S05 - Limb Darkening

ISSP workshop – 31 May 2023

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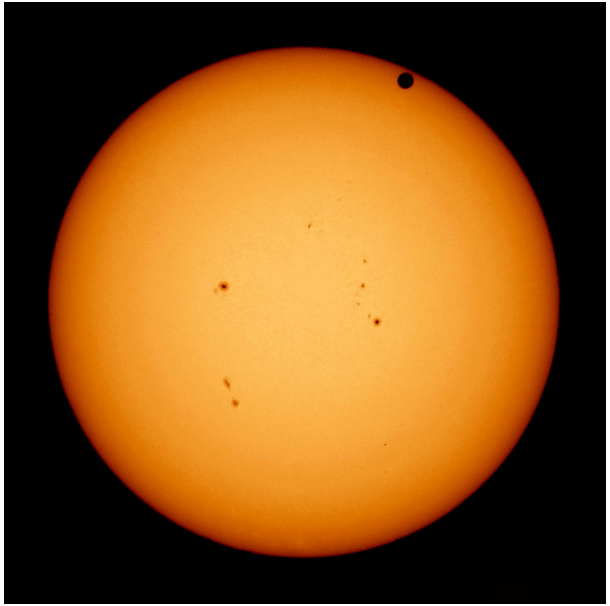
Limb Darkening

Limb Darkening (LD) is the variation of brightness distribution of a star from the centre to the limb of the star.

LD occurs due to the variation in Density and temperature from from centre to the limb.

Understanding LD is important to study stellar atmosphere and its structure.

Still there are only very few studies currently on LD



Credit: NASA

Importance of Limb Darkening

For accurate estimation on the fundamental parameters,

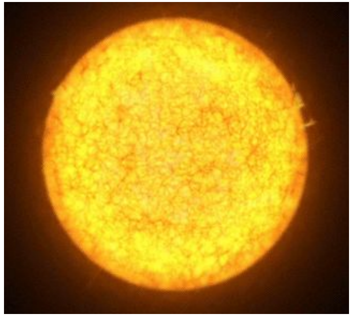
Such as T_{eff}, log g, radius etc.

Provides constraints on the stellar atmosphere models

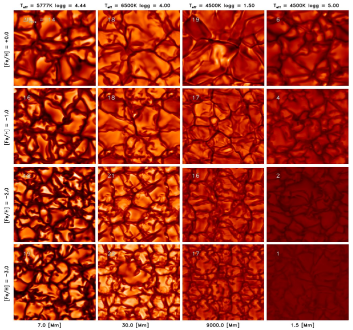
Help understand atmosphere structure

Analysing the transiting object, such as Exoplanets.

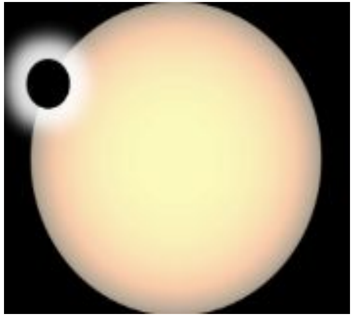
Crucial in missions like PLATO



Credit: NASA



Credit: Magic et al. 2013



Credit: NASA

With not much studies on the topic.
It is important to have a better understanding of limb darkening across the HR diagram.

CHARA/SPICA

Interferometric Survey of Stellar Parameter (ERC funded program)

We employ 6T interferometry with CHARA/SPICA to observe a large number of stars.

From this we get the angular diameter and (bottom table) the limb darkening of hundreds of stars.

Dwarfs	Challouf			Salsi-1			Salsi-2			Giants	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4	SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6	V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,10	1,00	3,35	6,28	11,82	22,25	39,94	70,70	125,14	0	0,24	1,09	3,16	6,72	11,79	20,68	36,41	62,26	106,46
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96	1	0,15	0,69	1,99	4,24	7,44	13,05	22,97	39,28	67,17
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82	2	0,10	0,44	1,26	2,68	4,69	8,23	14,49	24,79	42,38
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43	3	0,06	0,27	0,79	1,69	2,96	5,20	9,15	15,64	26,74
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83	4	0,04	0,17	0,50	1,07	1,87	3,28	5,77	9,87	16,87
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51	5	0,02	0,11	0,32	0,67	1,18	2,07	3,64	6,23	10,65
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90	6	0,02	0,07	0,20	0,42	0,74	1,30	2,30	3,93	6,72
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98	7	0,01	0,04	0,13	0,27	0,47	0,82	1,45	2,48	4,24
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14	8	0,01	0,03	0,08	0,17	0,30	0,52	0,91	1,56	2,67
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98	9	0,00	0,02	0,05	0,11	0,19	0,33	0,58	0,99	1,69
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25	10	0,00	0,01	0,03	0,07	0,12	0,21	0,36	0,62	1,06

Dwarfs	Challouf			Salsi-1			Salsi-2			Giants	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4	SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6	V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,10	1,00	3,35	6,28	11,82	22,25	39,94	70,70	125,14	0	0,24	1,09	3,16	6,72	11,79	20,68	36,41	62,26	106,46
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96	1	0,15	0,69	1,99	4,24	7,44	13,05	22,97	39,28	67,17
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82	2	0,10	0,44	1,26	2,68	4,69	8,23	14,49	24,79	42,38
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43	3	0,06	0,27	0,79	1,69	2,96	5,20	9,15	15,64	26,74
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83	4	0,04	0,17	0,50	1,07	1,87	3,28	5,77	9,87	16,87
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51	5	0,02	0,11	0,32	0,67	1,18	2,07	3,64	6,23	10,65
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90	6	0,02	0,07	0,20	0,42	0,74	1,30	2,30	3,93	6,72
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98	7	0,01	0,04	0,13	0,27	0,47	0,82	1,45	2,48	4,24
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14	8	0,01	0,03	0,08	0,17	0,30	0,52	0,91	1,56	2,67
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98	9	0,00	0,02	0,05	0,11	0,19	0,33	0,58	0,99	1,69
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25	10	0,002	0,011	0,032	0,067	0,118	0,207	0,364	0,623	1,065

Mourard et al.2022

S05 - Limb Darkening

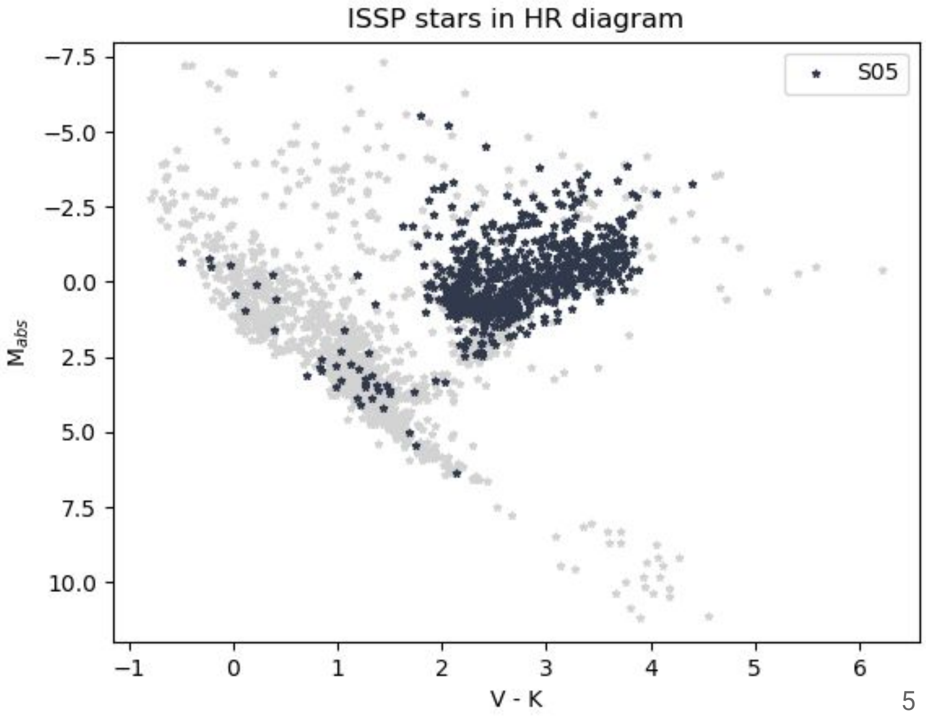
With CHARA/SPICA, we aim to observe a large sample of stars using the CHARA/SPICA over the span of 3 years.

162 stars from SpTy: B0 - M3 and
SpC: III-V

All stars are selected with:

- No activity
- DEC > -30^0
- Vmag< 6
- 0.7< angular diameter < 11 mas

Overall goal is to produce a **catalog** of directly measured intensity profiles, angular diameter (1% precision) and other fundamental parameters.



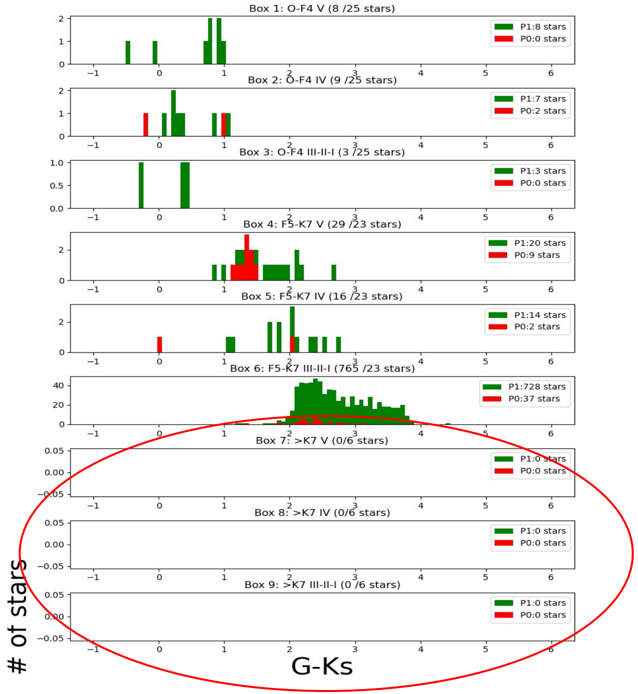
Catalog

In the catalog we have multiple star in each stellar types from **dwarfs**, **giants** and **main-sequence**.

Most stars are without stellar activity to isolate the LD.

Stars with different priorities of observations with highest priority to cover most of the HR diagram.

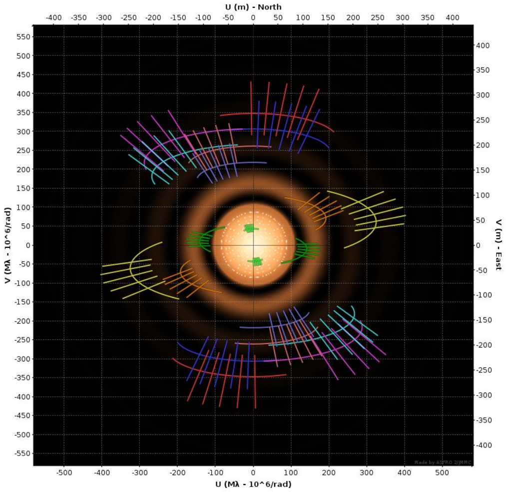
We couldn’t find much stars without stellar activities in these region. We are still looking for these.



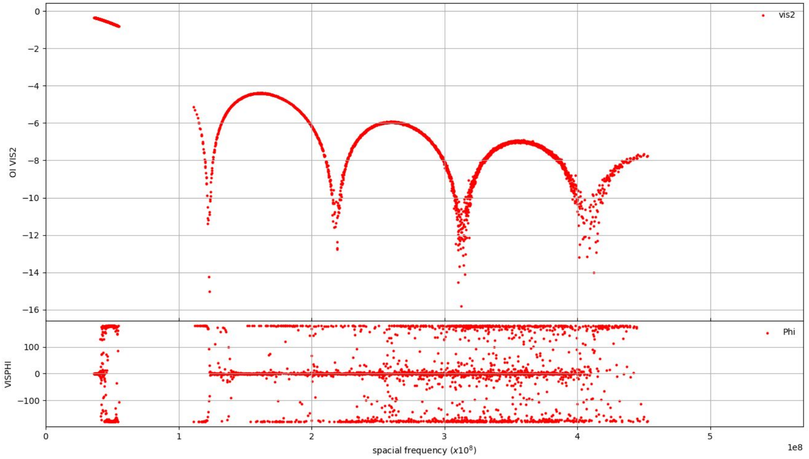
Credit: Nicolas Nardetto

Observation strategy

We use 60 spectral channels covering 600-900 nm to take multiple observation, with each taking 40 min.



We get the squared visibility of the star from we can get the angular diameter and other parameters.



For each star we will make **at least 2 observation** each.

Pipeline

- We have developed a pipeline to combine observations from **Spectroscopy**, **Interferometry** and **Photometry** to give an accurate estimation of the fundamental parameters.

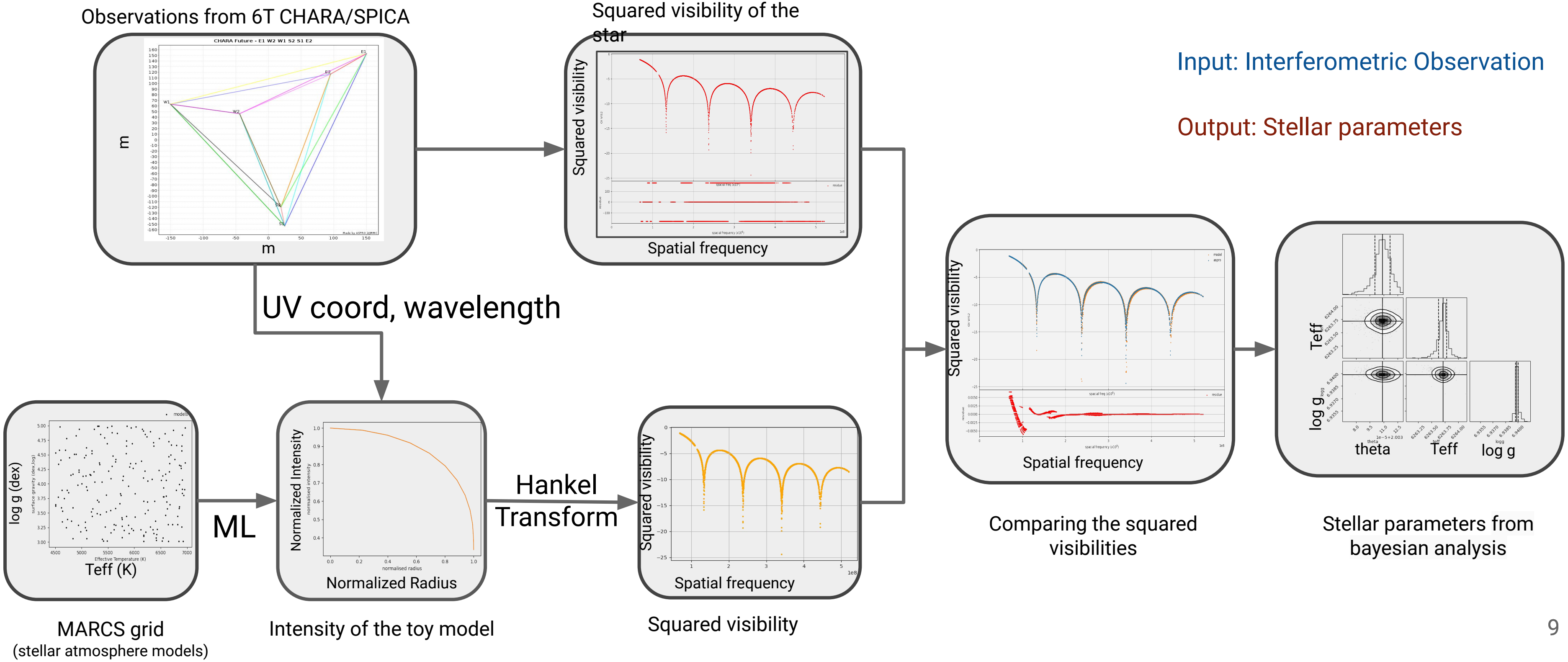
- Within the **SAPP (PLATO)** framework an artificial neural network has been developed to make a model fitting and estimate the parameter from this fitting. We employ similar technique in our work.

- The idea is to use the parameters from the **Spectroscopy** module similar to **SAPP** to initiate and guide the model fitting in the **Interferometry** and them combine this result with the **Photometry** to get an accurate estimation of stellar parameters.

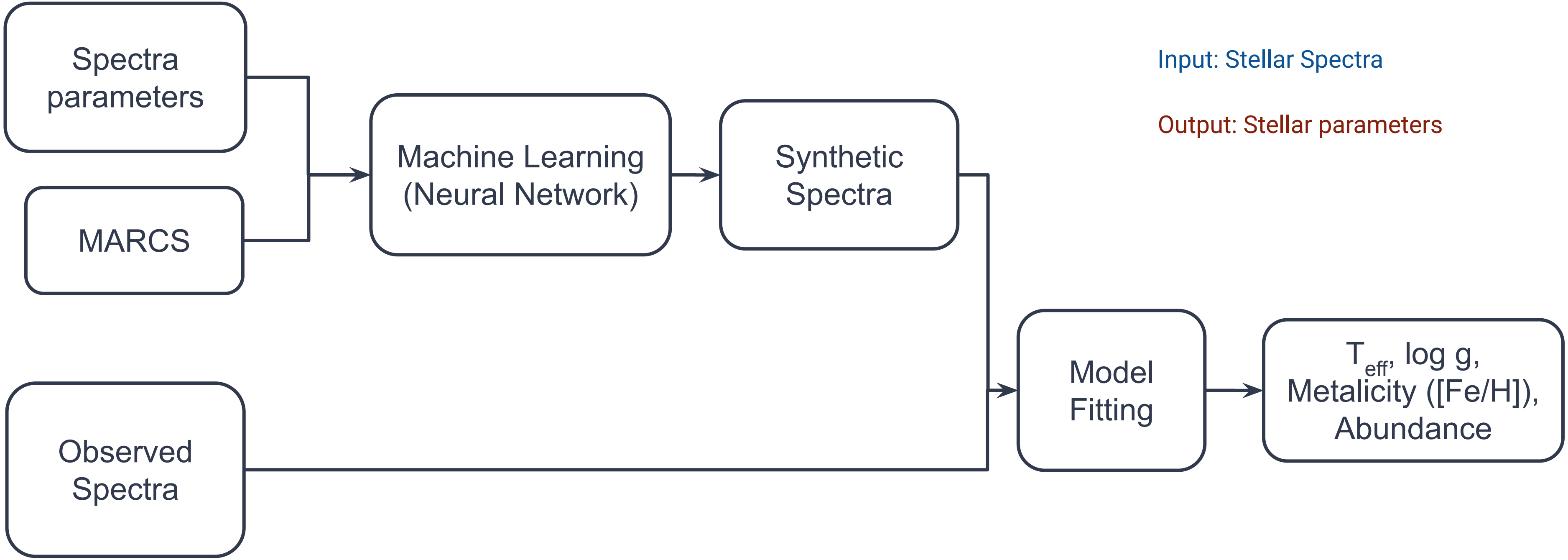
Interferometric Analysis

Input: Interferometric Observation

Output: Stellar parameters



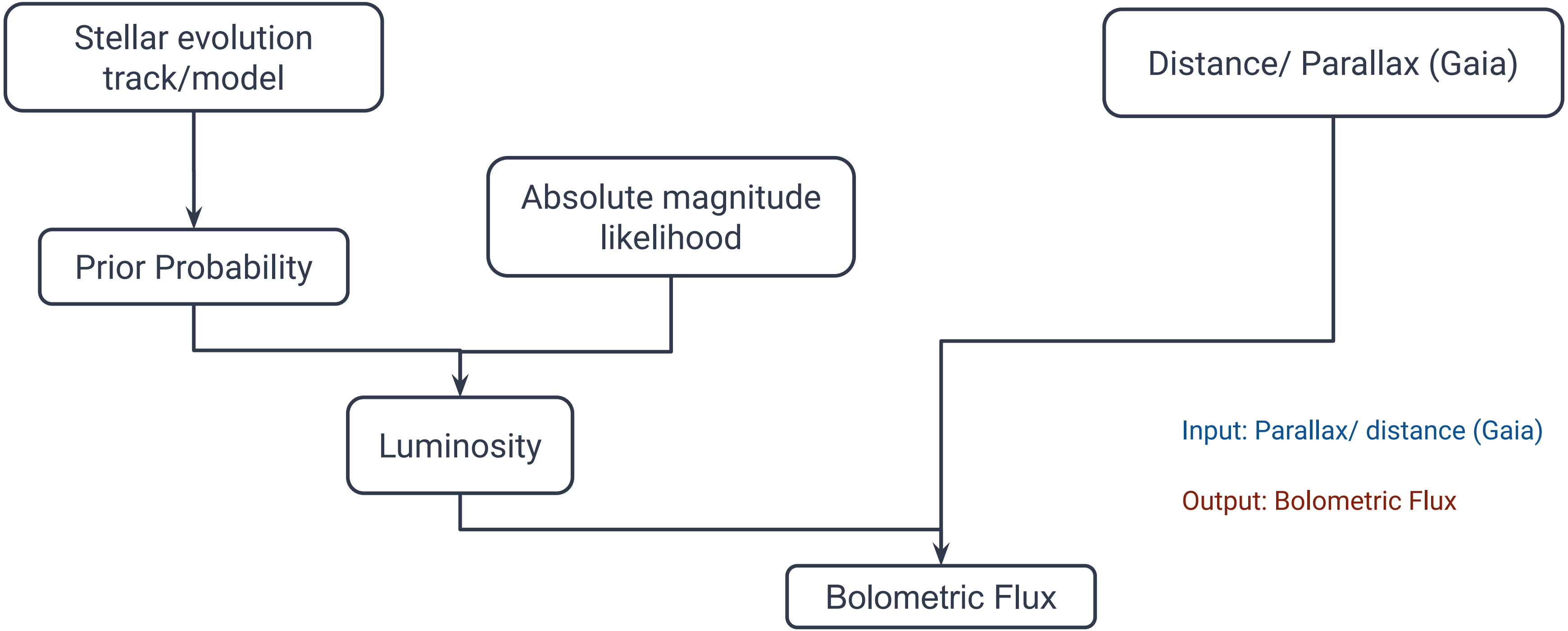
Spectroscopy



Input: Stellar Spectra

Output: Stellar parameters

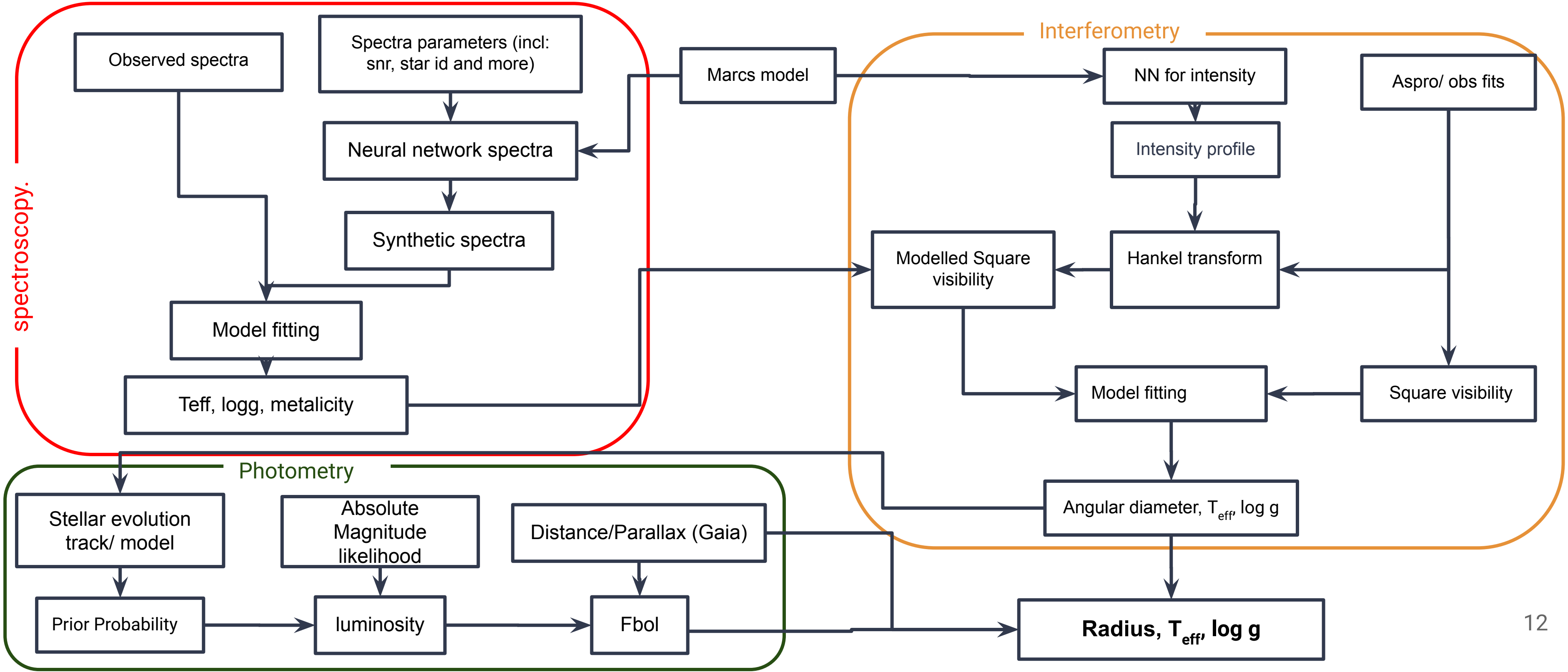
Photometry



Input: Parallax/ distance (Gaia)

Output: Bolometric Flux

Pipeline

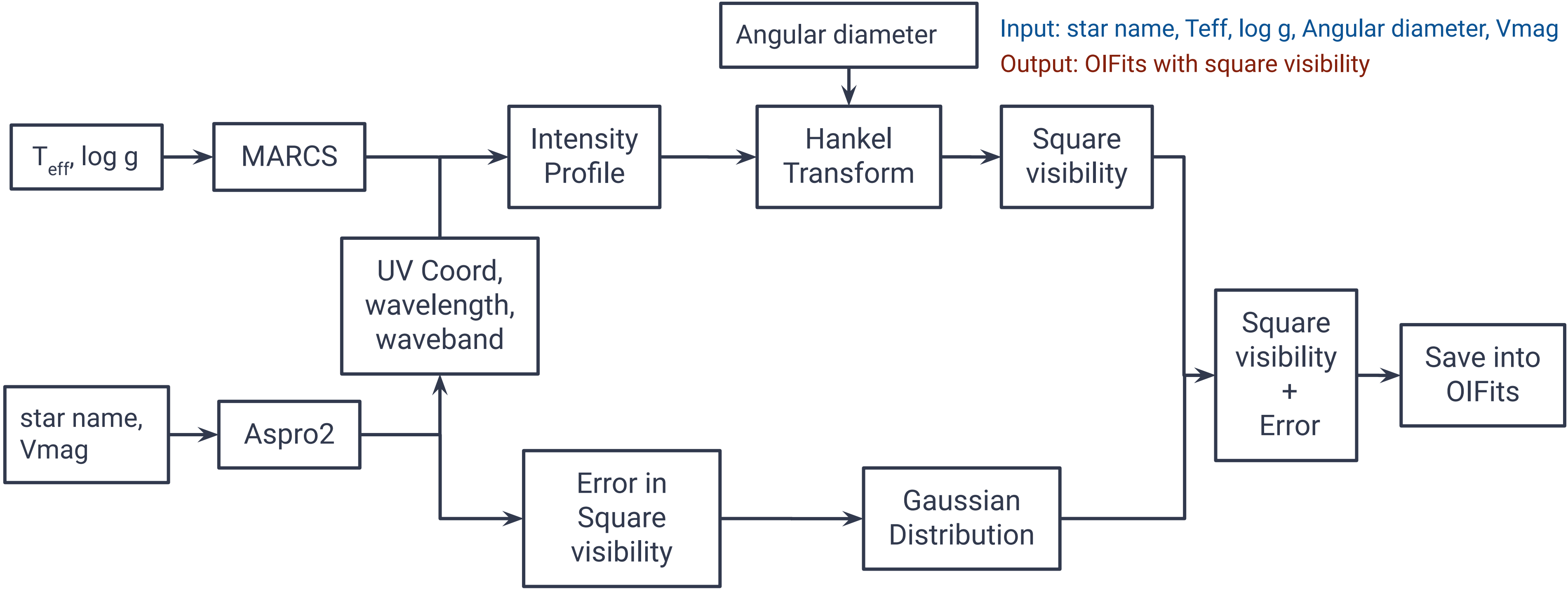


spectroscopy.
Observed spectra
Spectra parameters (incl: snr, star id and more)
Neural network spectra
Synthetic spectra
Model fitting
Teff, logg, metalicity
Marcs model
Interferometry
NN for intensity
Aspro/ obs fits
Intensity profile
Modelled Square visibility
Hankel transform
Model fitting
Square visibility
Angular diameter, T_{eff}, log g
Photometry
Stellar evolution track/ model
Absolute Magnitude likelihood
Distance/Parallax (Gaia)
Prior Probability
luminosity
Fbol
Radius, T_{eff}, log g

Simulating Interferometric Data

Input: star name, Teff, log g, Angular diameter, Vmag

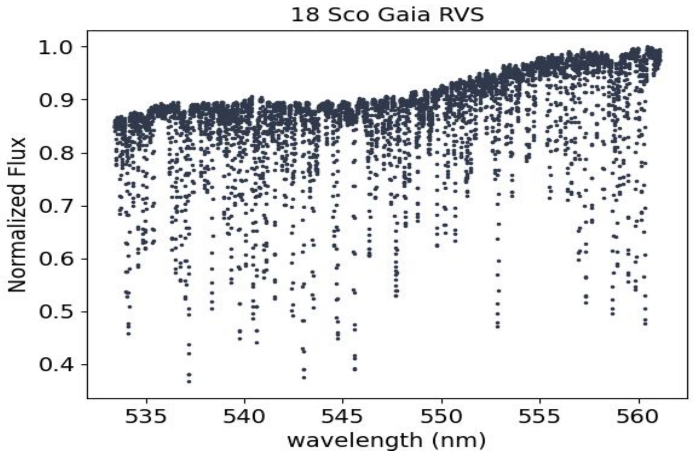
Output: OIFits with square visibility



Additional Data

Spectroscopic Data

For the spectral analysis we use Gaia RVS spectra available in Gaia archive.



It is also possible to analyse any given spectra with this module.

Photometry

For the photometric analysis, we are currently making use of stellar track model to generate synthetic photometric data.

Using the luminosity from this we calculate the bolometric flux.

But soon we will replace it with photometric observations of the targets from various archives and catalogs.

Results

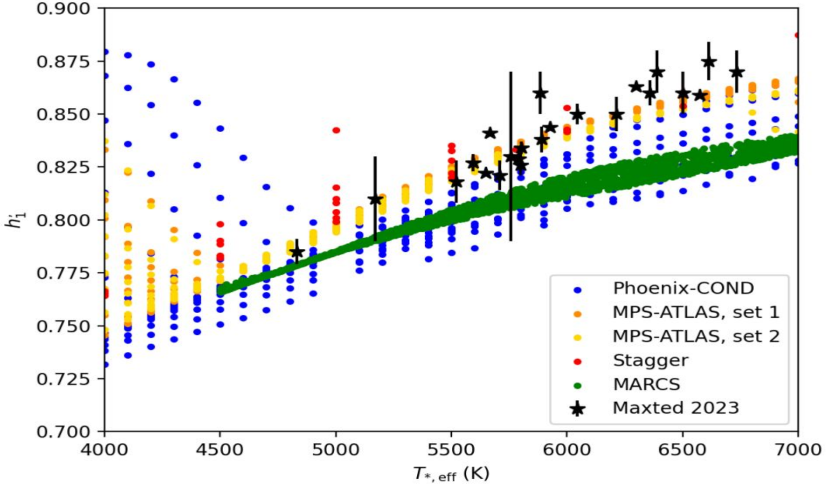
Different stars were simulated with the reference parameters sample of benchmark stars Table 1. In Gent et al. 2022.

Star	T_{eff} (Model) (K)	log g (model) (dex)	Angular Diameter (mas)(model)	T_{eff} (K)	log g (dex)	Angular Diameter (mas)	[Fe/H]	Luminosity ($L_\odot$)	Radius ($R_\odot$)
18 Sco	5810	4.44	0.665	5826.36 ±104.01	4.408 ± 0.053	0.6653 ± .0005	-0.0886 ± .2746	1.08 ± 0.03	1.009 ± 0.034
δ Eri	5022	3.76	2.405	5019.33 ± 94.94	3.737 ± 0.077	2.400 ± 0.0004	0.111 ± 0.246	3.12 ± 0.08	2.333 ± 0.111
η Boo	6099	3.79	2.179	6336.60 ± 122.40	3.892 ± 0.057	2.1760 ± 0.0003	0.158 ± 0.266	7.81 ± 0.30	2.671 ± 0.105
Procyon	6554	4.0	5.426	6619.08 ± 223.73	4.00 ± .086	5.4191 ± 0.0003	0.0795 ± 0.364	6.98 ± 0.39	2.047 ± 0.153

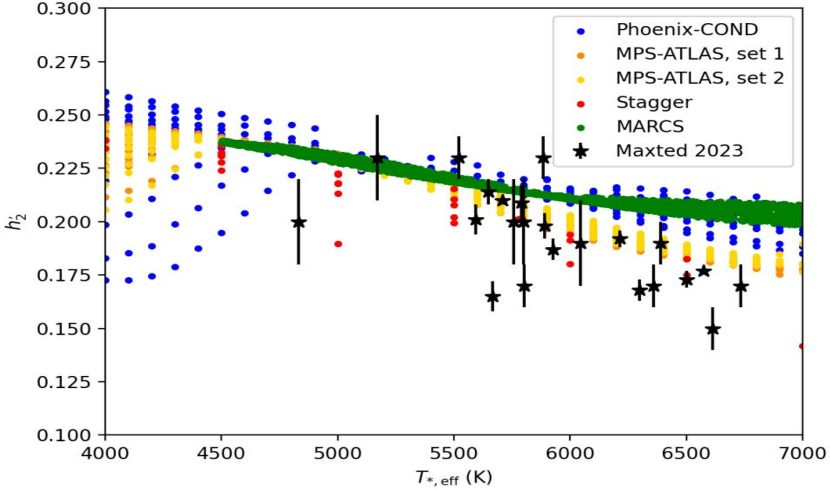
1D vs 3D

Comparison with Maxted 2023

$$h'_1 = I\left(\frac{1}{3}\right)$$



$$h'_2 = I\left(\frac{1}{3}\right) - I\left(\frac{2}{3}\right)$$



Credit: Morello - PLATO meeting Liege 2023

Link with PLATO

- The work explained is in close association with the PLATO WP 122 and this will be integrated with the MStesci1 pipeline in PLATO. This will be part of creating the benchmark star and getting their fundamental parameters.

- Within the PLATO framework an article is under preparation which will be submitted later this year.

- In addition, SPICA will also play part in WP145300m in the PLATO Ground Observation Program. In which we propose to do follow-up observations with possible interesting targets that will be detected by PLATO.

Conclusion

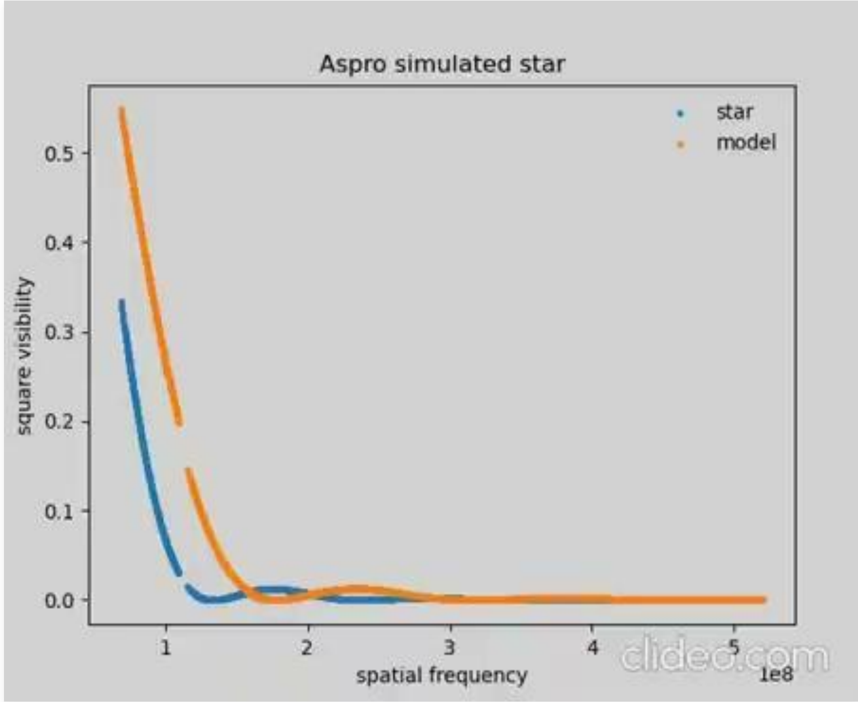
- By the end of the program we will have a catalog of stars across HR diagram to giving a better understanding of stellar LD.

- By combining **Spectrometry**, **Interferometry** and **Photometry**, we were able to estimate nad constrain the stellar parameters.

- We will keep improving the pipeline to include 3D models for the model-fitting and replace synthetic photometry with observations

- Also, an article (**Ebrahimkutty et al. 2023**) is under preparation which will be submitted this year.

Model Fitting



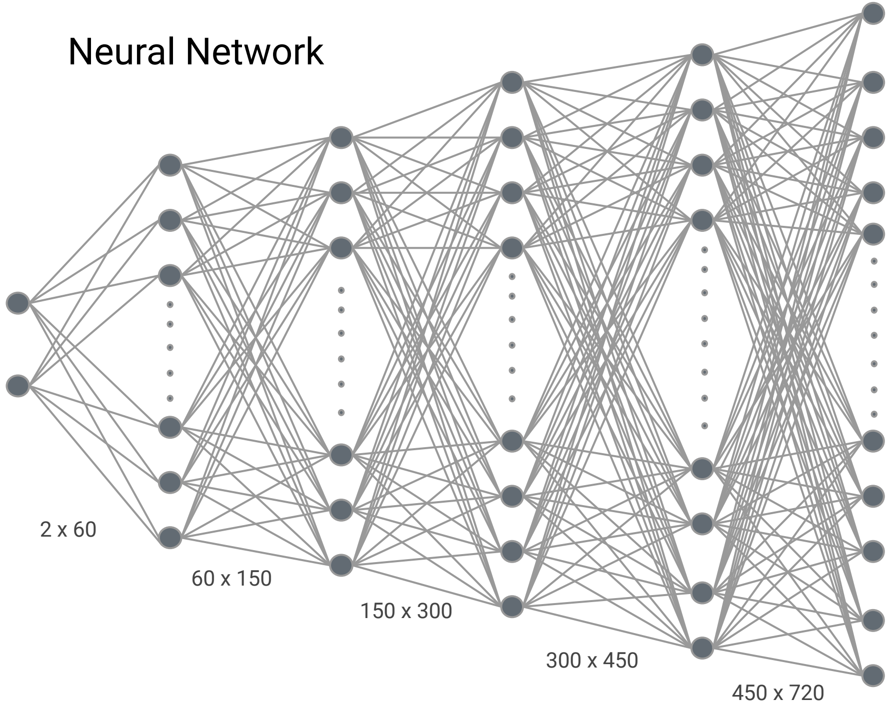
To get the best fit between the model and the observation we use Chi-square minimisation method.

This done by changing the values of free parameters (Teff, log g and angular diameter) before each iteration and valuation chi square.

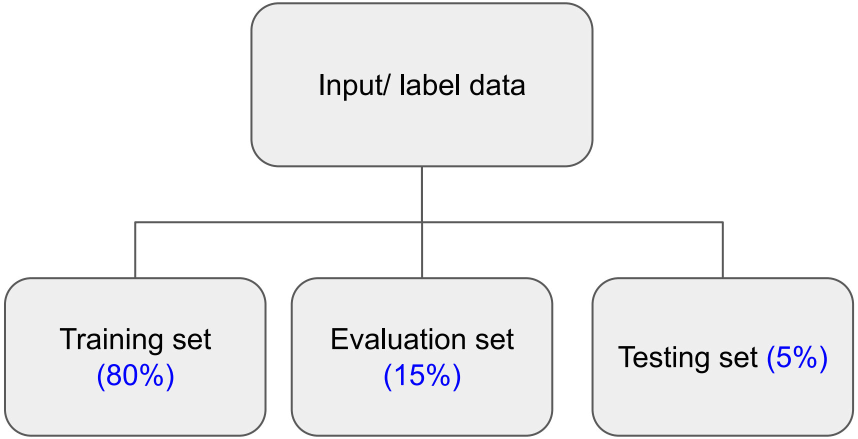
In addition we use MCMC on the fitting to get better sampling over the results.

Machine Learning

Neural Network

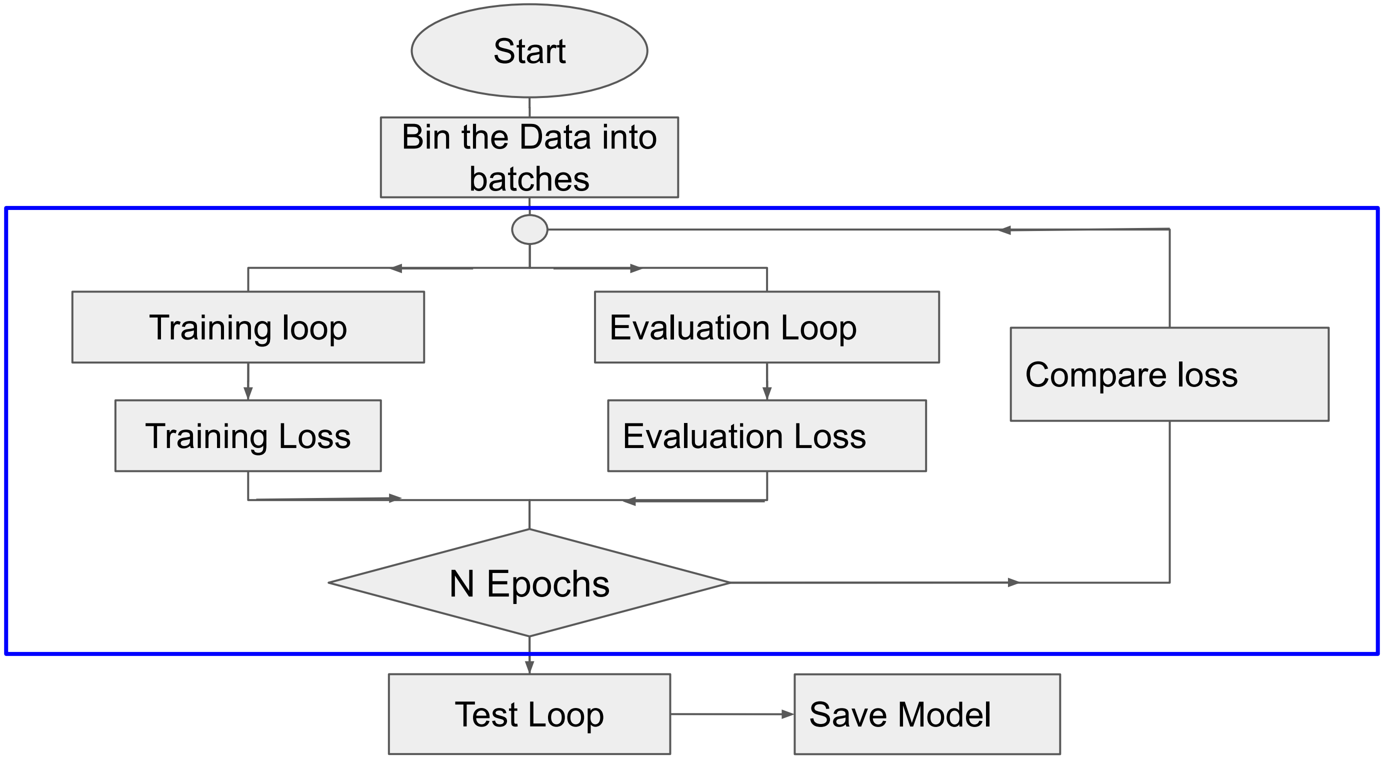


Input Data

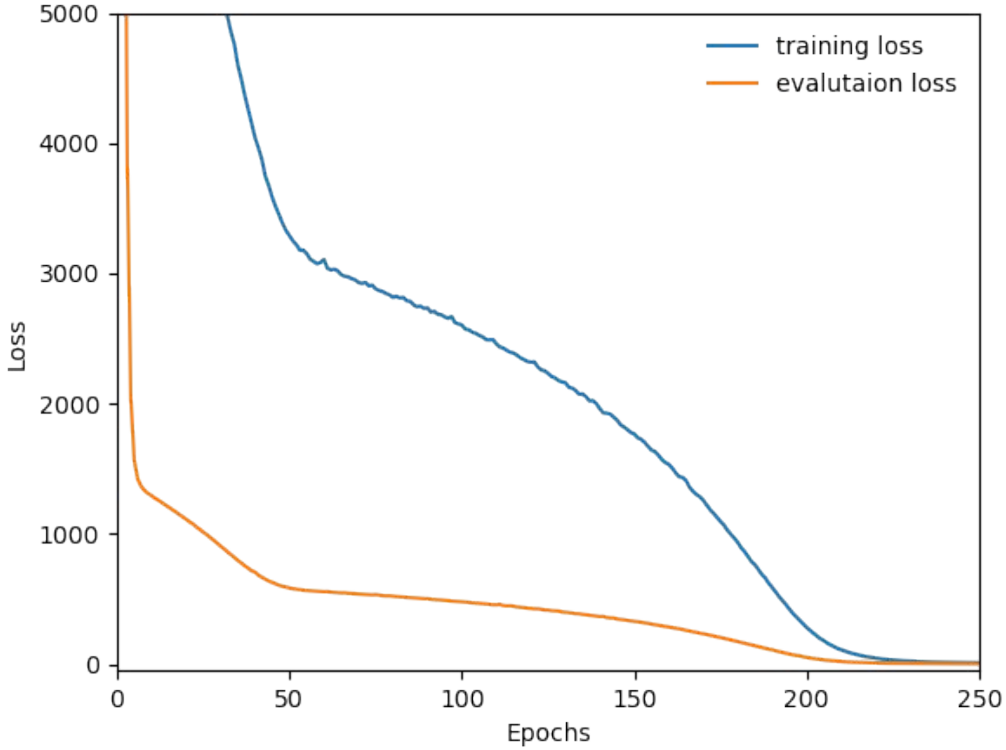


Machine Learning

Learning loop



Machine Learning



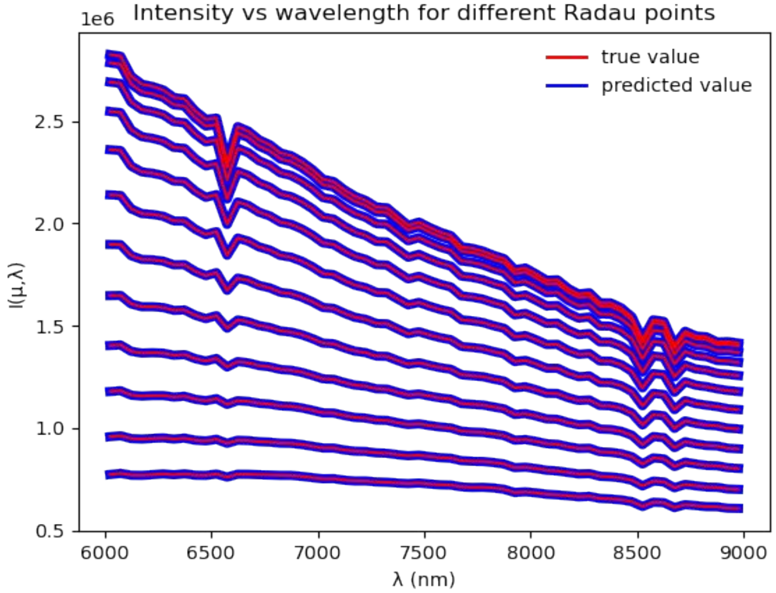
Neural network using Pytorch

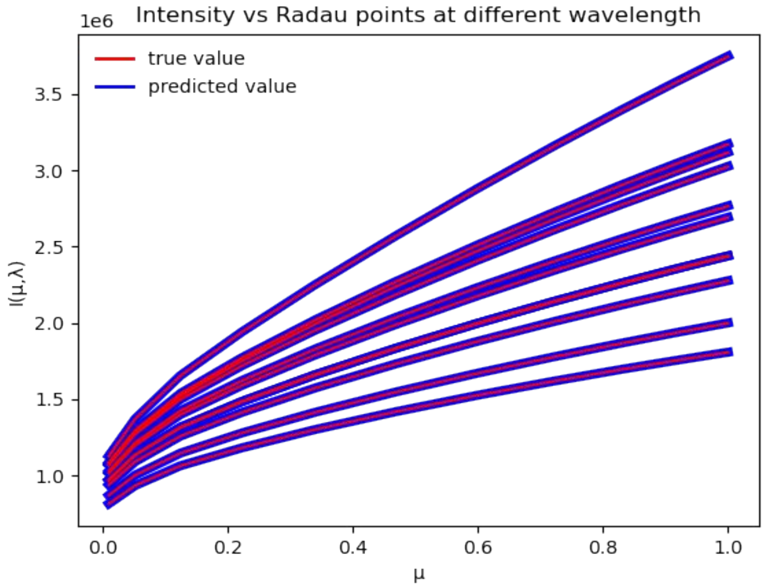
Learning Rate = 1e-5
Epoch = 10000
Loss <.01%

The blue line shows the loss from the neural network training at each epoch.

The orange line depicts the loss from in the evaluation of the NN training at each epoch

Machine Learning



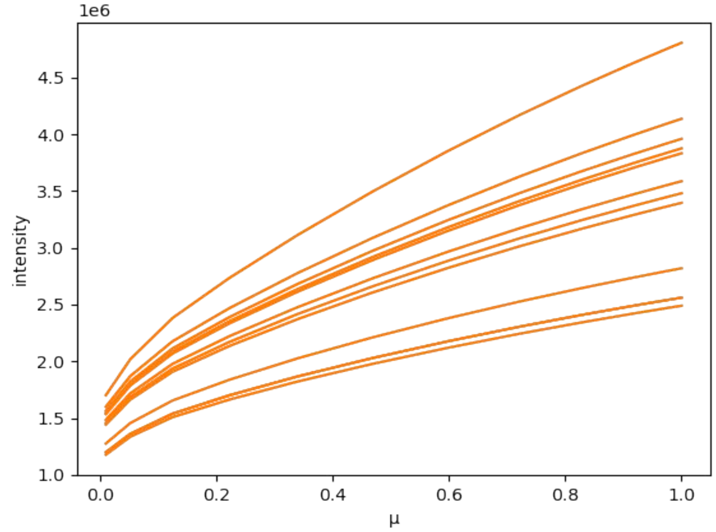


(left) true values (red) of intensity overplotted on the predicted values (blue) from the test set (taken in random) for 12 different Radau points as a function of wavelength and (right) same intensities for different wavelength as function of Radau points.

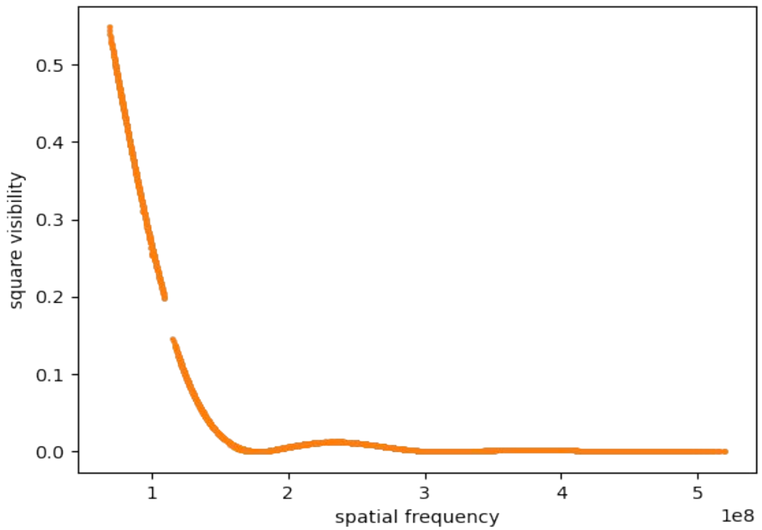
Star Model

With the intensity profile, we can get the square visibility of the star by taking the Fourier transform.

As it has spherical symmetry, we can easily replace the Fourier transform with Hankel transform and square it to get the square visibility.

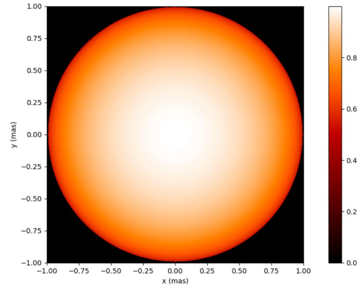


Hankel Transform

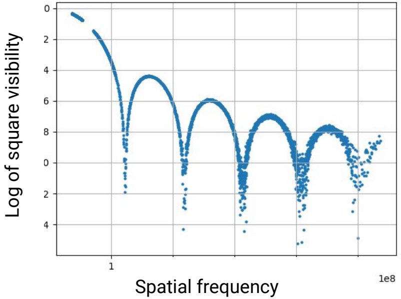


η Boo

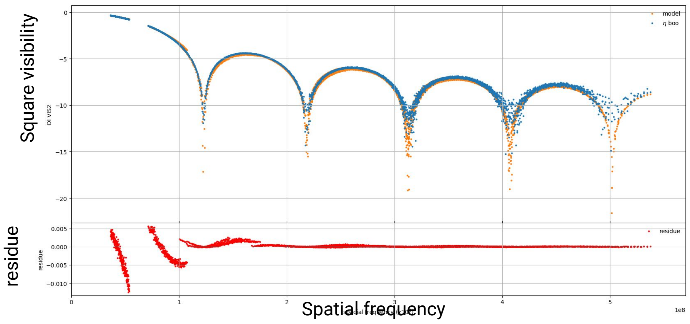
For η Boo



Angular Diameter - 2.179 mas,
Teff - 6099 K, log g - 3.79 dex

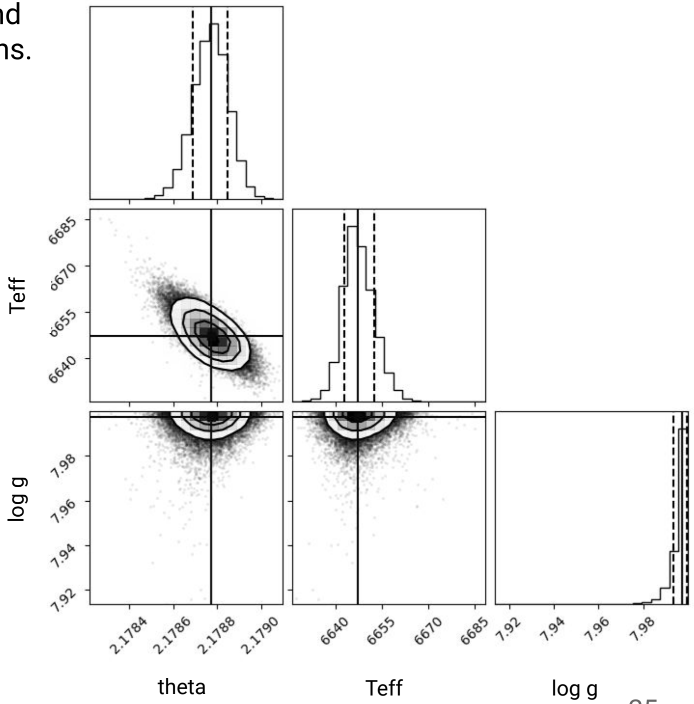


The fitting is done using chi-square fitting methods and multiple iteration is carried out using MCMC simulations.

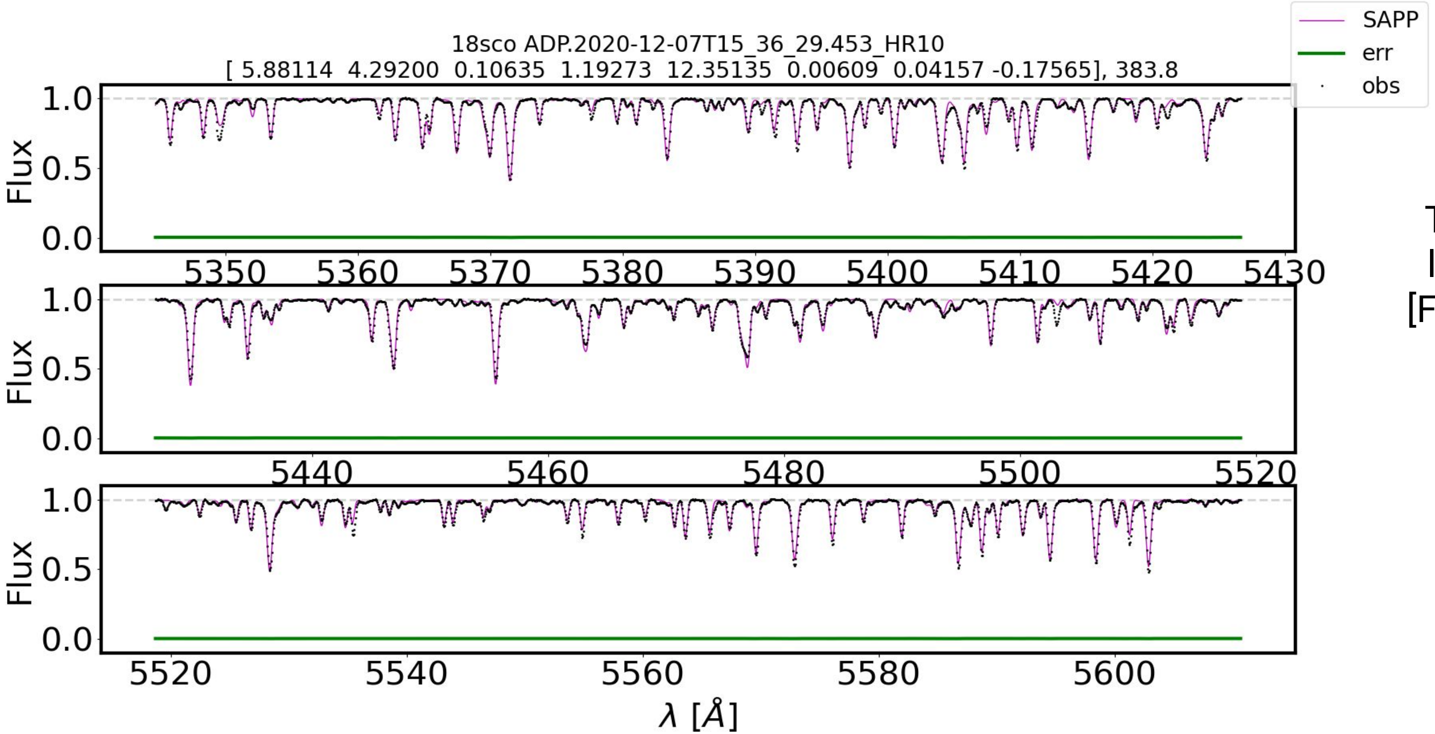


Fitted parameters

Angular diameter = 2.17877 ± 0.00081 mas
T_{eff} = 6647 ± 54.6 K
Log g = 7.9975 ± 0.0038 dex



Spectroscopy



Fitted parameters

Teff - 5881.14 ± 2.46

log g - 4.292 ± .0032

[Fe/H] - 0.1064 ± .0015

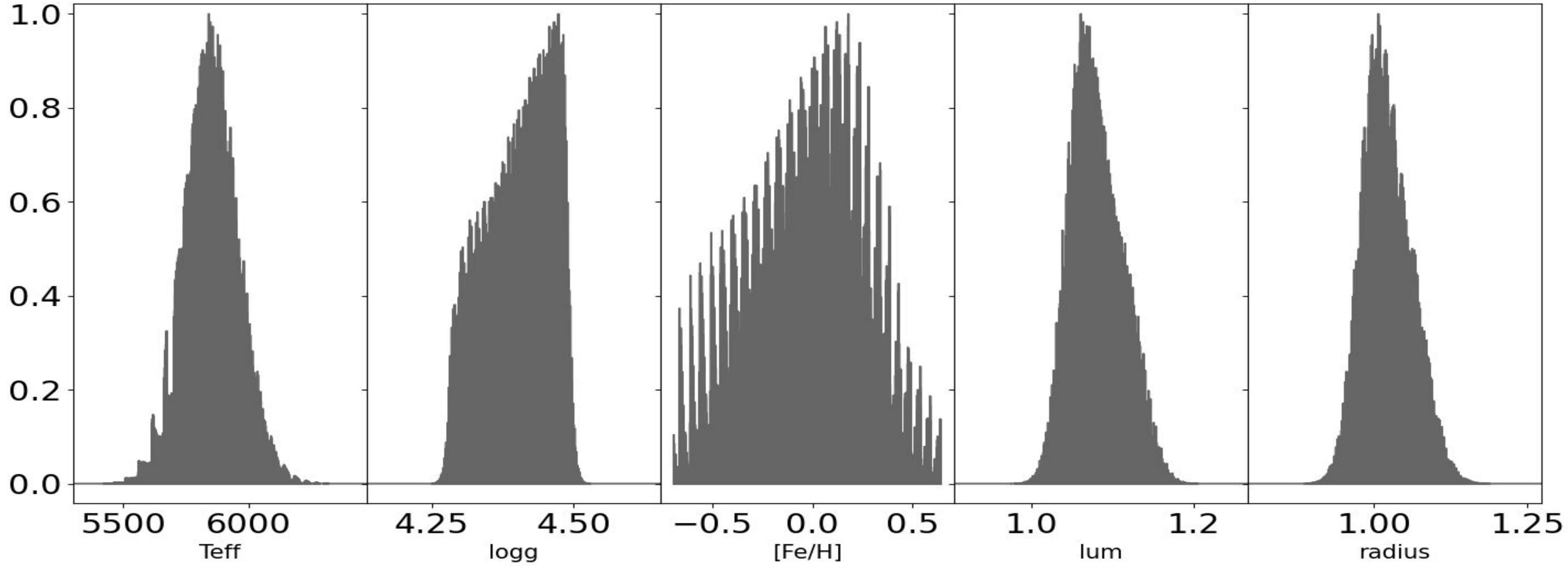
Draft paper in progress

Optimized use of spectroscopy, interferometry, and stellar atmosphere models for the determination of fundamental parameters of stars

Paper to be submitted within the framework of PLATO, with the below contents

1. General introduction on stellar parameters and the proposed method
2. From the MARCS grid to the intensity profiles with ML (discussion of models is needed)
3. Fit of synthetic interferometric data (hopefully with actual data before the summer) □ limitations
4. Inclusion of the interferometric pipeline in the general SAPP pipeline, and combination of spectroscopy and photometry for an optimized determination of R, Teff, log

18 Sco



5826.36 ±104.01 K | 4.408 ± 0.053 dex | -0.0886 ± .2746 | 1.0831 ± 0.0271 $L_\odot$ | 1.0093 ± 0.034 $R_\odot$