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

- **Author:** Enrique Solano. CAB (INTA-CSIC). Spanish Virtual Observatory. October 2019.

- **VO-Tools**: VOSA, TOPCAT

- **Scientific background:**

This science case comes from a recently published paper (*"Accurate, empirical radii and masses of planets with Gaia parallaxes"*, Stassun et al., 2017AJ....153..136S). The paper focuses 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.

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

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

where KRV is the velocity semi-amplitude and P, e, and i are period, eccentricity, and inclination of the planet's orbit, respectively. Mp 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.- Copy to your laptop the file "vosa_usecase_final.txt" available at:
    https://cloud.cab.inta-csic.es/index.php/s/YdtuvoBfyB63KS1

Case1: effective temperatures and parameters comparison

- 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 succesfully uploaded!*" will appear. Click **Continue**. If the message does not appear, go to **Your files** section and click **Select**.

- 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**.

  - 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.

  - Step 7.- Place the cursor on the **Objects** tag and then click **Distances**. Set the search radius to 10arcsec. Click **Search for Obj. Distances**. To make the Gaia DR2 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 Gaia2 in the first place. Click **Make all changes**. The Gaia DR2 coordinates will appear in bold in the *Final* column.

- 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 phometric 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 DR2 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 **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 (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.

- 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:
    - Teff: 4000-7000K
    - logg: 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: 5600K
    - TYC_9023: Teff: 5900K
    - TYC_9083: Teff: 4800K
    - TYC_9241: Teff: 5500K
    - TYC_9437: Teff: 5100K

    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. More information on how VOSA calculates masses and radii can be found at:
    http://svo2.cab.inta-csic.es/theory/vosa/helpw4.php?otype=star&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**. The BHAC15 collection of isochrones and evolutionary tracks (Baraffe et al. 2015) will be selected. 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.

    - Copy to your laptop the file *"vosa_usecase_paper_final.txt"* available at the web page.

    - Launch TOPCAT. Load the file in TOPCAT *(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/Chi-square 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*) may pop up asking for authorization. If so, 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 join 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 Figure 1).
  - In TOPCAT → Graphics / Plane Plot. A new window ("*Plane Plot*") pops up.
  - In this new window → Position → 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 drop-down panel, click on the fifth option starting from the top (**Add XYError**). In the box *Coordinates* → X Positive Error: error_radius. Y Positive Error: eRad1.
  - Repeat the previous step in the second uploaded table. X Positive Error: error_radius. Y Positive Error: eRad2.
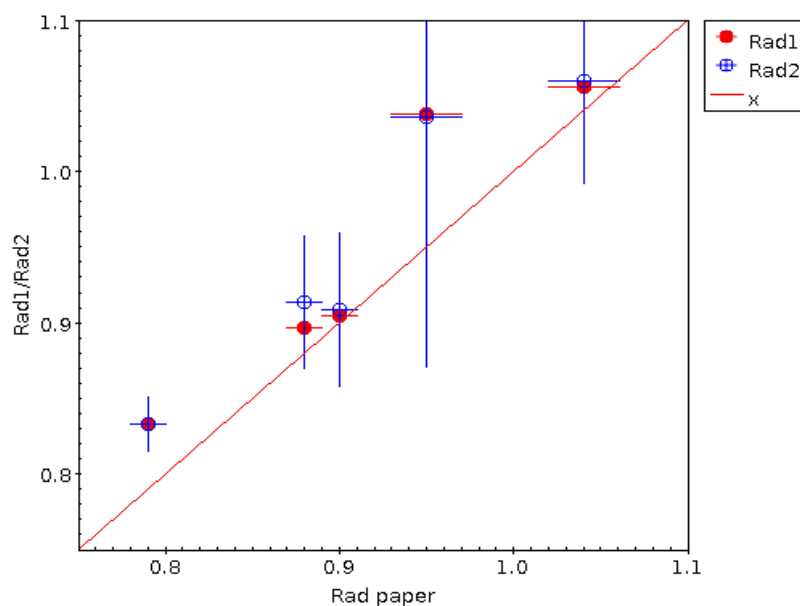
- You can carry out a similar analysis for masses.

Figure 1.

○ Going back to VOSA → 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 to carry out the workflow.

- Step 15.- Place the cursor on the **Results** *tag* 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 **Results** and click **Download results**. Click **Retrieve** (do not tick anything). A new window with 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.dat, refs.bibtex.bib)* including the bibliographic references of all the resources you have made use of (VO services, theoretical models,…).

○ Tag "Help"

- Step 17.- A detailed description of how VOSA works can be found in the **Help** tag.

Case 2: VOSA and infrared excess

- Copy to your laptop the file *"vosa_excess.txt"* available at the web page

- 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 succesfully uploaded!"* will appear. Click **Continue**. If this is not the case, look for your object in the **Your files** section and click **Select**.

- 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 units) will appear.

- Place the cursor on the **Build SEDs** tag and then click **SED edit/visualize**. VOSA implements an algoritm 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 2). 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.
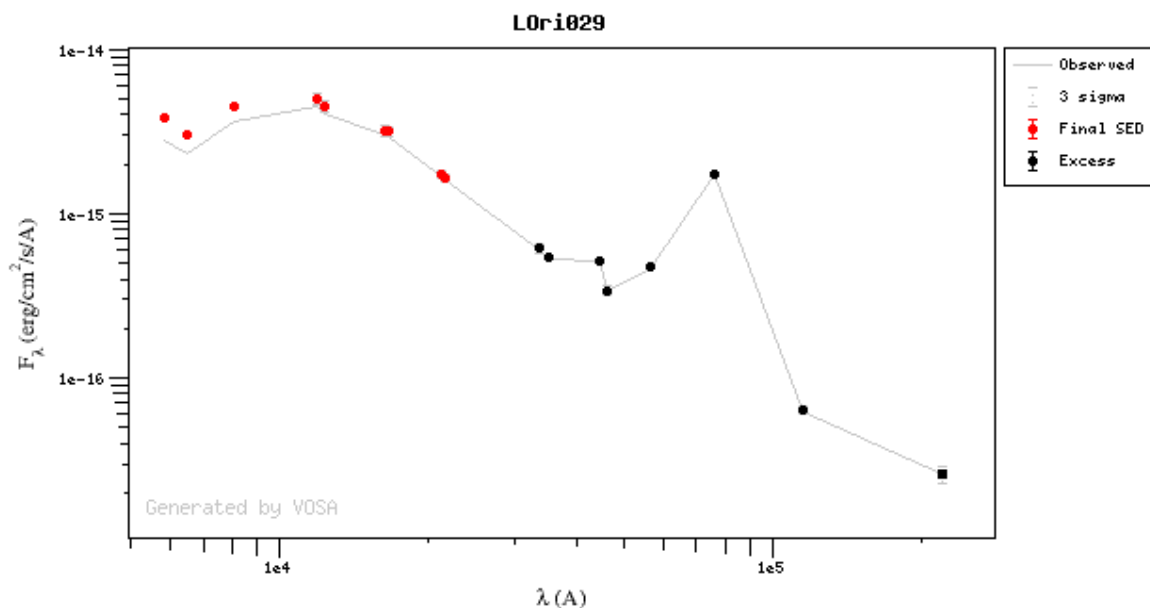

Figure 2.

- 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**.

- 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:
    - logg: 4.5-4.5 dex. Then, click **Make the fit.**

- We will see now a summary table with the best fit results. Click on **Show graphs** to have a look at the graphics. 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.

Case 3: The impact of extinction on the physical parameters obtained from SED fitting

- Step 1.- Go to the **Files** tag. On the right hand 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 has been succesfully uploaded*" will appear. Click **Continue**.

- Step 2.- 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 3.- 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.

- Step 4.- Place the cursor on the **Build SEDs** *tag* and then click **VO photometry**. Here we will be able to look for phometric 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, Stromgren (Paunzen 2015) and UBV (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 units) will appear.

- Step 5: 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 models". Click **Next: Select model params**.

- Step 6.- In this window, we can define the range of physical parameters that will be used for the fit. Do not change the parameter range. Then, click **Make the fit**.

- Step 7.- 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 temperature obtained after the (very good) fitting is Teff: 6500K

- Step8.- Open SIMBAD (http://simbad.u-strasbg.fr/simbad/sim-fid). 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 (Teff: 6500 K). What is the problem here?

- Step9.- Copy to your laptop the file *"vosa_extinction.txt"* available at the web page.

- Step10.- Go back to the **Files** tag and upload this file.

- Step11.- Repeat steps 2-7. Now we get Teff: 32000K with also a very good fit. What is causing the large differences in Teff when this value is compared to that calculated in Step7? The answer is extinction which has a strong impact on the SED shape. In the first case we were assuming no extinction while in the second case a value of Av: 2.4 is obtained from the SED fitting.

To have an idea of the importance of extinction, see Figure 3. Red circles represent the observed SED of a star with E(B-V)=0.76. Blue squares represent the SED of the same star after the reddening correction. Forget about the green triangles.
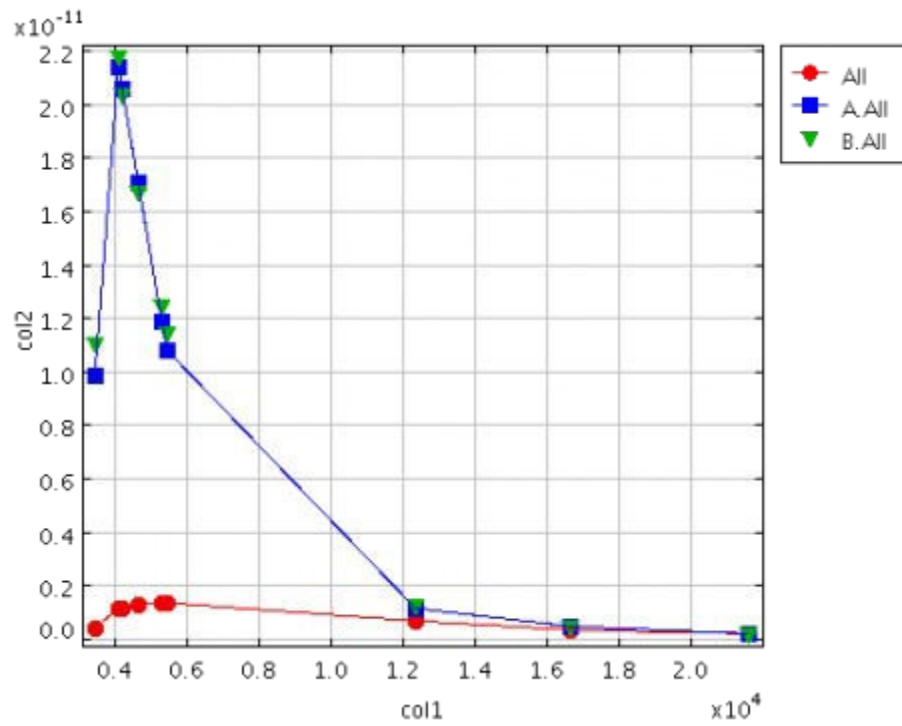

Figure 3.