

- **Title:** Determination of stellar physical parameters using VOSA.
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- **Scientific background:**

This science case comes from a recently published paper (“*Accurate, empirical radii and masses of planets with Gaia parallaxes*”, Stassun et al., [2016arXiv160904389S](#)). The paper is focused on the determination of radii and masses of extrasolar planets 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 planet formation and evolution theories. For instance, the origin of “inflated hot Jupiters” (planets in the range 0.1-2 Jupiter masses whose radii is 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 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 (1) and (2), an accurate knowledge of the radius and mass of an extrasolar planet requires a very good determination of the mass and radius of the hosting star.

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

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

where K_{RV} is the velocity semi-amplitude and P , e , and i are period, eccentricity, and inclination of the planet's orbit, respectively. M_p is the mass of the planet and M_* is 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 Gaia/TGAS distances in a largely empirical manner.

- **Goal of the tutorial:** Estimation of radii and masses of star-hosting planets using [VOSA](#).
- **Workflow:**
 - 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 passwd).

- Step 3.- Cut and paste in a file the list of objects in “VOSA format” included in vosa_usecase_final.txt
- Tag "Files"
 - Step 4.- Upload the file in VOSA (“File to upload”). Give a description (free text). And then, click “Upload”. The message “*your-file-name has been succesfully uploaded!*” will appear. Click “Continue”.
- Tag "Objects"
 - Step 5.- Place the cursor on the tag “Objects” 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 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”).
 - Step 7.- Place the cursor on the tag “Objects” and then click “Distances”. Click on “Search for Obj. Distances”. To make the Gaia TGAS 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 Gaia/TGAS in the first place. Click “Make all changes”.
- Tag “Build SEDs”
 - Step 8.- Place the cursor on the tag “Build SEDs” 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 DR1 and Galex. 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.
 - Step 9.- Place the cursor on the tag “Build SEDs” 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 (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. If you have a look at the SED of TYC_9023-815-1 you will notice that the two DENIS photometric points are clearly discrepant. This is due to their poor quality and, thus, VOSA has flagged them accordingly.

Also 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. The user can manually override it and specify a new limit in the “Excess” panel. Veiling can also be taking 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.

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

○ Tag “Analyse SEDs”

▪ Step 10: Place the cursor on the tag “*Analyse SEDs*” and then click “*Model fit*”. Different grids of theoretical models covering different ranges of physical parameters are displayed. For this tutorial select only the “BT-Settl-CIFIST”. To save time, do not tick either of the options given at the bottom of the page (“*Options for this fit*”). Click “*Next: Select mode params*”.

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

- T_{eff} : 4000-7000K
- $\log g$: 4.5-4.5 dex.

Then, click “*Make the fit*”

▪ Step 12.- We can now see 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: T_{eff} : 5700K
- TYC_9023: T_{eff} : 5900K
- TYC_9083: T_{eff} : 4800K
- TYC_9241: T_{eff} : 5500K
- TYC_9437: T_{eff} : 5100K

Radii and masses obtained using two different approaches are also given in this table. More information on how VOSA calculates masses and radii are can be found at: <http://svo2.cab.inta-csic.es/theory/vosa/helpw4.php?otype=star2&action=help&what=fit#fit:radius>

○ Tag “HR Diag.”

▪ Step 13.- This tag allows the estimation of masses and ages using theoretical models. Click on “*HR diagram*”. A new window with the BHAC15 isochrones and evolutionary tracks (Baraffe et al. 2015) will be displayed. 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. Click on “*Data range*” (below the HR diagram) for a more clear view of it.

○ Data analysis

▪ VOSA has computed radii and masses using different approaches. Now let's compare them with those given in the paper.

- Open TOPCAT in your laptop. Upload the file “*vosa_usecase_paper_final.txt*”. (*File / load table / Filestore Browser. IMPORTANT: Choose “Table Format: ASCII”*). The file contains five columns (object name, radius, error in radius, mass, and error in mass).
- In VOSA, go to the “*Analyse SEDs/Model fit*” tag. Click “*Send table to SAMP hub*”. The table will be sent to TOPCAT.

NOTE: SAMP broadcasting requires user authorization. A new window (“*SAMP*”

- *Hub Security*) will pop up asking for authorization. Click “Yes”.
- Similarly, go to the “*HR diagram*” tag. Click “Send results table to SAMP hub” to send the table to TOPCAT.
- Now, in TOPCAT, we will joint the three tables to have a single one.
 - Joins/Triple Match → A new window (“*Match Tables*”) will appear.
 - In the “*Match Tables*” window:
 - Algorithm: Exact values
 - Table1: vosa_usecase_paper_final.txt. Matched Value column: object_id
 - Table2: bestfitp.xml. Matched Value column: Object
 - Table3: hrd.xml. Matched Value column: Object
 - Click “Go”. A new table “*match(x,y,z)*” will be created.
- Let's now plot the different measurements of radii included in the matched table (see Fig.1).
 - In TOPCAT → Graphics / Plane Plot. A new window (“*Plane Plot*”) pops up.
 - In this new window → Table: match(x,y,z); X=radius, Y:Rad1
 - In this new window → Layers/Add position control → Table: match(x,y,z); X=radius, Y:Rad2
 - In this new window → Layers/Add Function control → Function expression: x.
 - In this new window → Axes / Labels (bottom panel) → Remove tick from the “*Auto*” boxes → include the label you wish for X and Y axes.
 - In this new window --> Click on the first uploaded table (bottom panel left). Click “*Form*”. In the row with symbols, click on the fifth one starting from the left (error bars). In the box “*Coordinates*” → X Positive Error: error_radius. Y Positive Error: eRad1.
 - Repeat the previous step but now. X Positive Error: error_radius. Y Positive Error: eRad2.
- You can carry out a similar analysis for masses.

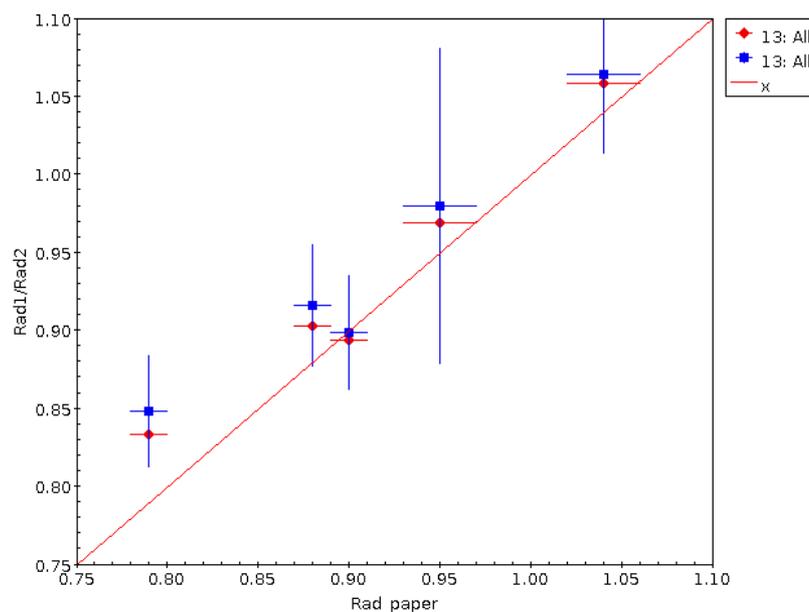


Figure 1.

- Tag “Results”
 - Step 14.- Place the cursor on the tag “Results” and then click “Activity Log”. You will find here a summary of all steps executed to carry out the workflow.
 - Step 15.- Place the cursor on the tag “Results” and then click “Download Results”. You can save here different type of results (plots, VO photometry, HR diagram,...) in different formats.
 - Step 16.- Place the cursor on the tag “Results” and then click “References”. A *refs.bibtex.bib* file including the bibliographic references of all the resources you have made use of (VO services, theoretical models,...) can be got here.
- Tag “Help”
 - Step 17.- A detailed description of how VOSA works can be found in the “Help” tag.