MEGAPOPSTAR: HIGH-SPECTRAL RESOLUTION EVOLUTIONARY SYNTHESIS MODELS USING THE MEGASTAR EMPIRICAL LIBRARY

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ABSTRACT

- MEGARA is the optical integral field and multi-object fibre-based spectrograph for the 10.4m Gran Telescopio Canarias that offers medium-to-high spectral resolutions (FWHM) of R=6000, 12000, and 20000.
- We have created MEGASTAR an instrument-oriented **empirical stellar spectral library** observed with MEGARA-GTC at high-resolution R=20000 (HR-R and HR-I VPH-grating configurations).
- To correctly interpret the observations of galaxies and stellar clusters obtained with this instrument, we aim to develop **an evolutionary synthesis model** to produce Spectral Energy Distributions for Simple Stellar Populations of different ages and metallicities by using MEGASTAR stellar spectra.
- To achieve this task we need **the stellar parameters**, namely effective temperature, surface gravity and metallicity for the stars in the library. This will allow us to associate, the stellar spectrum that better fit the theoretical parameters (Teff, and log g) of each point of the isochrone, selected according the metallicity.
- This work describes how we have performed this task for stars cooler than B2.

1. We present here the rectified spectra
2. We use a χ^2 technique: by comparing theoretical stellar models with the observed MEGASTAR spectra, we obtain their stellar parameters from the best fits.
3. We show preliminary predictions obtained with the evolutionary synthesis MegaPopStar model, using spectra from this MEGASTAR stellar library for Z_O metallicity and τ= 40 Myr without early-B, O and WR stars.

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MEGASTAR stellar spectral library - III. Estimating the stellar parameters for using in the MEGAPOPSTAR evolutionary synthesis model

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ABSTRACT

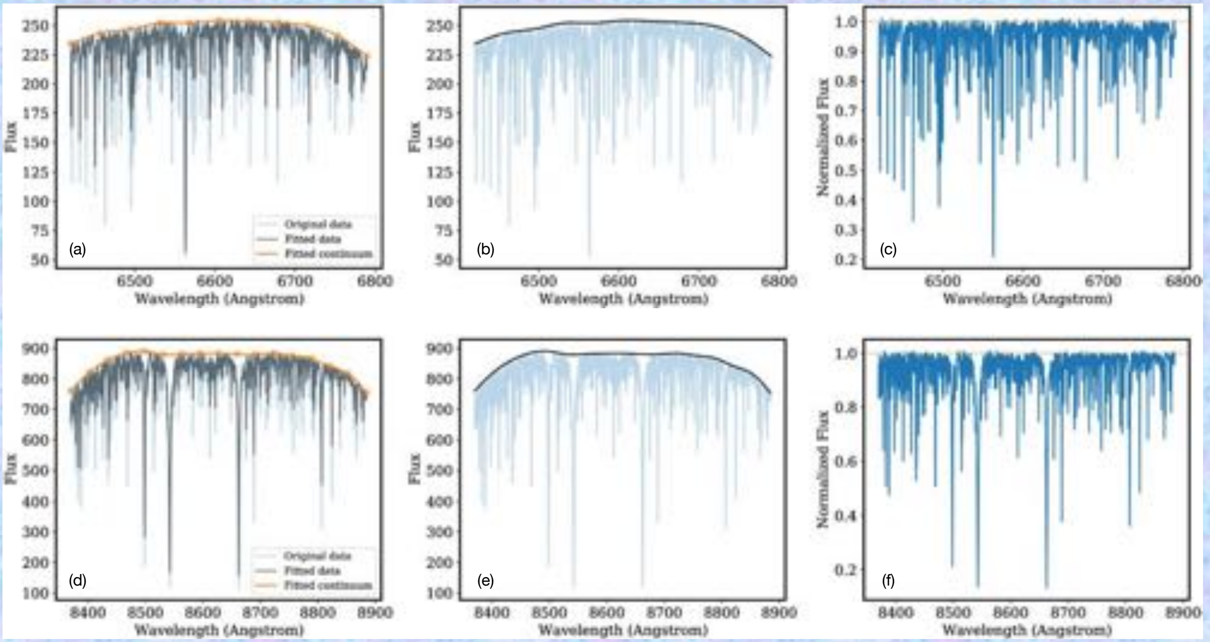
MEGARA is the optical integral field and multi-object fibre-based spectrograph for the 10.4m Gran Telescopio Canarias that offers medium-to-high spectral resolutions (FWHM) of $R \simeq 6\,000$, $12\,000$ and $20\,000$. We have created MEGASTAR, an instrument-oriented empirical stellar spectral library observed with MEGARA-GTC at high-resolution $R = 20\,000$ (HR-R and HR-I VPH-grating configurations). To correctly interpret the observations of galaxies and stellar clusters obtained with this instrument, we aim to develop an evolutionary synthesis model to produce Spectral Energy Distributions for Simple Stellar Populations of different ages and metallicities by using MEGASTAR stellar spectra. To achieve this task we need the stellar parameters, namely effective temperature, surface gravity and metallicity for the stars in the library. This will allow us to associate, once selected the most appropriate isochrone for the target metallicity, the stellar spectrum that better fit the theoretical parameters ($T_{\rm eff}$, and $\log g$) of a given point of the isochrone. This piece of work describes how we have performed this task for 349 stars (2 of them repeated) cooler than spectral type B2. We present here the rectified spectra (once divided by their best-fitted continuum), as MEGASTAR spectra are taken in filler-type GTC time so lack of an absolute flux calibration. We use a χ^2 technique with which, by comparing theoretical stellar models with the observed MEGASTAR spectra, we obtain their stellar parameters from the best fits. Finally, we show preliminary predictions obtained with the evolutionary synthesis MEGAPOPSTAR

1º To rectify the spectra with boundfit: finding the continuum to obtain a flat spectrum (Cardiel 2009)

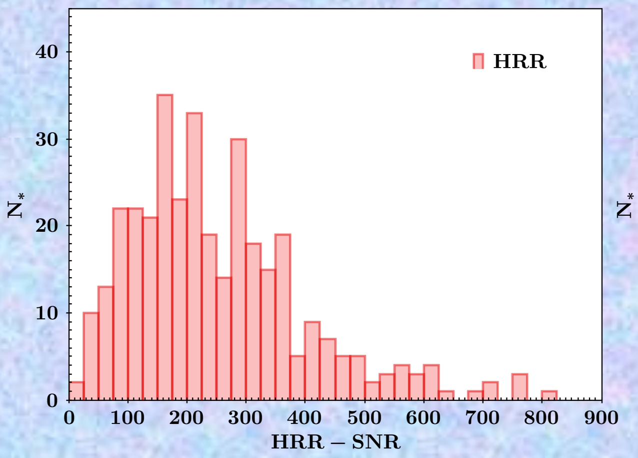
2º To compare with theoretical stellar spectra from Munari et al. (2005,MUN05), also rectified, to estimate the radial velocity and thus to correct them

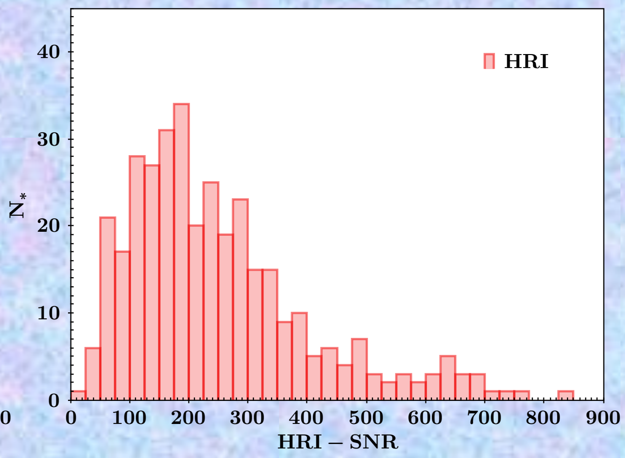
3º To do a fit with a χ^2 technique and find the best MUN05 model able to reproduce the observed spectrum. The SNR gives the uncertainty of the data

$$\chi^2 = \sum_{i=1}^{nl} \frac{[F_{\mathrm{mod}}(\lambda) - F_{\mathrm{obs}}(\lambda)]^2}{\sigma^2}$$

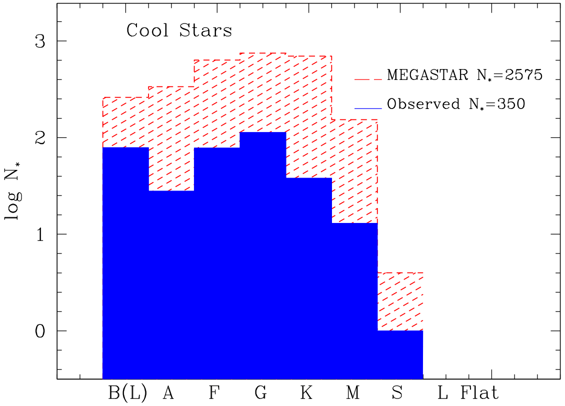


https://boundfit.readthedocs.io/en/latest/

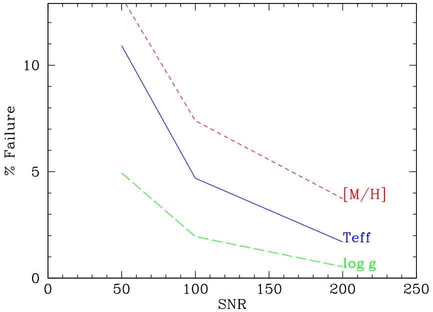


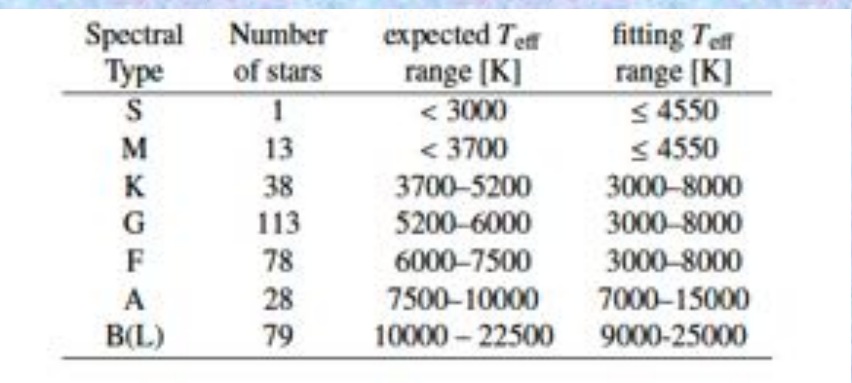


- Our sample: 351 stars from the DR1, spectral types cooler than B2



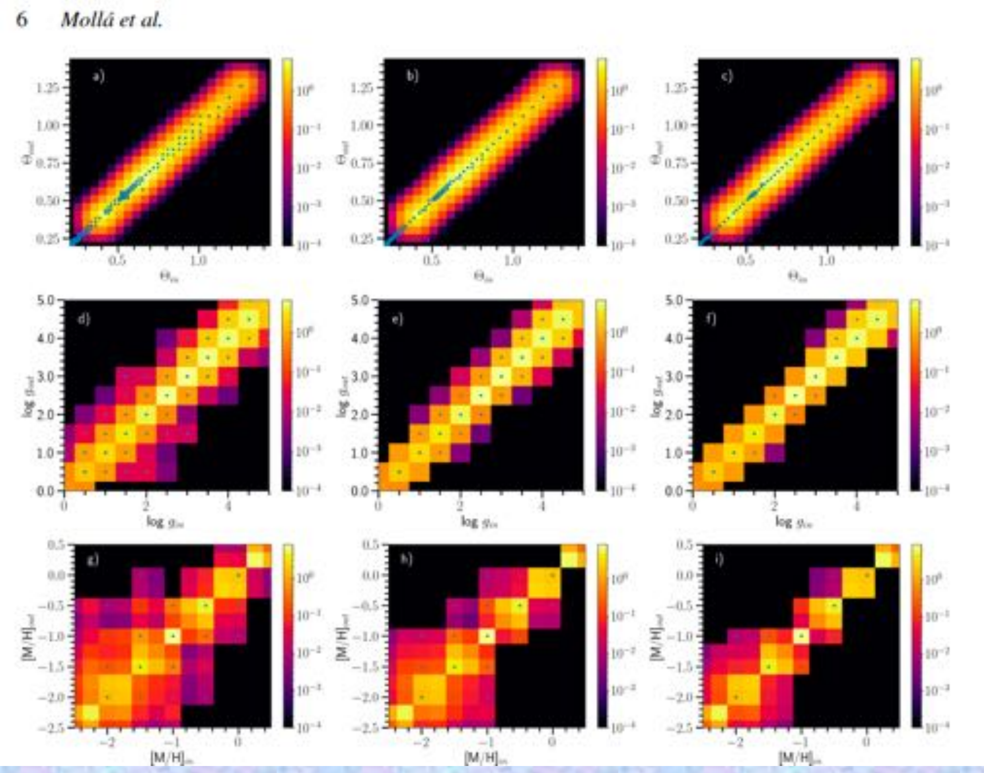
- Our code of fitting uses the MUN05 models with different temperaturas following the spectral type of stars
- We have first applied the method to the same MUN05 models, after to be added noise according different SNR=50,100 and 200





Spectral Type	Number of stars	expected $T_{\rm eff}$ range [K]	fitting $T_{\rm eff}$ range [K]
S	1	< 3000	≤ 4550
M	13	< 3700	≤ 4550
K	38	3700–5200	3000–8000
G	113	5200–6000	3000–8000
F	78	6000–7500	3000–8000
A	28	7500–10000	7000–15000
B(L)	79	10000 – 22500	9000-25000

SNR=50 **SNR=100** **SNR=200**



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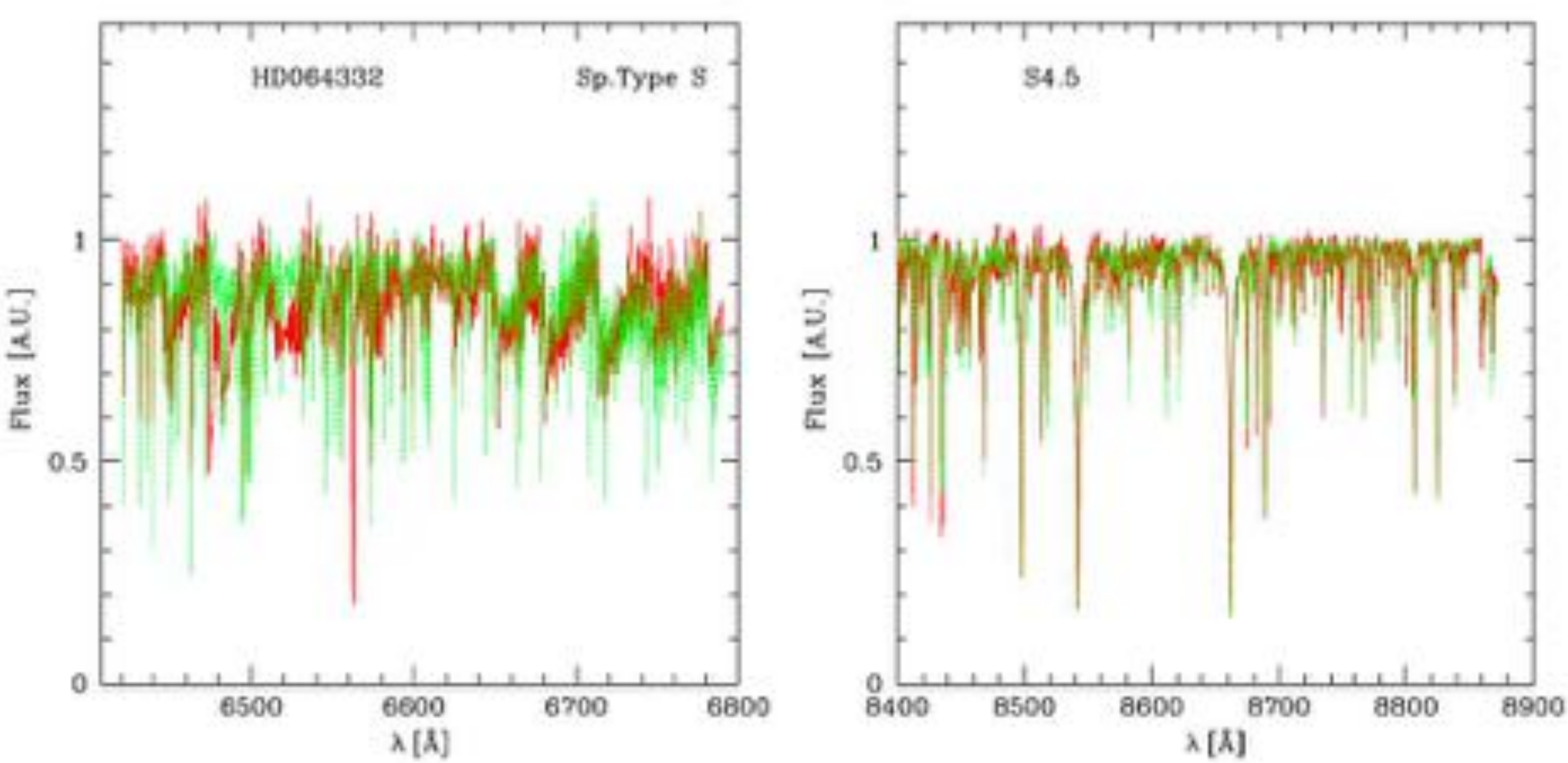
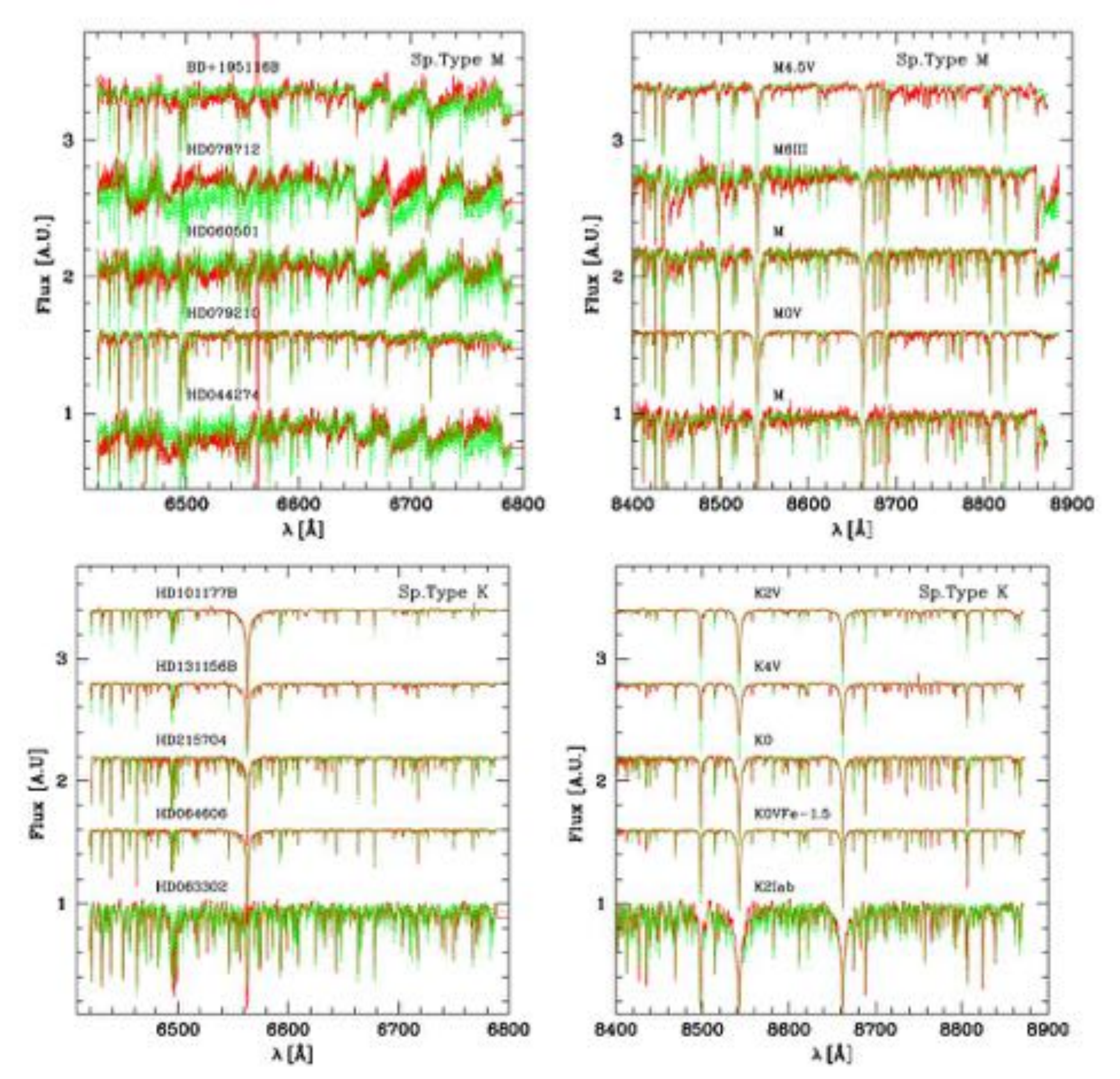
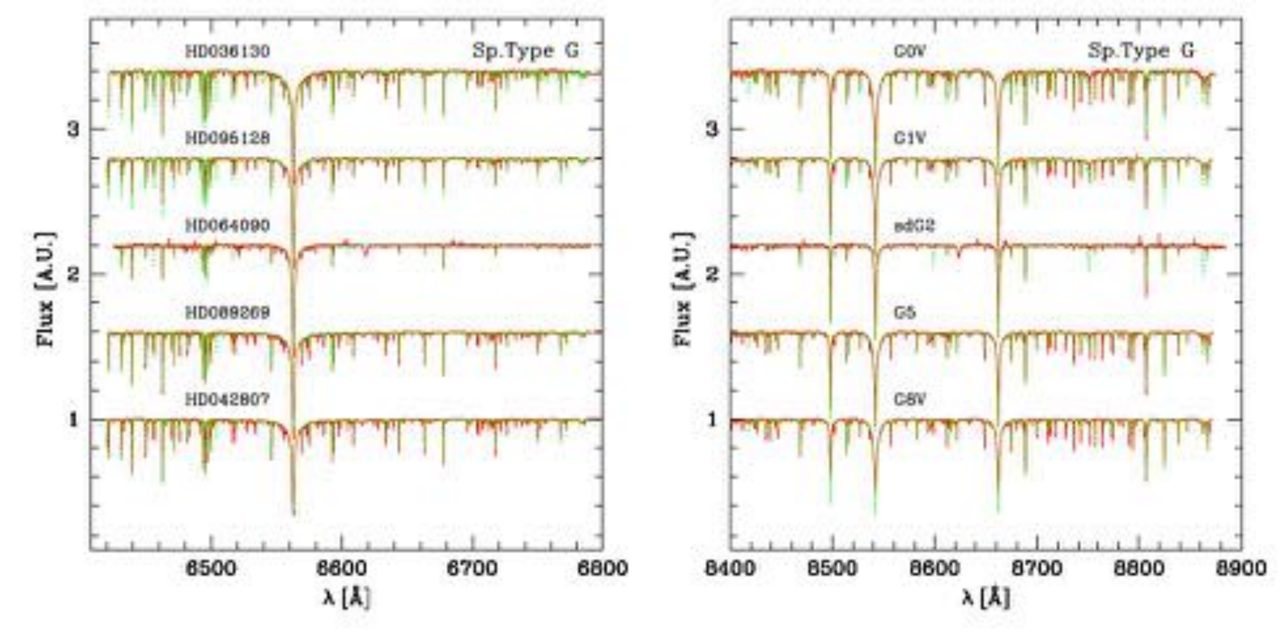
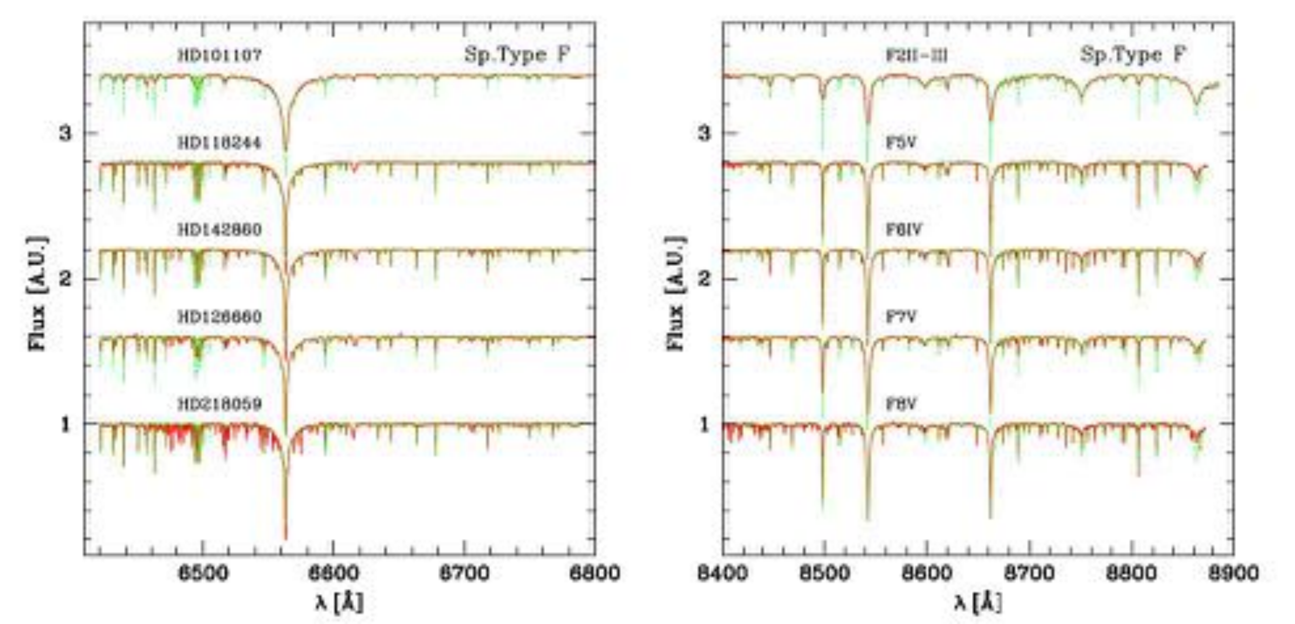
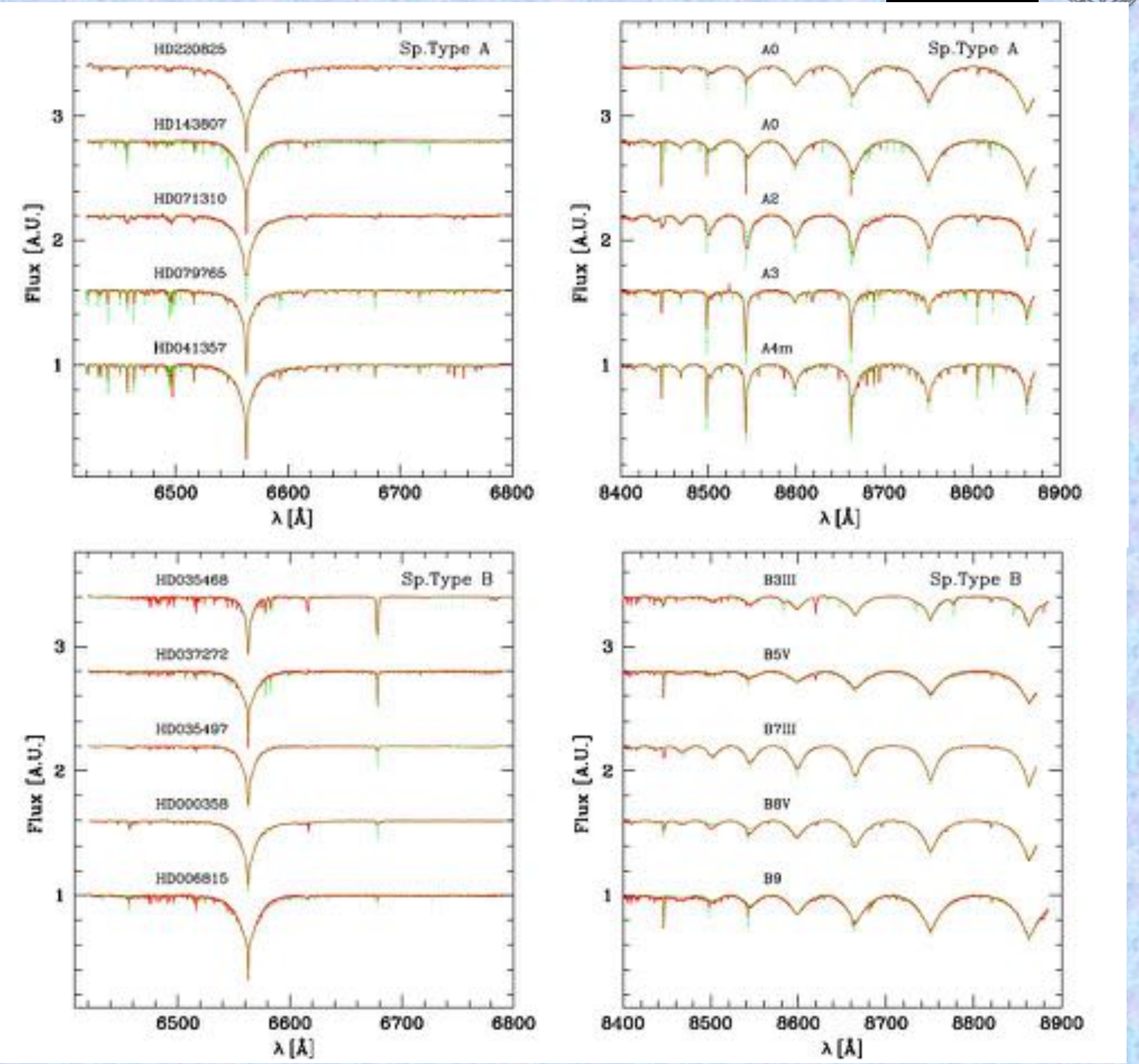
OUR FITS ALONG THE SEQUENCE OF SPECTRAL TYPES:




BD+195116B
Sp.Type M
HD078712
HD060501
HD079210
HD044274
3
2
1
Flux [A.U.]
6500
6600
6700
6800
λ [Å]
M4.5V
Sp.Type M
M6III
M
M0V
M
8400
8500
8600
8700
8800
8900
HD101177B
Sp.Type K
HD131156B
HD215704
HD064606
HD063302
K2V
Sp.Type K
K4V
K0
K0VFe-1.5
K2Iab


HD036130
HD095128
HD064090
HD089269
HD042807
Sp.Type G
Flux [A.U.]
1
2
3
6500
6600
6700
6800
λ [Å]
G0V
G1V
sdG2
G5
G8V
Sp.Type G
Flux [A.U.]
1
2
3
8400
8500
8600
8700
8800
8900
λ [Å]


HD101107
HD118244
HD142860
HD126660
HD218059
Sp.Type F
Flux [A.U.]
1
2
3
6500
6600
6700
6800
λ [Å]
F2II-III
F5V
F6IV
F7V
F8V
Sp.Type F
Flux [A.U.]
1
2
3
8400
8500
8600
8700
8800
8900
λ [Å]


HD220825
Sp.Type A
HD143807
HD071310
HD079765
HD041357
Flux [A.U.]
3
2
1
6500
6600
6700
6800
λ [Å]
A0
Sp.Type A
A0
A2
A3
A4m
8400
8500
8600
8700
8800
8900
HD035468
Sp.Type B
HD037272
HD035497
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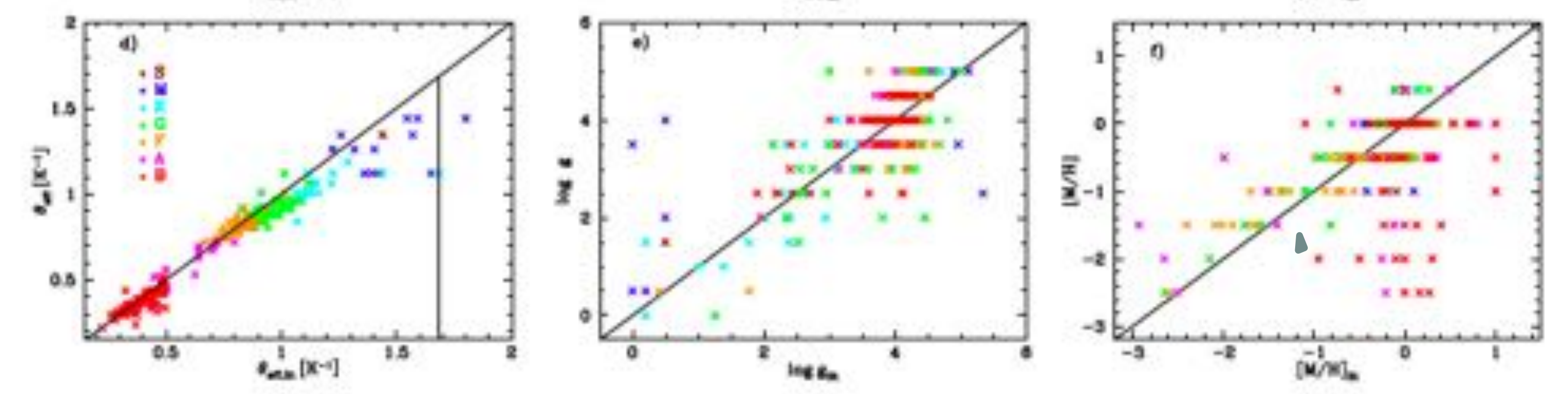
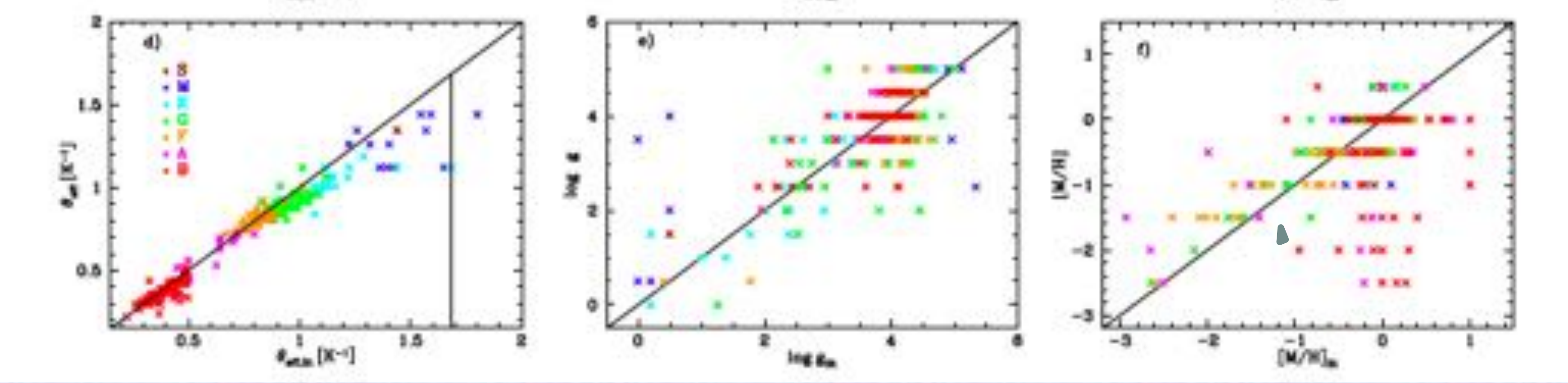
B3III
Sp.Type B
B5V
B7III
B8V
B9



- Good results for Teff except for the coolest stars that do not exist in MUN05 (Teff < 3500)
- Worst estimates for log g and [M/H]
- In particular, we find lower metallicities for a set of stars with solar values in the literature

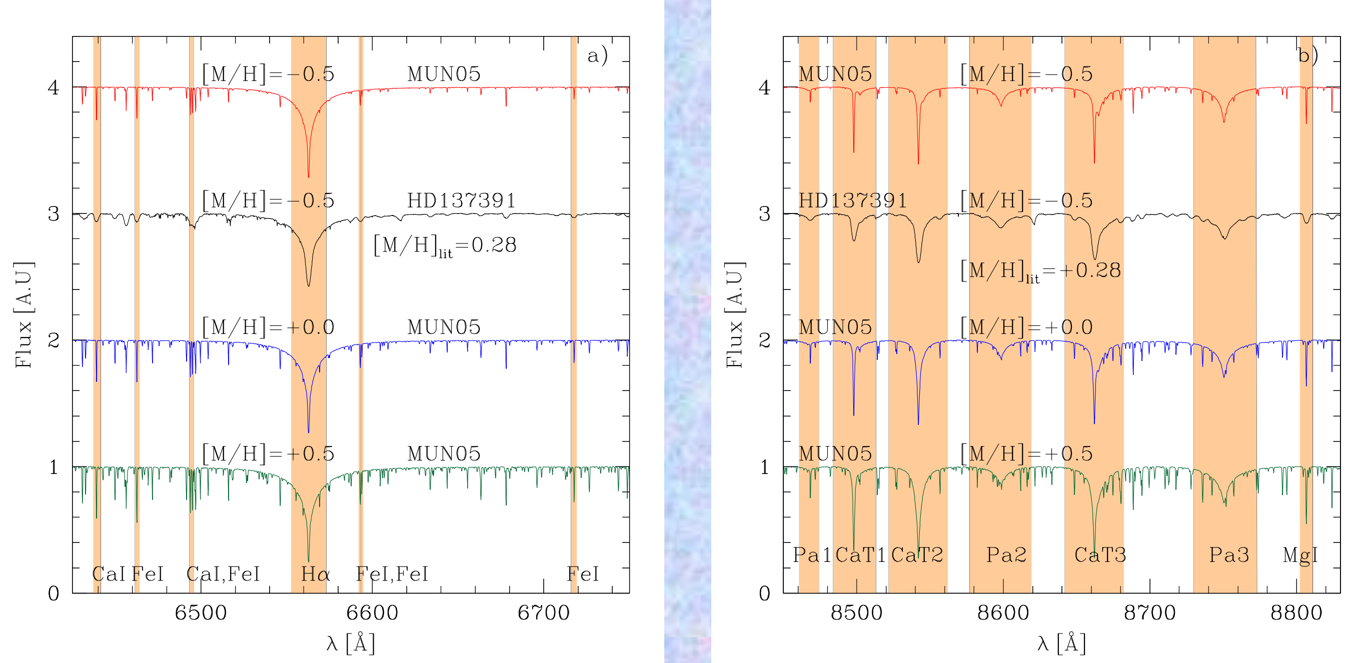
Table 2. Stellar Parameters as obtained from our best fits to Munari models using both HR-R and HR-I setups. The complete table for the 350 stars of our subsample is given online. The star name is in (1): the stellar parameters, effective temperature, T_{eff}, in K units, gravity log g and metallicity [M/H], as found in the literature –when available– are in (2),(3) and (4): the spectral type is in (5), the radial velocity and its error in (6) and (7), the signal-to-nois in HR-R and HR-I set-ups are in (8) and (9): The stellar parameters effective temperature, T_{eff}, in K units, gravity log g and metallicity [M/H], obtained by the χ^2 technique are in columns (10), (11) and (12); the χ^2_{min} is in (13): The associated likehood L is in (14); In (15) there is the number of wavelengths used in each stellar fit: The number of models with similar L and the minimum χ^2_{min} is in (16): The stellar parameters, effective temperature, T_{eff}, in K units, gravity log g and metallicity [M/H], with their corresponding errors, obtained as averaged of those models are in columns (17) to (22).

Name (1)	T_{eff} literature (2)	log g literature (3)	[M/H] literature (4)	Sp. Type (5)	Rvel ±Δ (6) (7)	SNR HRR (8)	SNR HRI (9)	T_{eff} minimum χ^2 (10)	log g minimum χ^2 (11)	[M/H] minimum χ^2 (12)	$\chi^2_{min,red}$ (13)	L (14)	N_λ (15)	N_M (16)	(T_{eff} ± Δ) averaged (17) (18)	(log g ± Δ) averaged (19) (20)	([M/H] ± Δ) averaged (21) (22)
BD-032525	5750	3.60	−1.90	F5	41.3 ± 0.8	151.9	124.1	6250	5.0	−1.5	0.0356	99.8	7721	247	5750 ± 375	3.50 ± 1.25	−2.00 ± 0.50
BD-122669	6855	4.00	−1.41	A5	48.7 ± 0.7	103.8	89.2	7000	5.0	−1.5	0.0285	99.9	7718	57	7250 ± 250	4.50 ± 0.50	−1.50 ± 0.50
BD+083095	5728	4.12	−0.36	G0V	−85.0 ± 0.3	97.8	114.7	6000	4.0	−0.5	0.0479	99.7	7703	209	5500 ± 375	3.00 ± 1.25	−1.00 ± 0.50
BD+092190	6316	4.56	−2.93	A0	256.3 ± 0.1	124.0	128.3	7000	5.0	−1.5	0.0654	99.6	7622	31	7000 ± 125	4.50 ± 0.50	−1.50 ± 0.50
BD+200603	6121	4.32	−2.09	F0	−208.2 ± 0.7	208.5	199.7	6250	4.5	−1.5	0.0409	99.8	7623	158	6000 ± 375	3.50 ± 1.00	−2.00 ± 0.50
BD+262606	...	...	...	A5V	4.6 ± 0.1	373.9	173.5	7000	5.0	−1.5	0.0989	99.2	7737	16	7000 ± 125	5.00 ± 0.25	−1.50 ± 0.50
HD017081	15320	3.64	0.03	B7IV	7.5 ± 0.3	413.2	428.4	15000	4.0	+0.0	0.1050	99.1	7737	40	14000 ± 500	4.00 ± 0.25	−1.00 ± 0.75



- Good results for Teff except for the coolest stars that do not exist in MUN05 (Teff > 3500)
- Worst estimates for log g and [M/H]
- In particular, we find lower metallicities for a set of stars with solar values in the literature

1. The literature gives [M/H]=+0.28 dex
2. We find [M/H]=-0.5 dex
3. Following the sequence in metallicity, our results are more probable



SPECTRAL LINES AND STELLAR INDICES

- We have measuredin HR-I some classical equivalent widths or spectral indices as CaT, PaT or MgI
- HR also allows to us, to measure the equivalent widths of some other lines in HR-R

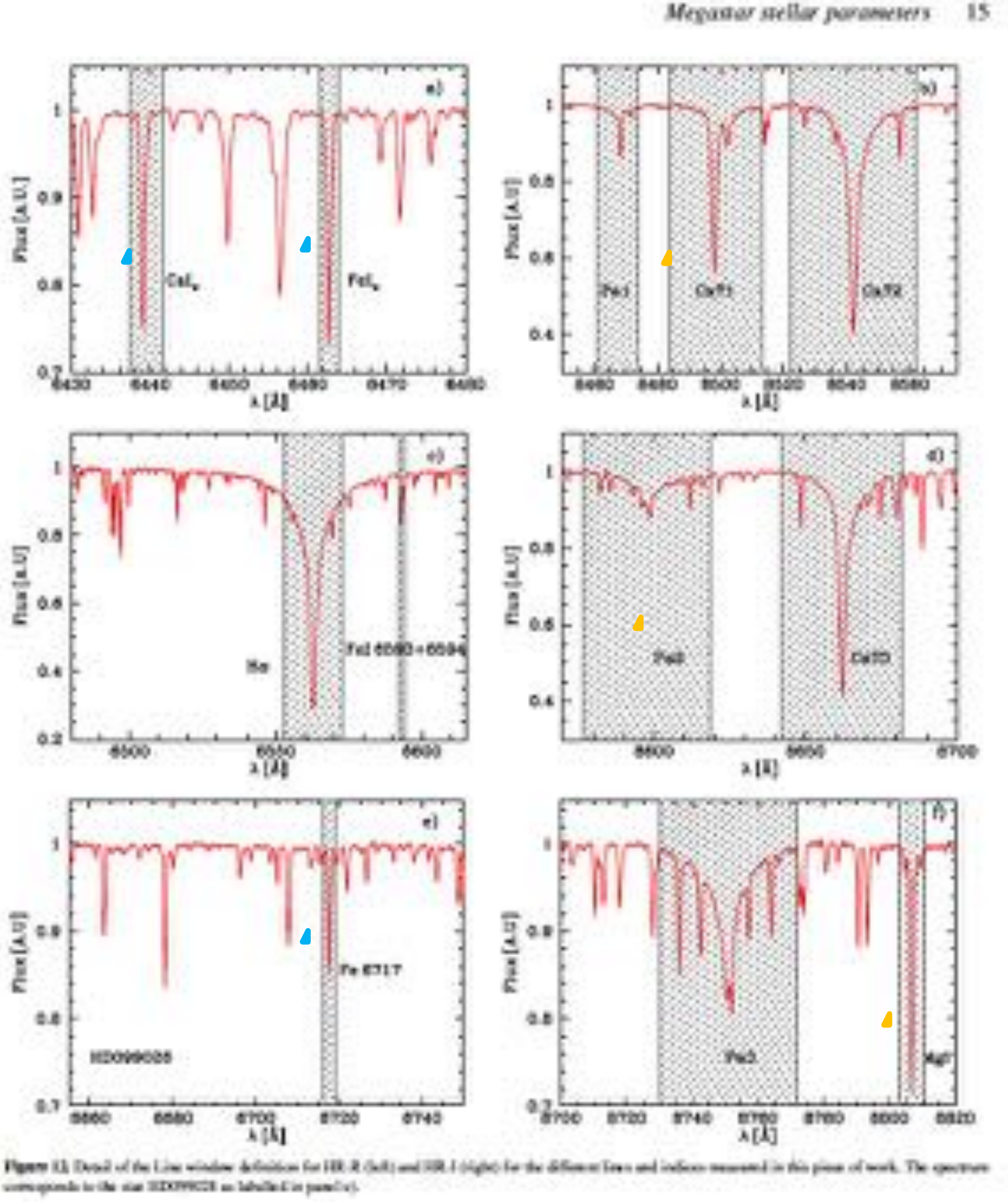


Figure 12. Detail of the Line window definition for HR-R (left) and HR-I (right) for the different lines and indices measured in this piece of work. The spectrum corresponds to the star HD099028 as labelled in panel (e).

- Variations with luminosity class

- Variations with spectral type

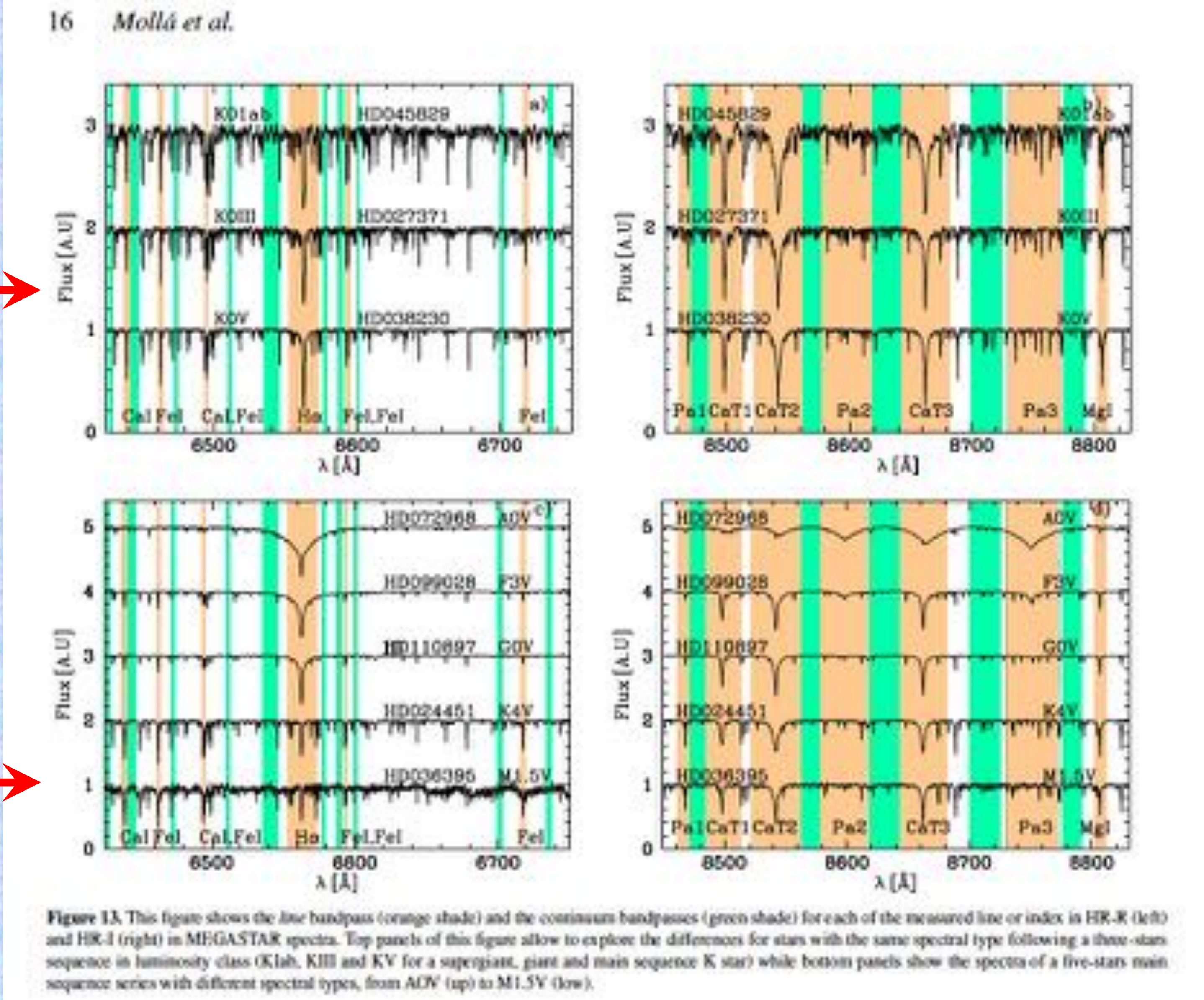

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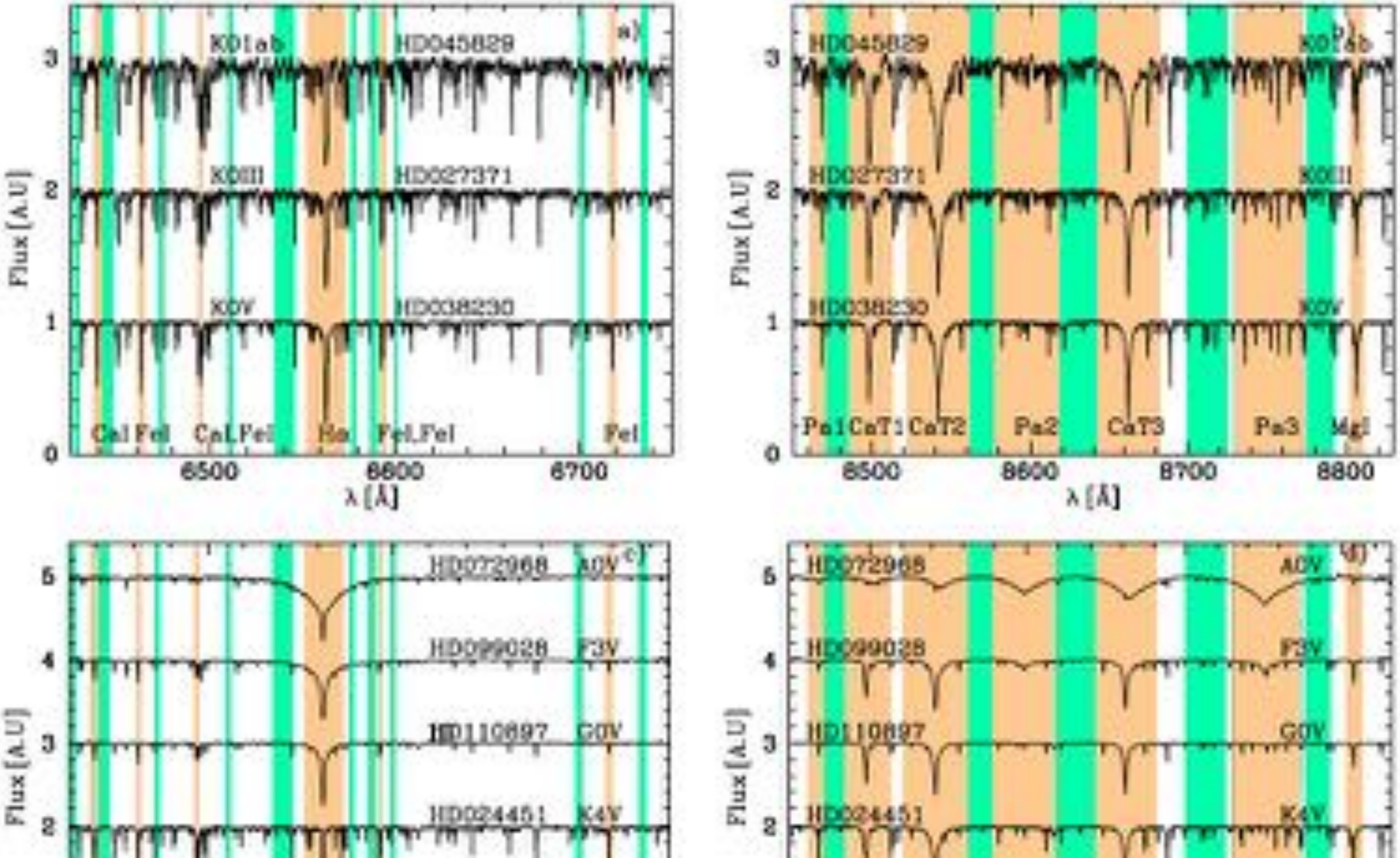
Figure 13. This figure shows the *line* bandpass (orange shade) and the continuum bandpasses (green shade) for each of the measured line or index in HR-R (left) and HR-I (right) in MEGASTAR spectra. Top panels of this figure allow to explore the differences for stars with the same spectral type following a three-stars sequence in luminosity class (KIab, KIII and KV for a supergiant, giant and main sequence K star) while bottom panels show the spectra of a five-stars main sequence series with different spectral types, from A0V (up) to M1.5V (low).


a)
K0Iab HD045829
K0III HD027371
K0V HD038230
CaI FeI CaI,FeI Hα FeI,FeI FeI
b)
HD045829 K0Iab
HD027371 K0III
HD038230 K0V
Pa1 CaT1 CaT2 Pa2 CaT3 Pa3 MgI
c)
HD072968 A0V
HD099028 F3V
HD110897 G0V
HD024451 K4V
d)
HD072968 A0V
HD099028 F3V
HD110897 G0V
HD024451 K4V
Flux [A.U]
λ [Å]
6500
6600
6700
8500
8600
8700
8800
0
1
2
3
4
5

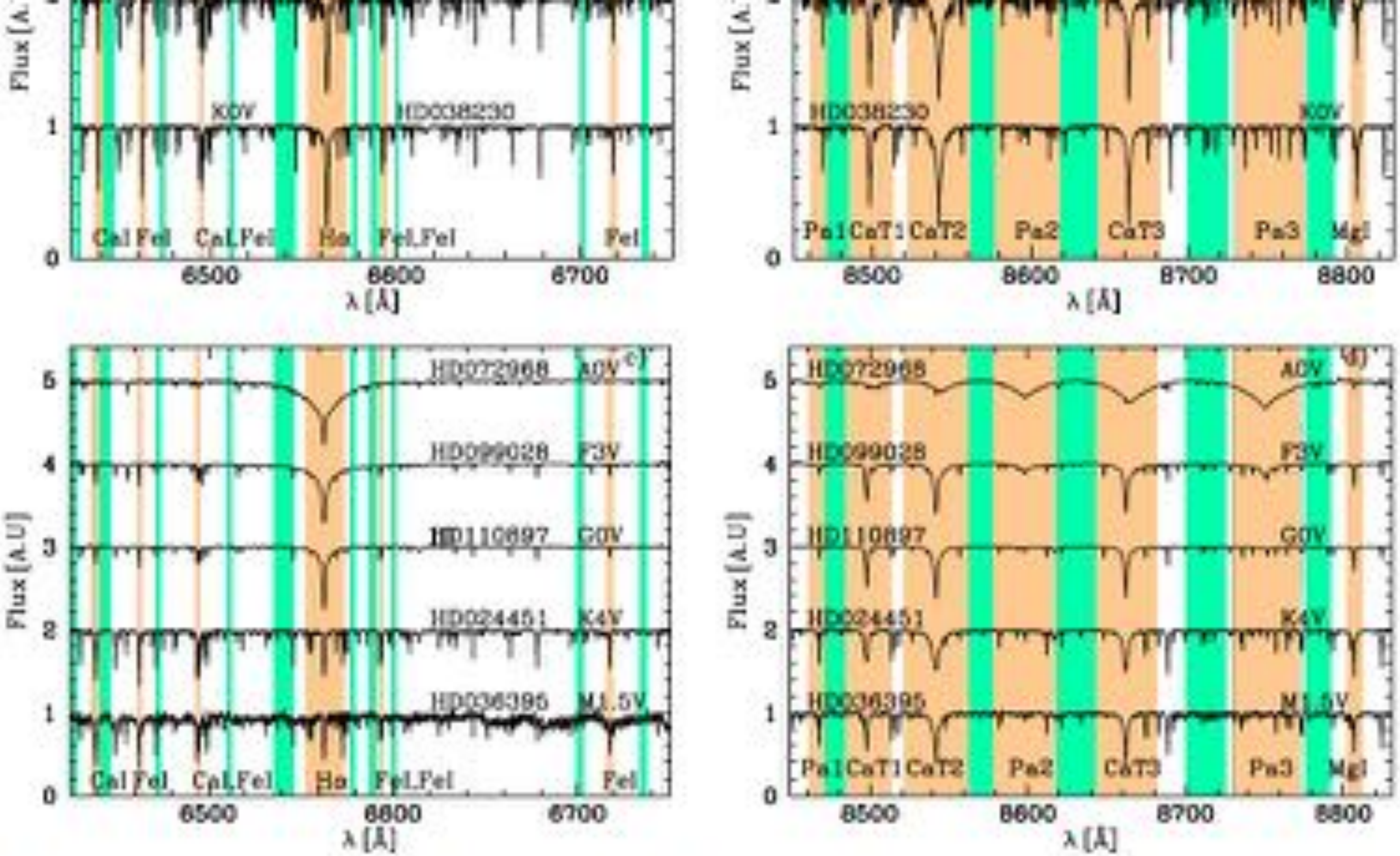
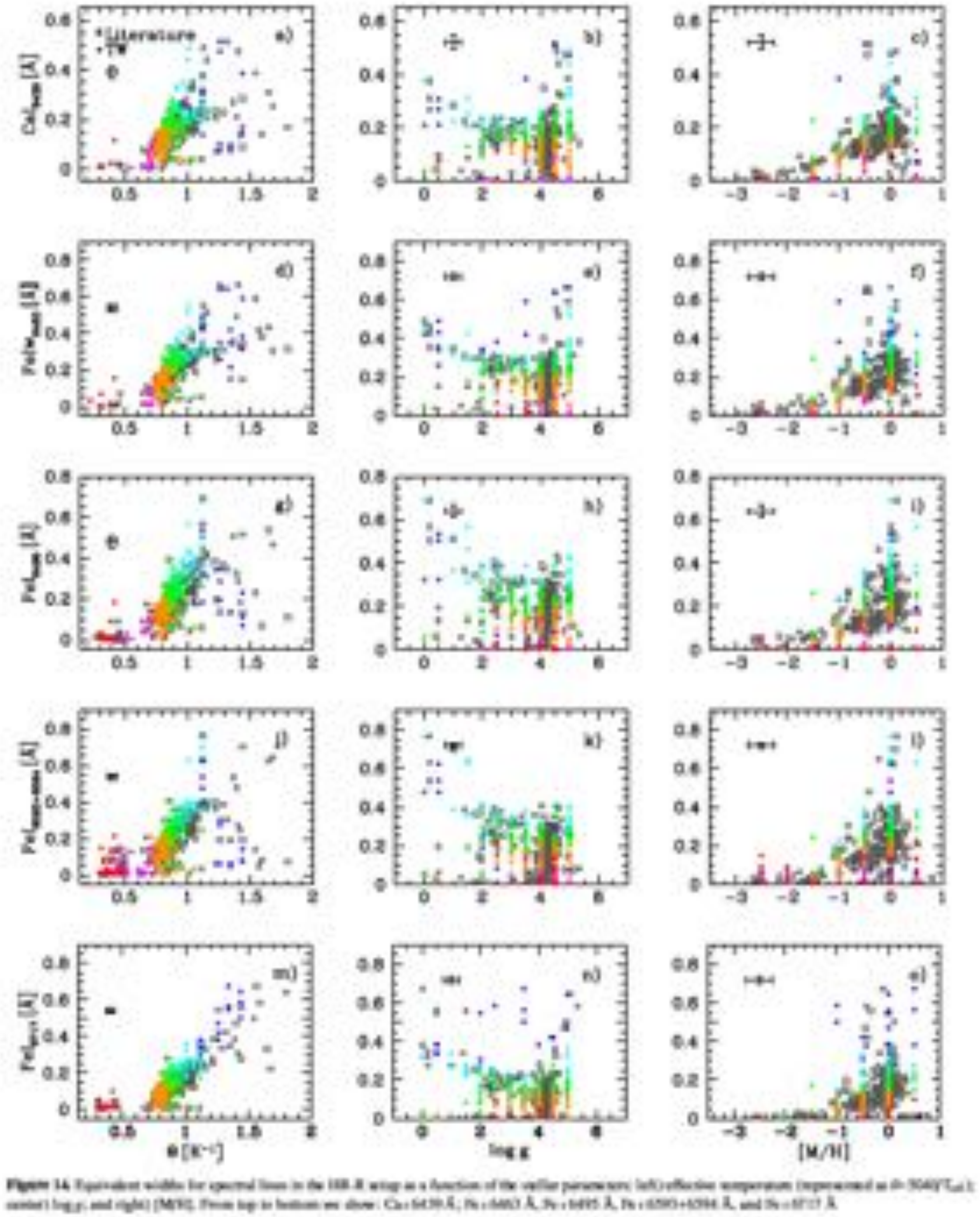


Figure 13. This figure shows the *line* bandpass (orange shade) and the continuum bandpasses (green shade) for each of the measured line or index in HR-R (left) and HR-I (right) in MEGASTAR spectra. Top panels of this figure allow to explore the differences for stars with the same spectral type following a three-stars sequence in luminosity class (KIab, KIII and KV for a supergiant, giant and main sequence K star) while bottom panels show the spectra of a five-stars main sequence series with different spectral types, from A0V (up) to M1.5V (low).


Literature
a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
k)
l)
m)
n)
o)
0.8
0.6
0.4
0.2
0
0.5
1
1.5
2
0
2
4
6
−3
−2
−1
0
1
θ [K⁻¹]
log g
[M/H]

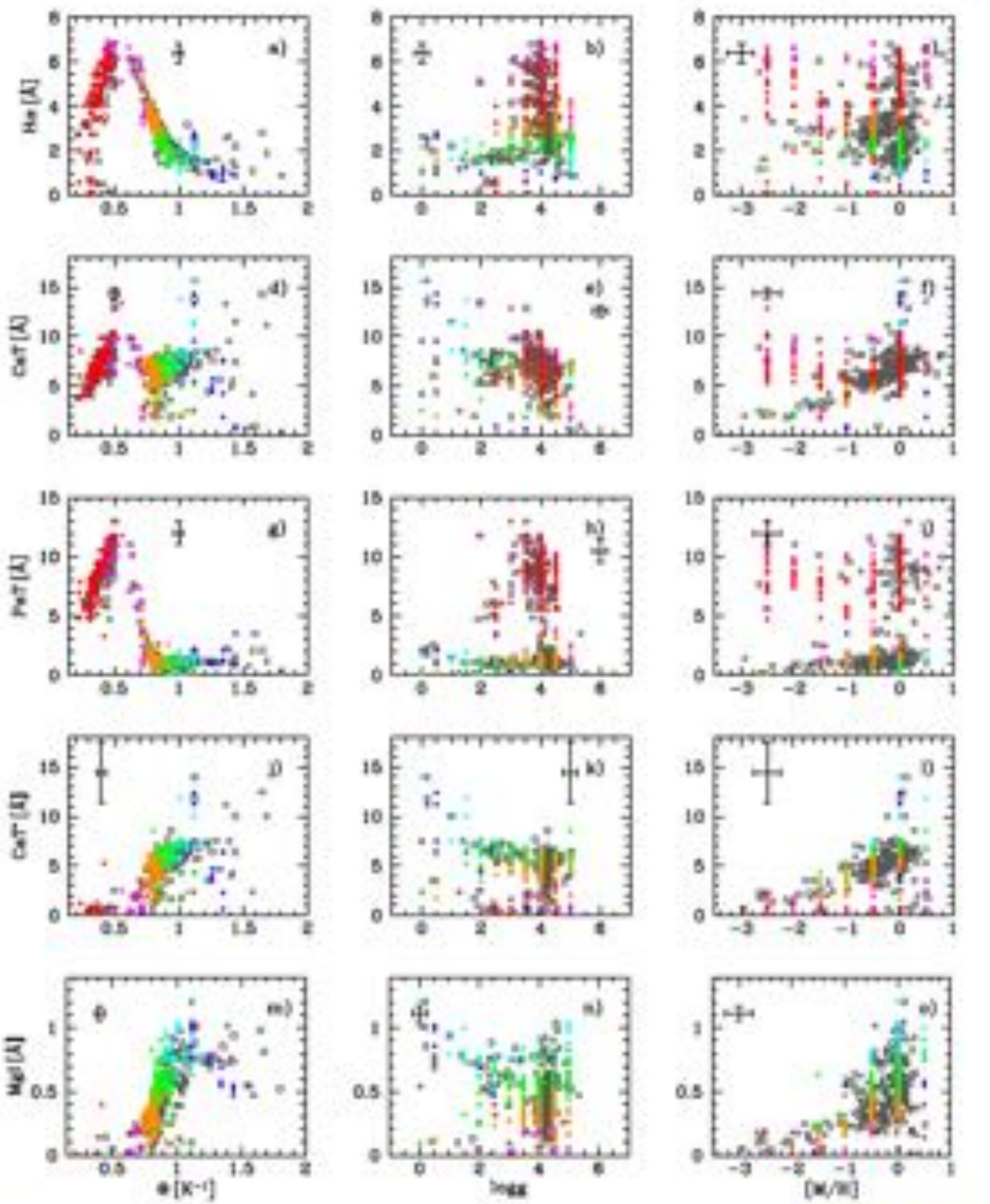
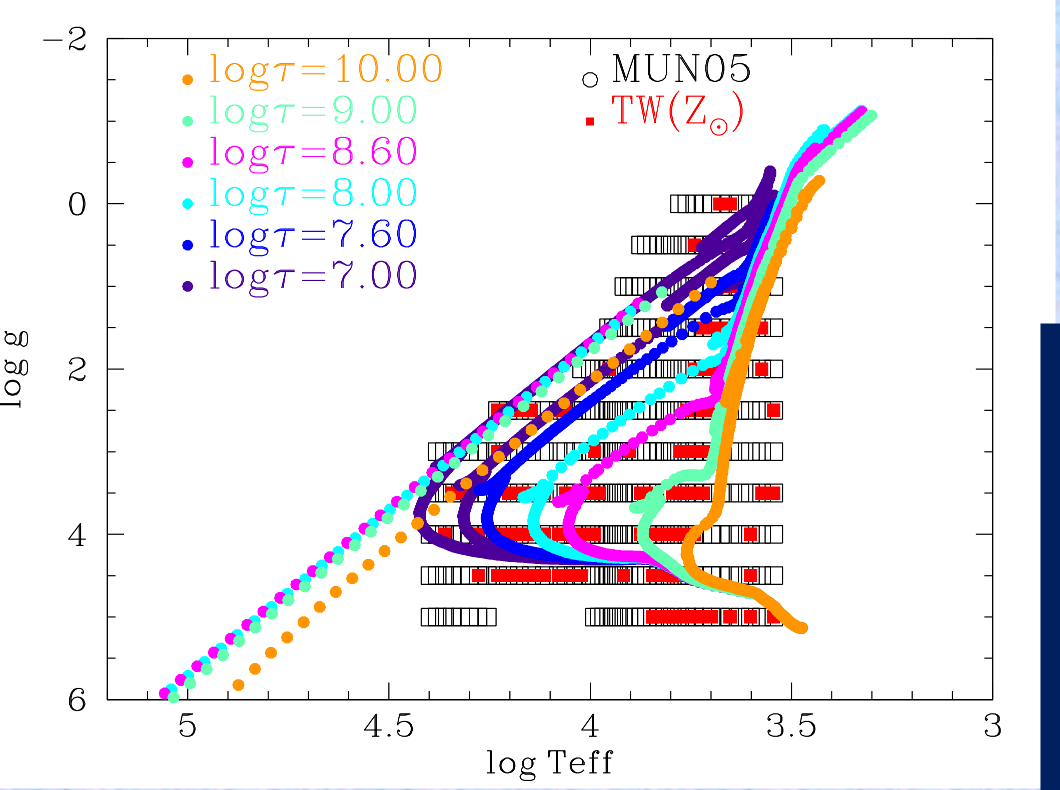


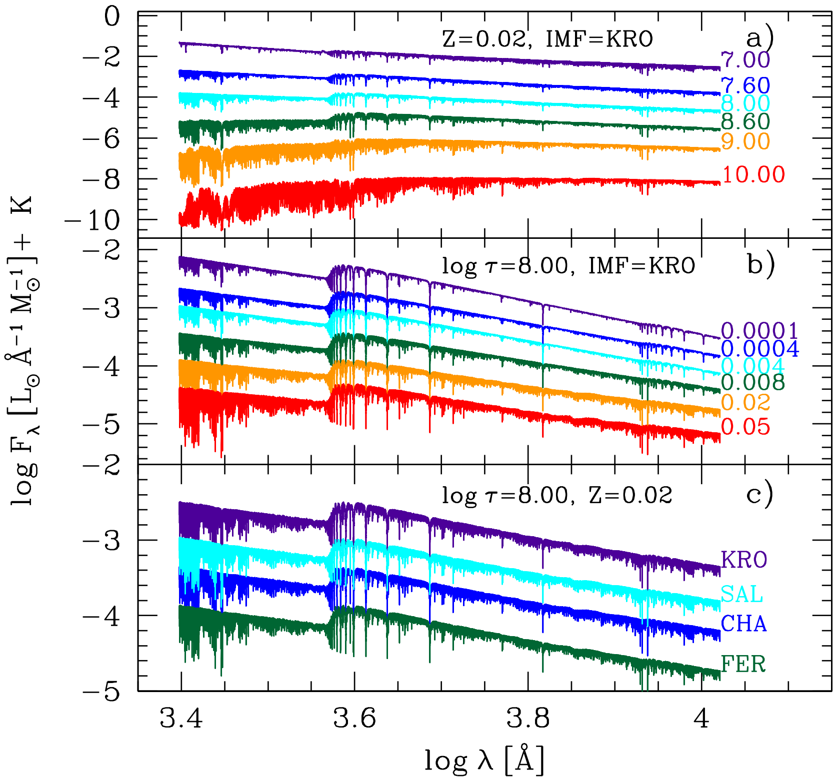
Figure 15. Stellar indices, equivalent widths in Å, as a function of the physical stellar parameters for Ho, in HR-R, as defined by González Delgado, et al.

MEGAPOPSTAR: EVOLUTIONAY SYNTHESIS MODELS



1. The classical Padova isochrones
2. A stellar library:
   - Theoretical
     - ✓ HR-pyPopStar (Millán-Irigoyen+ 2021) with Coelho+2014 plus Hainich+2016 plus Rauch (2003)
     - ✓ HR-pyPopStar with Munari+ 2005 (Millán-Irigoyen in preparation)
   - Empirical
     - ✓ MILES group (Vazdekis +2016)
     - ✓ **MEGASTAR**

EVOLUTIONARY SYNTHESIS MODELS WITH MUNARI+2005 STELLAR SPECTRA



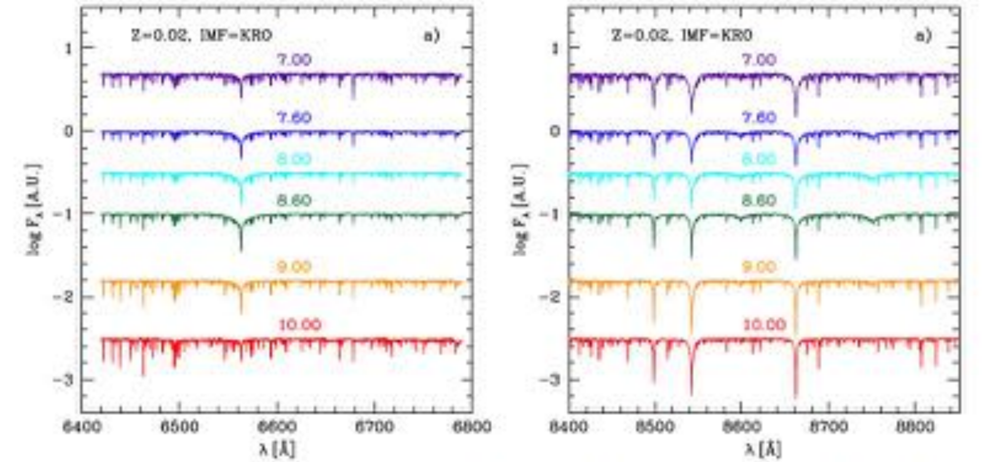
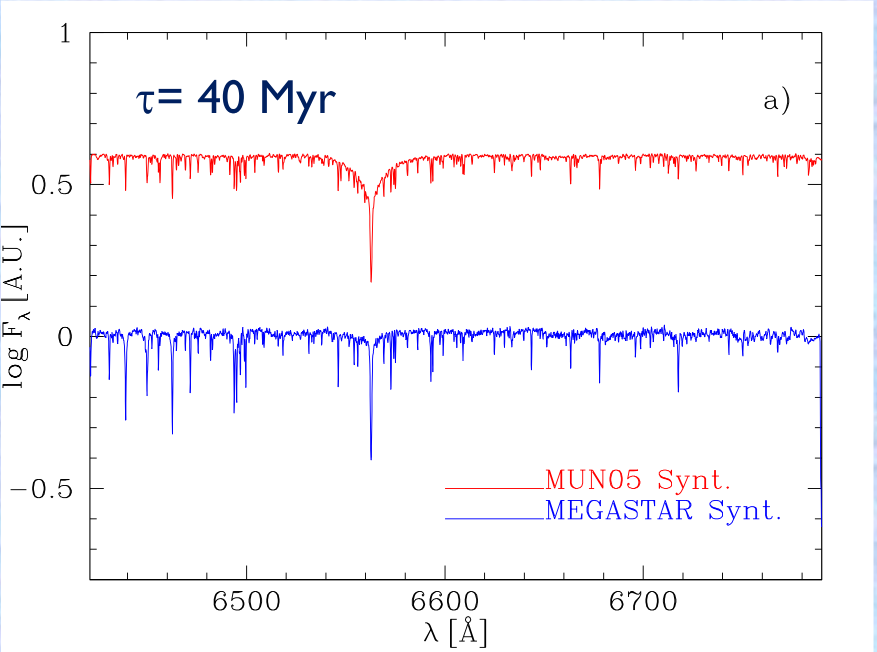


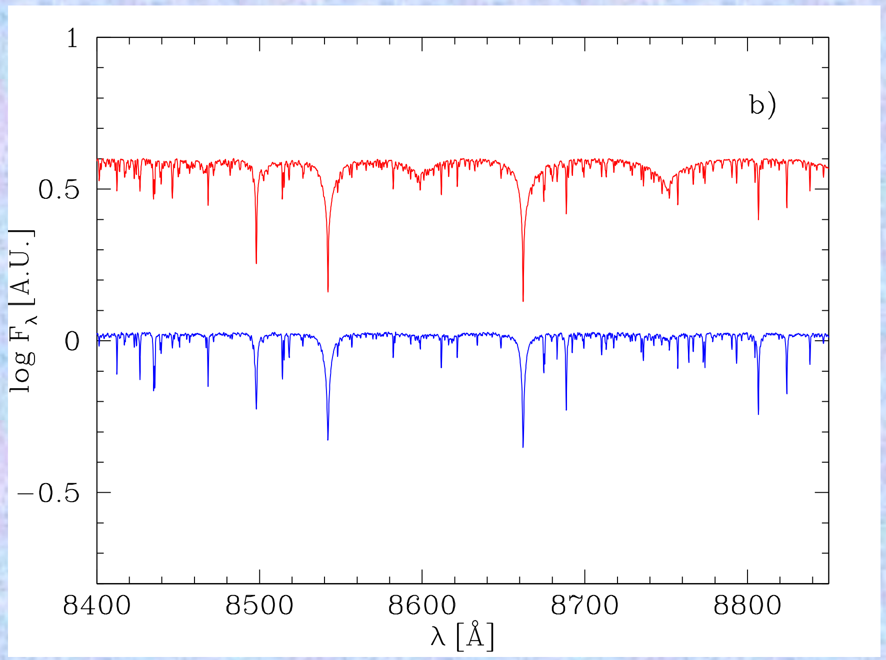
Figure 17. Normalized spectra obtained with the code HR-pyPopStar by using the MUN05 stellar models for normal stars for Z = 0.02, the IMF from KRO and several ages older than 10 Myr in the spectral ranges of the MEGARA set-ups: a) HR-R and b) HR-I.

1. SED obtained with HR-pyPopStar and MUN05 stellar models
2. SED rectified and normalized by bounfit to have flat spectra in the same HR-R and HR-I as our MEGASTAR ones
3. We substitute this theoretical library from MUN05 with our MEGASTAR library
4. For $Z=Z_0$, only 134 stars from our 350
5. Only valid for τ > 20 Myr

MEGAPOPSTAR

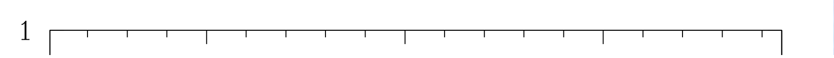
- By using the HRpyPopStar code
- By taking the isochrones from Padova group
- By selecting the stars from MEGASTAR closer in Teff and logg
- Each spectra is weighthed taking into account the Lbol, the number of stars (IMF) in each point of the isochrone and the luminosity in the spectral ranges of HR-R and HR-I setups
- Applied to an stellar population of metallicity $Z=Z_0$ and age τ = 40 Myr

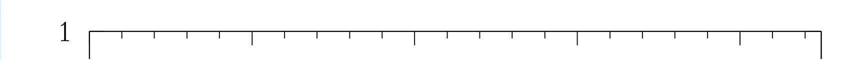




MEGAPOPSTAR

- By using the HRpyPopStar code
- By taking the isochrones from Padova group
- By selecting the stars from MEGASTAR closer in Teff and log g
- Each spectrum is weighthed taking into account the Lbol, the number of stars (IMF) in each point of the isochrone and the luminosity in the spectral ranges of HR-R and HR-I setups
- Applied to a stellar population of metallicity $Z=Z_0$ and age $\tau = 40$ Myr





There are still differences due to the lack of certain stars:

- The variety of stellar parameters in the present subsample of stars compared with the models is still small
- This produces an artificial spectra shift towards stellar populations with stars more similar to the ones presented in MEGASTAR at this moment.
- Thus, there are only 3 A-stars with solar metallicity included in this first version of the model
- We need continue with the Project ☺

SUMMARY

- We have presented our project in García-Vargas et al. (2021)
- We have presented our first Data Release in Carrasco et al. (2022) with 414 stars (828 spectra in HR-R and HR-I setups), as E. Carrasco has presented before.
- We have analyzed spectra for 350 stars in the cool spectral range: from later tan B2 until S stars, by determining their stellar parameters, Teff, log g and [M/H] from the comparison with Munari et al. (2005) models.
- We have included these spectra as stellar library in the evolutionary synthesis model (HR-pyPopStar, Millán-Irigoyen et al. 2021), showing the preliminary spectra models obtained with MEGAPOPTAR for $Z=Z_{\odot}$ and τ= 40Myr.
- This new code still needs more types of stars, with a higher variation in gravity and metallicity, so we will continue our observations (if possible) next semesters in GTC-MEGARA
- We will present our DR2 soon (Carrasco et al. in preparation).
- We will do a similar analysis to this one for the hottest stars in MEGASTAR (S.R.Berlanas et al. in preparation). This will allows to us to extend MEGAPOPSTAR to ages τ < 20 Myr.
- It is our intention, to check the MEGAPOPSTAR model with observations of the galaxy NGC 628. We have been already granted with 20 hrs, 4 pointings along the radius of this galaxy for these same setups . This is a disk dynamically cold (σ=14 km/s) where we expect to see the advantage of the high spectral resolution.