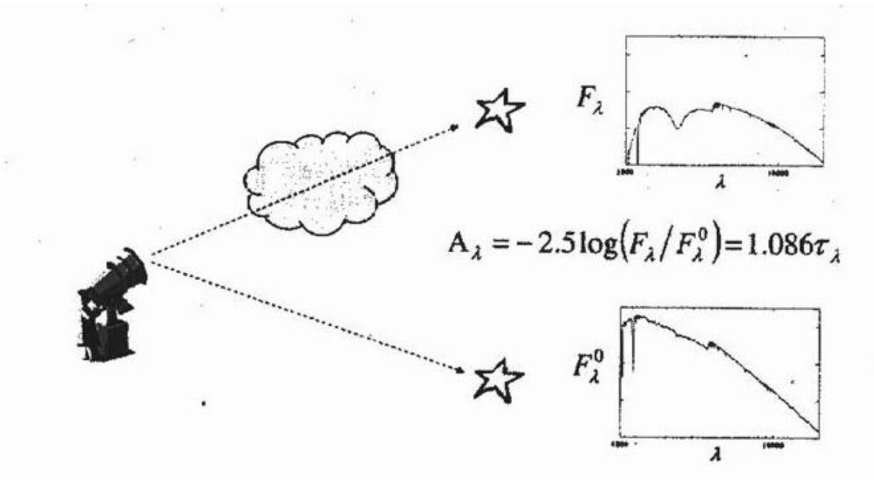


Figure 9. Effect of the extinction on the SED (source: Wikimedia commons).

Workflow:

Open VOSA

– *Step 1* – If you have closed the application, then, go to VOSA. If the application is still open, then, move to the “Files” tag.

Tag “Files”

– *Step 2* – Go to the ***Files*** tag. On the righthand side (section *Create a single object data file)*, type HD302505 in the *Obj. Name* box. Include a description (e.g. “third VOSA case”. Including a description is not a compulsory step). Click ***Create***. The message “*HD302505.txt has been successfully uploaded*” will appear. Click ***Continue***.

Tag “Objects”

– *Step 3* – Place the cursor on the ***Objects*** tag and then click ***Coordinates****.* The message *“There are objects in your file without coordinates. Please, try to find them using Sesame”*, will appear. Click ***Search for Obj. coordinates****.*

– *Step 4* – Once Sesame has been used to find the coordinates of our object, we have to make them the “final” coordinates. To do so, we have to click ***Make all changes*** in the left panel (the one labelled as *Actions for all the objects in the file*). The Sesame coordinates will appear in bold in the *Final* column.

Tag “Build SEDs”

– *Step 5* – 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. In order not to slow down too much the tutorial, click ***unmark All*** and select only 2MASS, DENIS, WISE, Tycho-2, Stroemgren-Crawford (Paunzen 2015) and UBV (*Homogeneous Means in the UBV System*, Mermilliod 1991). Then, 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.

Tag “Analyse SEDs”

– *Step 6* – 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 “Kurucz ODFNEW/NOVER, alpha: 0.0”. Click **Next: Select model params**.

– *Step 7* – In this window, we can define the range of physical parameters that will be used for the fit. To save time we will make the following assumptions:

log g: 4.0 – 4.0 dex

Meta: -1.0 – +0.5

Then, click ***Make the fit.***

– *Step 8* – We will see now a summary table with the best fit results. Click on **Show graphs** to have a look at the graphic. The effective temperature obtained after the (very good) fitting is T_{eff}: 6250 K.

Check with SIMBAD

– *Step 9* – Open SIMBAD (here). Type HD302505 in the Identifier box. Click **submit id**. This star has a B2 spectral type, which is inconsistent with the effective temperature derived from the SED fitting (T_{eff}: 6250 K).

What is the problem here? What is causing the large differences in T_{eff} when this value is compared to that calculated in *Step 8*? The answer is extinction which has a strong impact on the SED shape, impact that we are not taking it into account.

Let's repeat the workflow but now considering extinction.

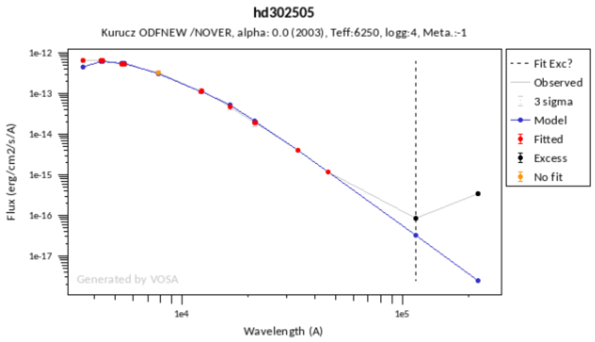
Tag “Files”

– *Step 10* – Copy the file “vosa_extinction.txt” available at the school webpage (link here).

– *Step 11* – Go back to the **Files** tag and upload this file. If you have a look at the “vosa_extinction.txt” you will see that the value in the 10th column is “Av:0.0/3.0”. This means that, during the fitting process, VOSA will consider Av as a free parameter ranging from Av:0.0 to Av:3.0.

Another approach could be to look for information on extinction in VO services using the "*Objects / Extinction*" tag. However, there is no information for HD302505 in the catalogues consulted by VOSA.

– *Step 12* – Repeat *Steps 3-7*. Now we get T_{eff}: 32000 K, a much more realistic determination given the spectral type and also with a very good fit.



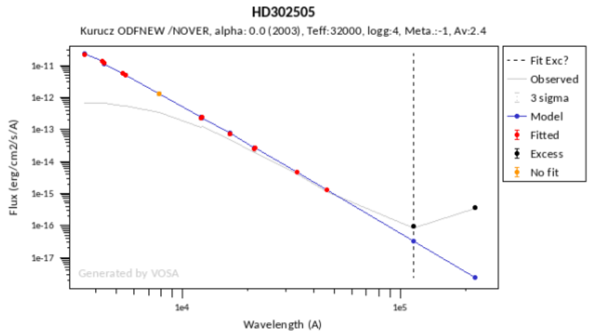


Figure 10. Plot of the SED fitting before and after correcting from interstellar extinction (*Step 12*).

A detailed description of how VOSA estimates the interstellar extinction can be found here.