Carbon and nitrogen in a sample of solar analogues using molecular lines:
thin disc stars with/without giant planets

Rafael Botelho, **André Milone**
(INPE, Brazil)
& Ronaldo da Silva (SSDC/ASI, Italy)

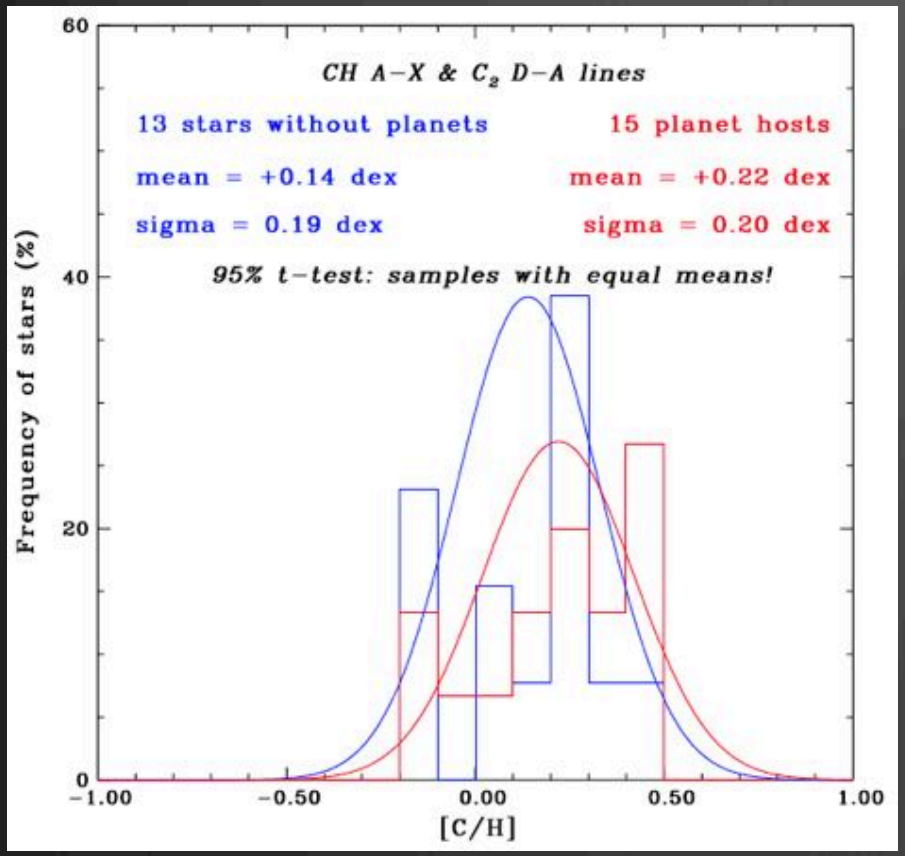
andre.milone@inpe.br

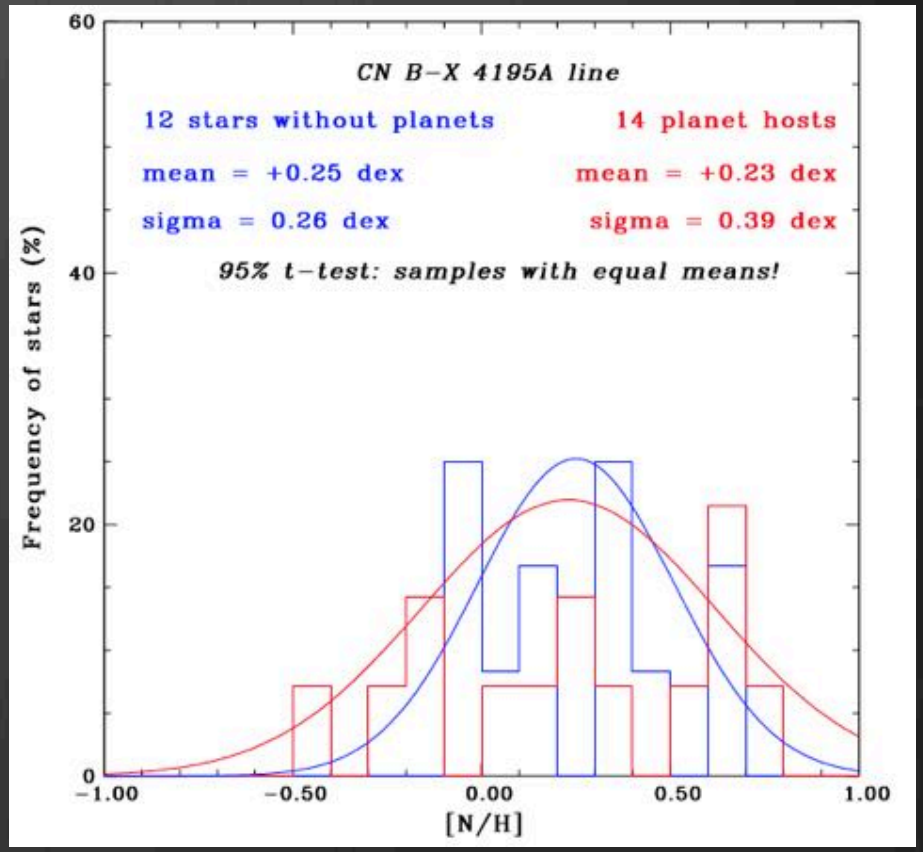
Precision Spectroscopy 2017 – IAG/USP
1-4 August

Topics

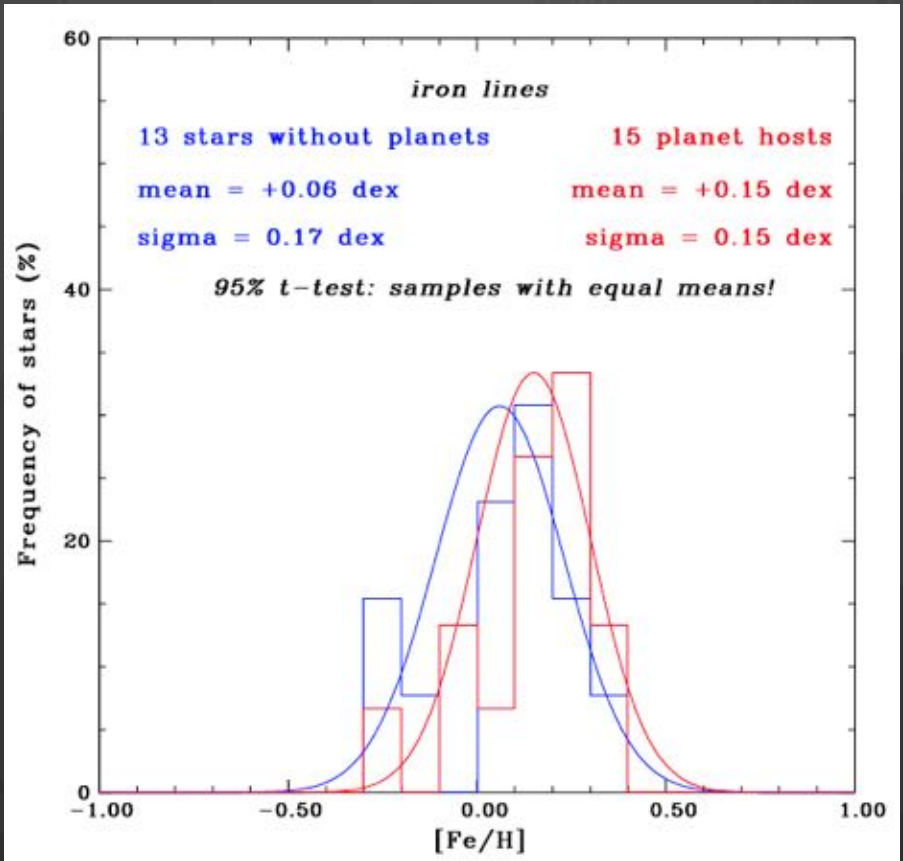
- Sample & high resolution spectra
- Selection of lines of CH, C_2, CN (and NH)
- Spectral synthesis
- Abundance results and their errors
- Conclusions & perspectives

Our results at beginning !!!





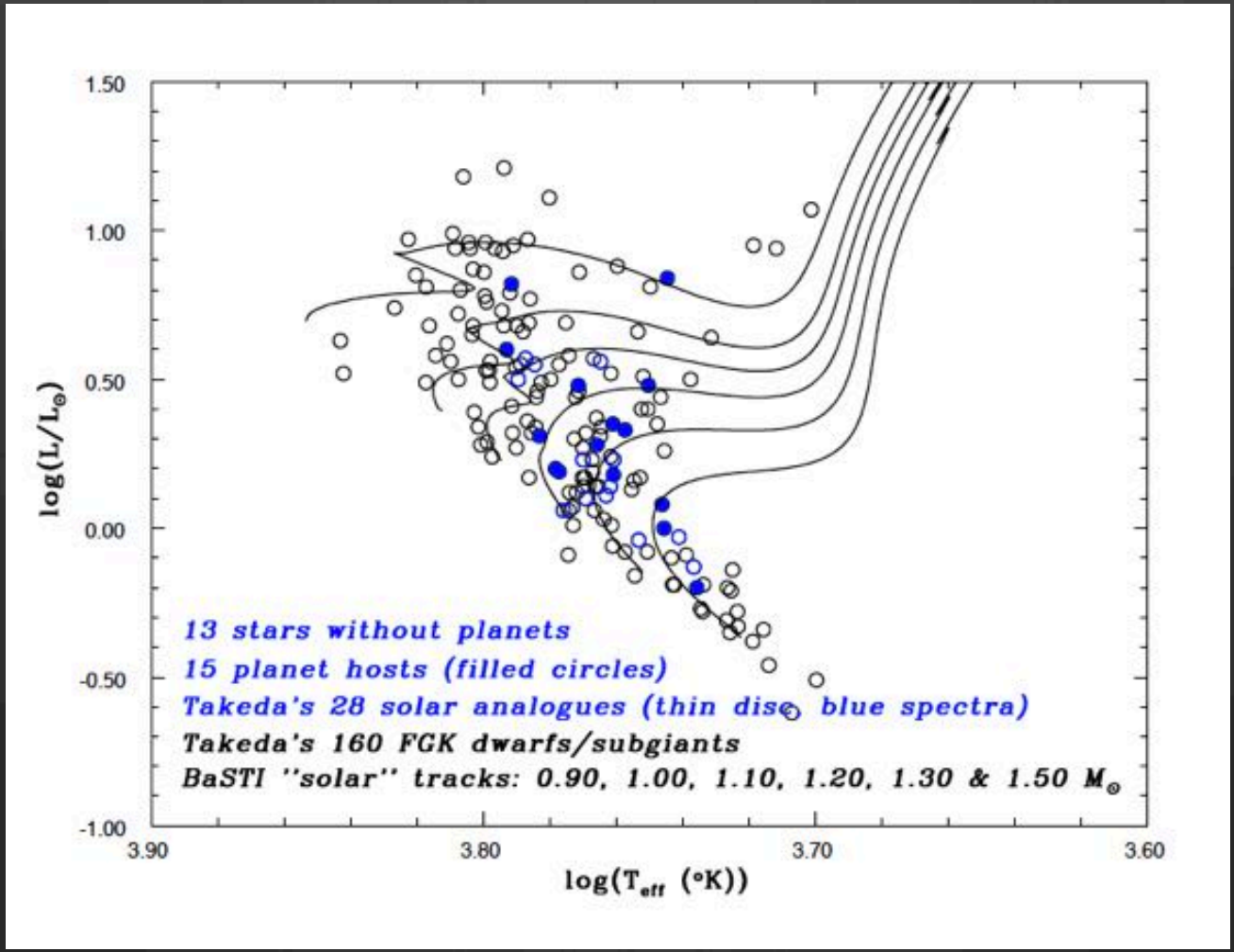
Takeda et al. (2005): [Fe/H]



Sample & Spectra

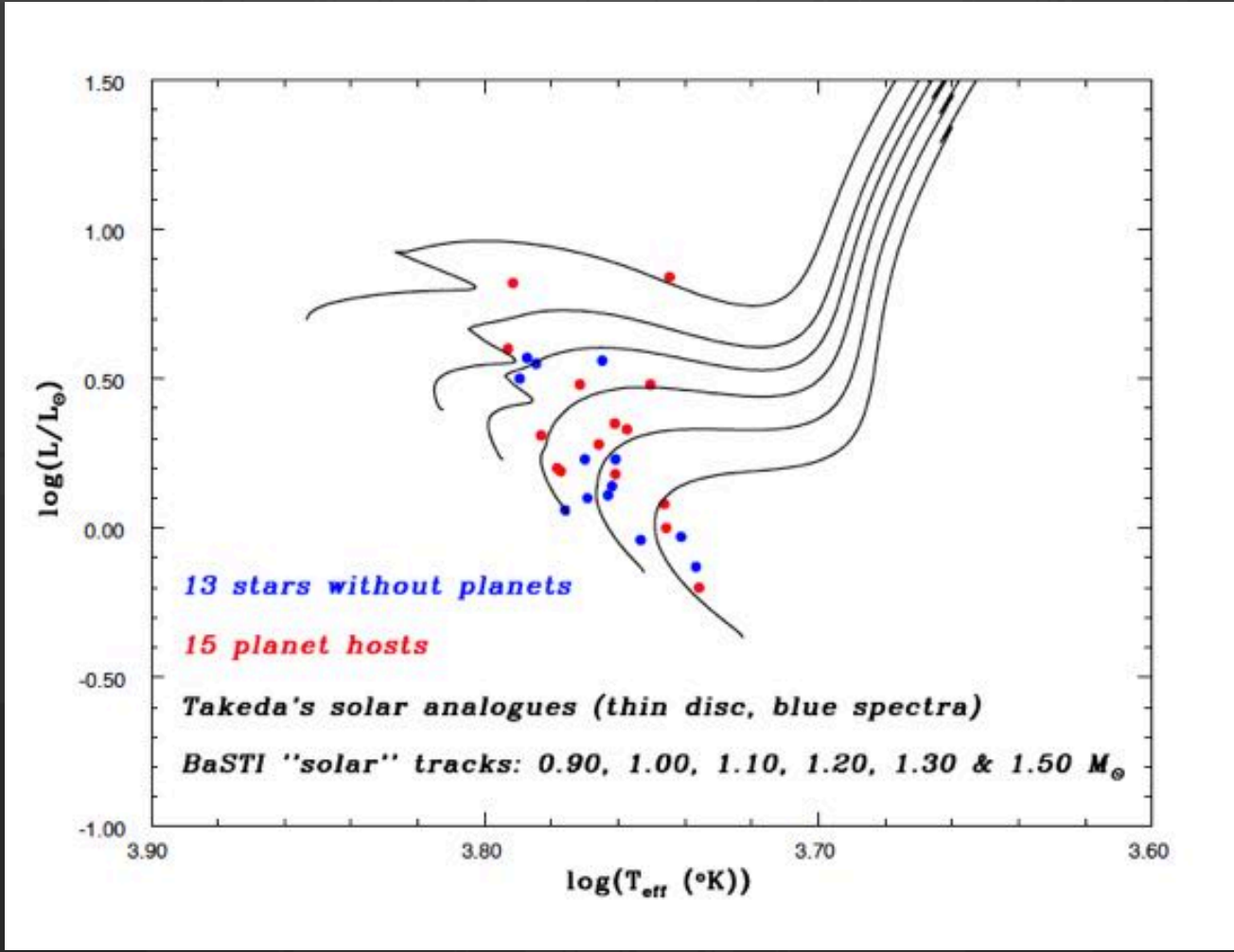
- 28 out of 89 solar analogues from Takeda's sample of 160 nearby mid-F to early-K dwarfs and subgiants (Takeda+ 2005)
  - blue spectra & thin disc (our kinematics classification)
  - 15 are planet hosts (exoplanet.org on 20 Jul 2017)
- **$5277 \leq T_{eff} \leq 6277$ K; $3.84 \leq \log g \leq 5.04$; $-0.33 \leq [Fe/H] \leq +0.33$**
  (500 K, 0.60 dex & 0.33 dex around solar value)
  - **$\langle e(T_{eff}) \rangle = 15$ K ; $\langle e(\log g) \rangle = 0.04$ dex ; $\langle e([Fe/H]) \rangle = 0.016$ dex**
- **Spectra**
  - Okayama Observ. 1.88m+HIgh-Dispersion Echelle Spectrograph
  - **R = 70,000**
  - **blue** : 3900-5100 Å <S/N> = 320
  - **green-yellow** : 5000-6200 Å <S/N> = 207 (R=90,000 for 13 stars only, narrower slit)

Sample



age of sample stars: from 2 up to 9 Gyr

Sample


1.50
1.00
0.50
0.00
-0.50
-1.00
log(L/L⊙)
3.90
3.80
3.70
3.60
log(T_eff (°K))
13 stars without planets
15 planet hosts
Takeda's solar analogues (thin disc, blue spectra)
BaSTI "solar" tracks: 0.90, 1.00, 1.10, 1.20, 1.30 & 1.50 M⊙

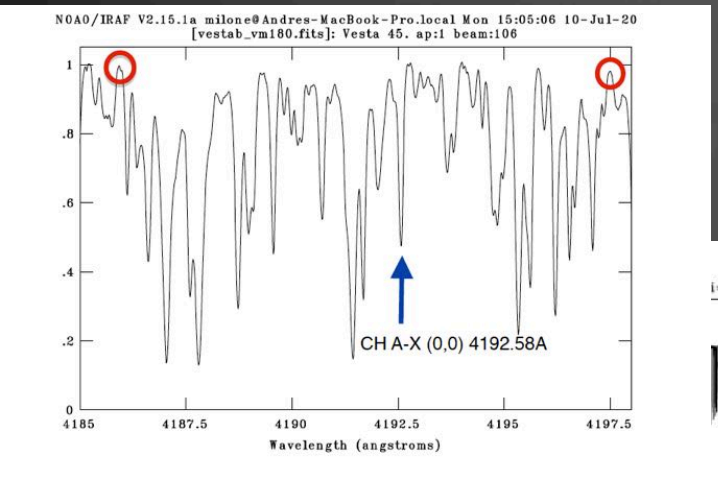
Selection of molecular lines

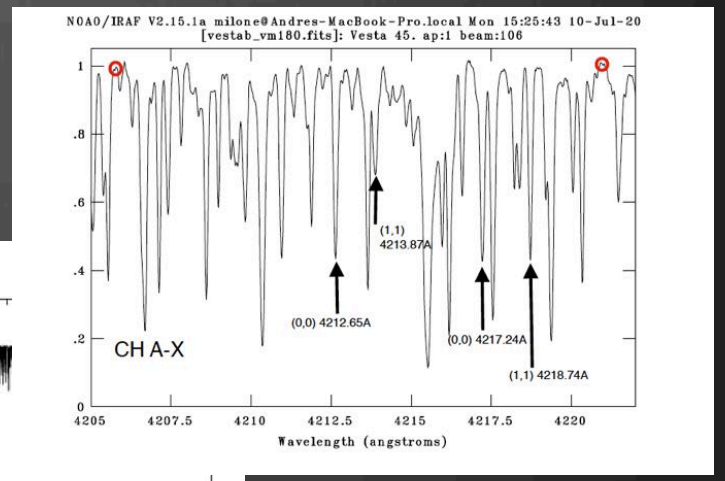
- Visual inspection on a solar atlas to look for candidates of "isolated"/sensitive spectral features
- Spectral synthesis diagnostic
- Calibration to the solar spectrum

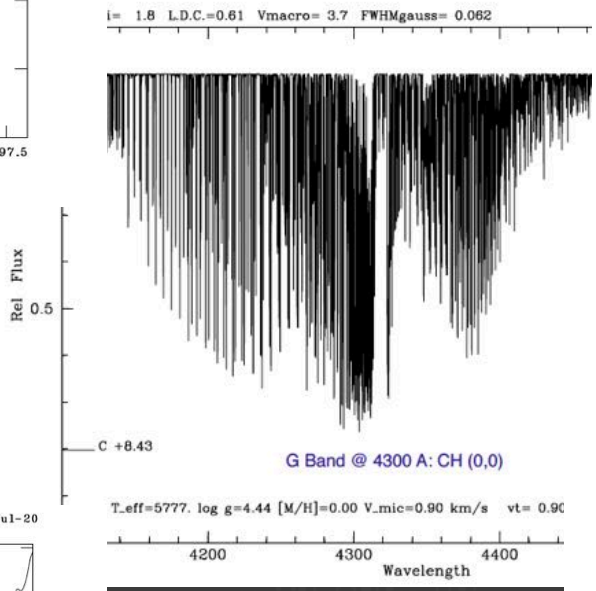
Spectral synthesis

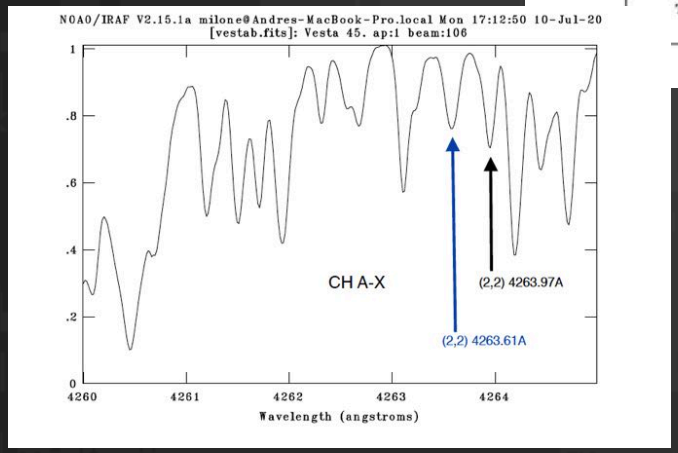
- **MOOG 2014 + VALD atomic & Kurucz molecular lines**
  - D_0 (CH)=3.464 eV, $D_0(C_2)$=6.156 eV, D_0(CN)=7.65 eV
- **Castelli & Kurucz (2004) model atmospheres**
  - Galactic [alpha/Fe]-[Fe/H] trend from nearby stars
- **Solar chemical pattern by Asplund+2009 & Grevesse+2010**
  - $\log \varepsilon$ (C)=8.43, $\log \varepsilon$ (N)=7.83, $\log \varepsilon$ (O)=8.69 & $\log \varepsilon$ (Fe)=7.50
- **Python script to derive [X/H] from the spectral synthesis (*rms* based)**

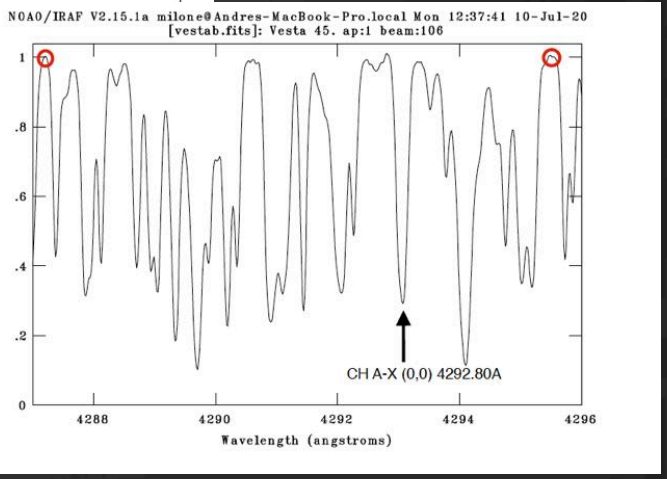
CH A-X: 8 lines


NOAO/IRAF V2.15.1a milone@Andres-MacBook-Pro.local Mon 15:05:06 10-Jul-20
[vestab_vm180.fits]: Vesta 45. ap:1 beam:106
CH A-X (0,0) 4192.58A
Wavelength (angstroms)

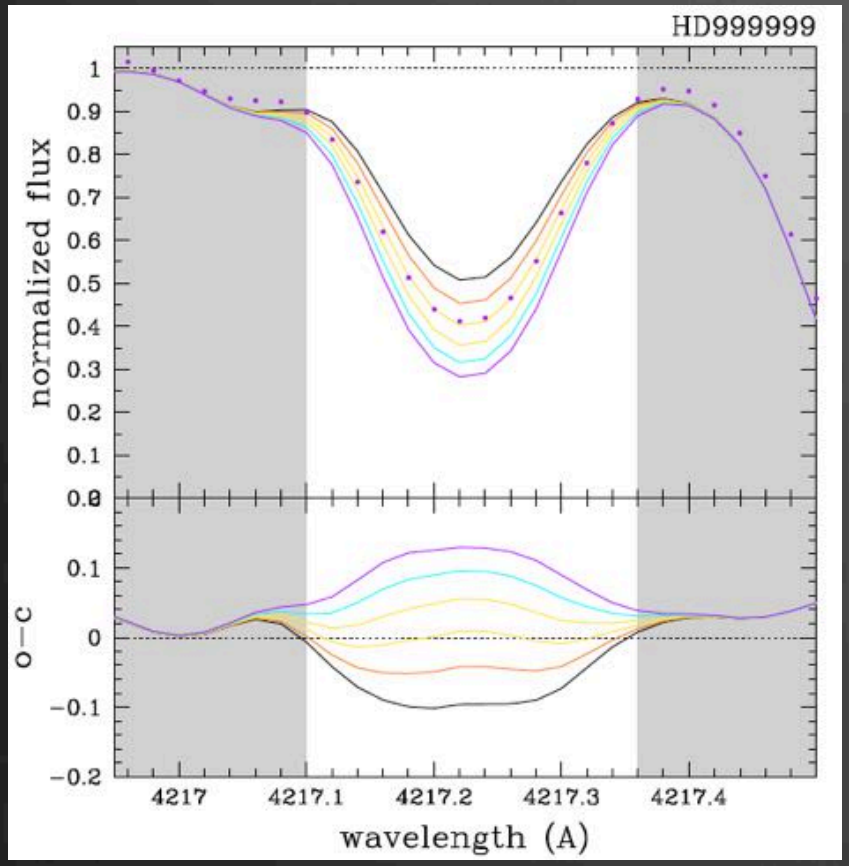

NOAO/IRAF V2.15.1a milone@Andres-MacBook-Pro.local Mon 15:25:43 10-Jul-20
[vestab_vm180.fits]: Vesta 45. ap:1 beam:106
CH A-X
(0,0) 4212.65A
(1,1) 4213.87A
(0,0) 4217.24A
(1,1) 4218.74A
Wavelength (angstroms)

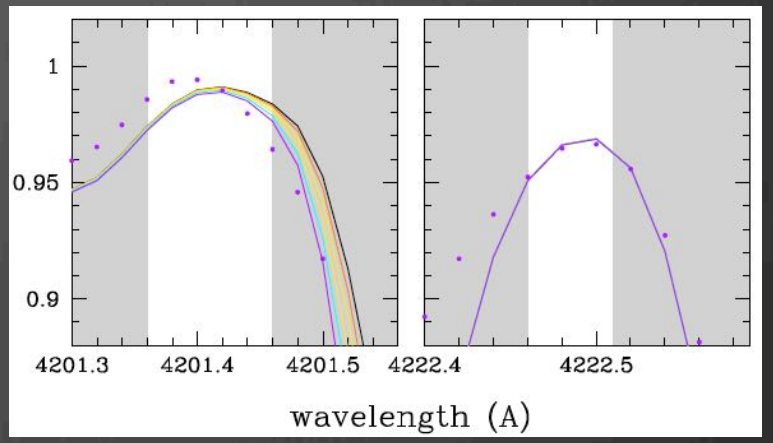

i= 1.8 L.D.C.=0.61 Vmacro= 3.7 FWHMgauss= 0.062
Rel Flux
0.5
C +8.43
G Band @ 4300 A: CH (0,0)
T_eff=5777. log g=4.44 [M/H]=0.00 V_mic=0.90 km/s vt= 0.90
Wavelength

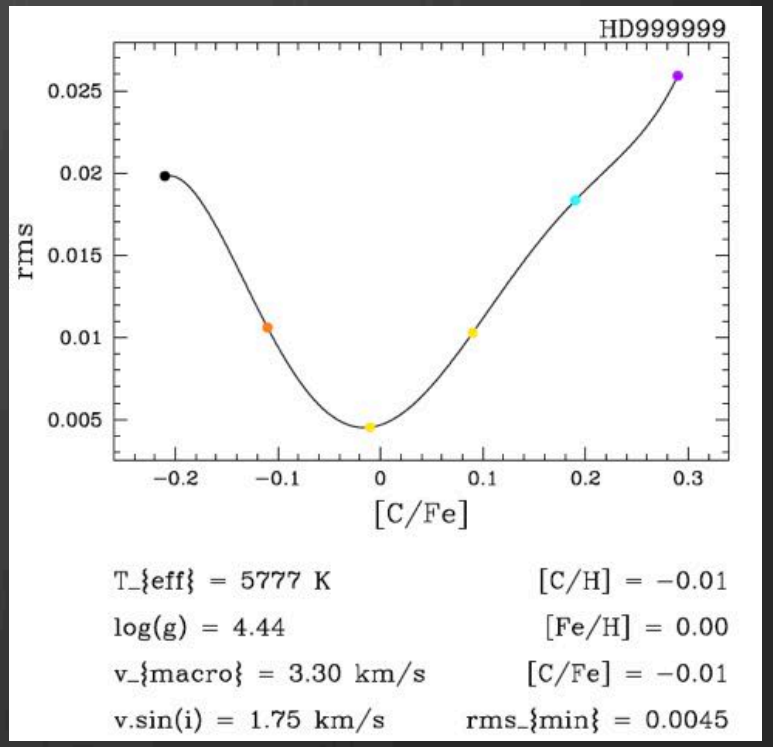

NOAO/IRAF V2.15.1a milone@Andres-MacBook-Pro.local Mon 17:12:50 10-Jul-20
[vestab.fits]: Vesta 45. ap:1 beam:106
CH A-X
(2,2) 4263.97A
(2,2) 4263.61A
Wavelength (angstroms)


NOAO/IRAF V2.15.1a milone@Andres-MacBook-Pro.local Mon 12:37:41 10-Jul-20
[vestab.fits]: Vesta 45. ap:1 beam:106
CH A-X (0,0) 4292.80A
Wavelength (angstroms)

CH A-X lines: example of calibration to Sun



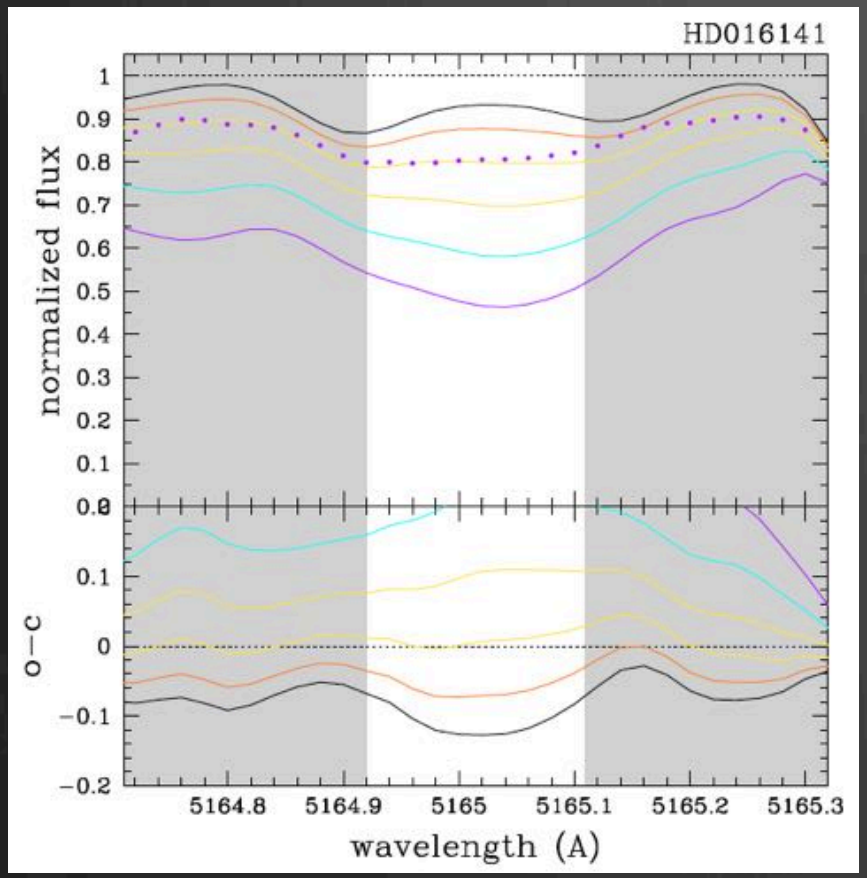


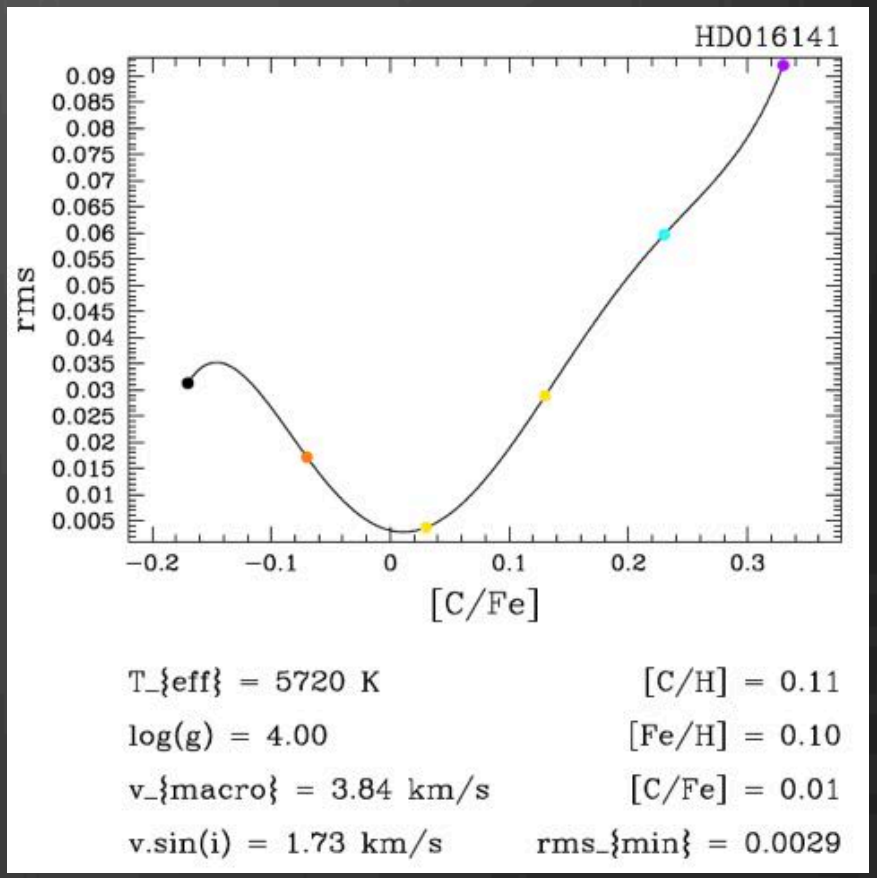


CH A-X: 8 lines
(electronic system of G band)

Line (Å)	Vibrational band (v',v")	Spectral range (Å)	Blue Continuum point (Å)	Red Continuum point (Å)
4192.58	(0,0)	4180-4210	4185.91	4197.50
4212.65	(0,0)	4200-4230	4205.70	4221.85
4213.87	(1,1)	4200-4230	4205.70	4221.85
4217.24	(0,0)	4200-4230	4205.70	4221.85
4218.74	(1,1)	4200-4230	4205.70	4221.85
4263.61	(2,2)	4256-4286	4257.85	4283.28
4263.97	(2,2)	4256-4286	4257.85	4283.28
4292.80	(0,0)	4276-4307	4287.25	4295.52

2 lines of C_2 D-A (Swan System): example for (0,0) λ 5165Å





[C/H]

- **variance-weighted** of $[C/H]_{CH}$ and $[C/H]_{C2}$
- **errors** in $[C/H]_{CHj}$ and $[C/H]_{C2j}$ of individual lines
  - due to spectral synthesis and parameters errors
  - HD016141 as "average" star
    - typical lines: CH B-X λ 4217Å & C_2 D-A λ 5165Å

$$\mathrm{error}[C/H] = \mathrm{sqrt}(e[C/H]^2_{\mathrm{Teff}} + e[C/H]^2_{\log g} + e[C/H]^2_{[Fe/H]} + e[C/H]^2_{\mathrm{synthesis}})$$

$$\mathrm{error}[C/H]_{CHj} = \mathrm{sqrt}(0.007^2 + 0.005^2 + 0.000^2 + 0.01^2) = 0.013\,\mathrm{dex}$$

$$\mathrm{error}[C/H]_{C2j} = \mathrm{sqrt}(0.008^2 + 0.002^2 + 0.009^2 + 0.01^2) = 0.016\,\mathrm{dex}$$

$[C/H]_{CH}$ and $[C/H]_{C2}$ →

$$\overline{[X/H]} = \frac{\sum_i([X/H]/e^2)}{\sum_i(1/e^2)}$$

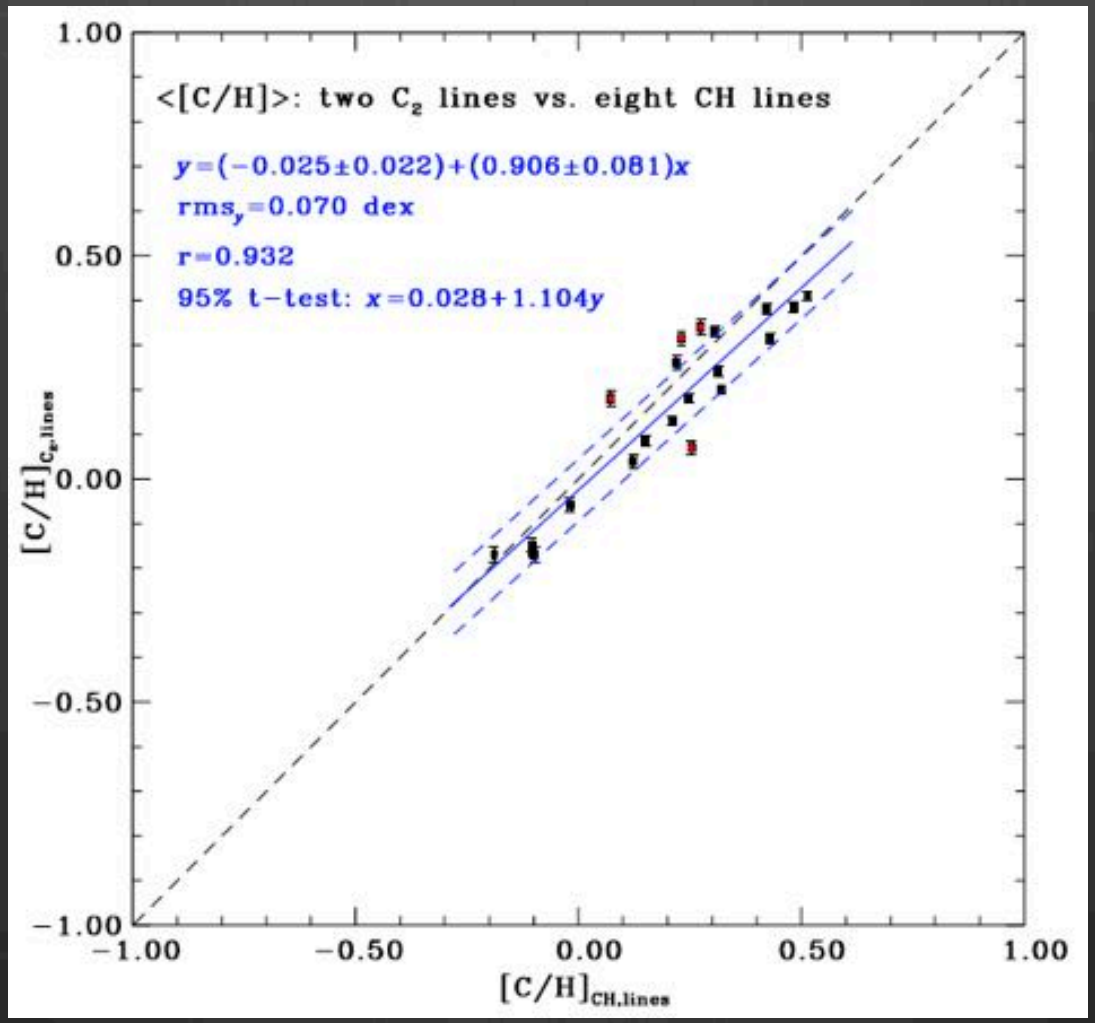
$$e\overline{[X/H]} = \sqrt{\frac{1}{\sum_i(1/e^2)}}$$

→ **[C/H]**

mean errors
±0.005 & ±0.014 dex

mean error
±0.004 dex

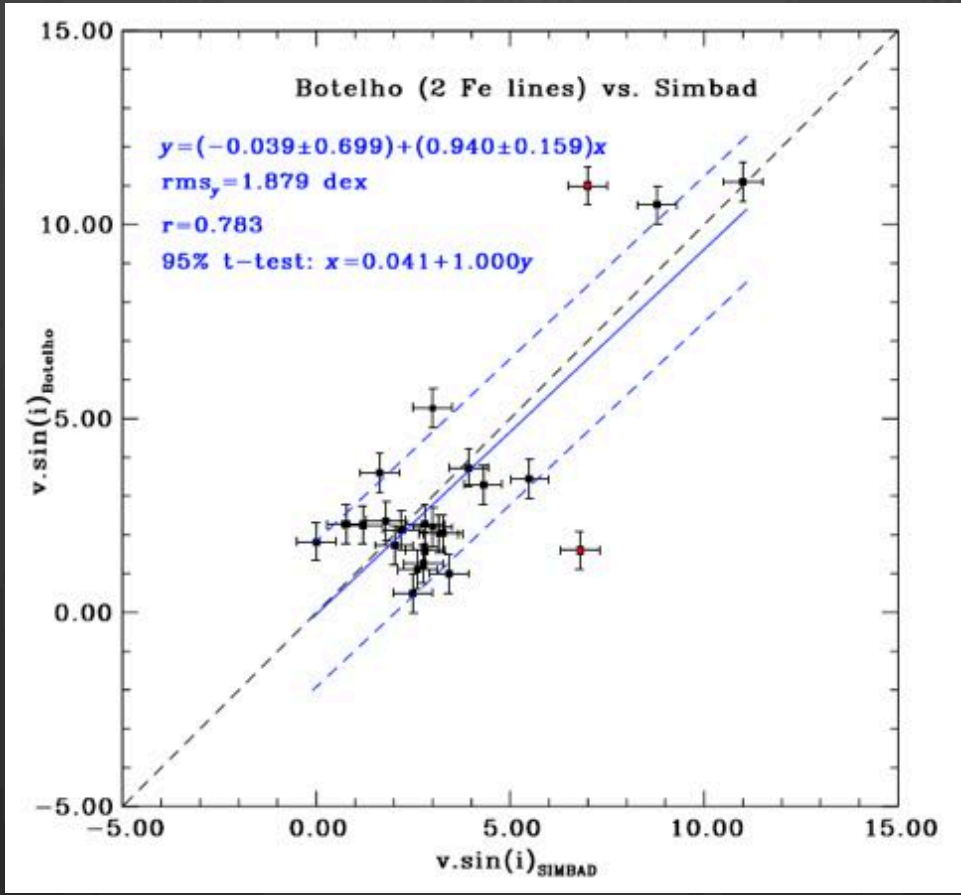
$[C/H]_{C2}$ vs. $[C/H]_{CH}$


<[C/H]>: two C2 lines vs. eight CH lines
y=(−0.025±0.022)+(0.906±0.081)x
rms_y=0.070 dex
r=0.932
95% t−test: x=0.028+1.104y
[C/H]C2,lines
[C/H]CH,lines
1.00
0.50
0.00
−0.50
−1.00
−1.00
−0.50
0.00
0.50
1.00

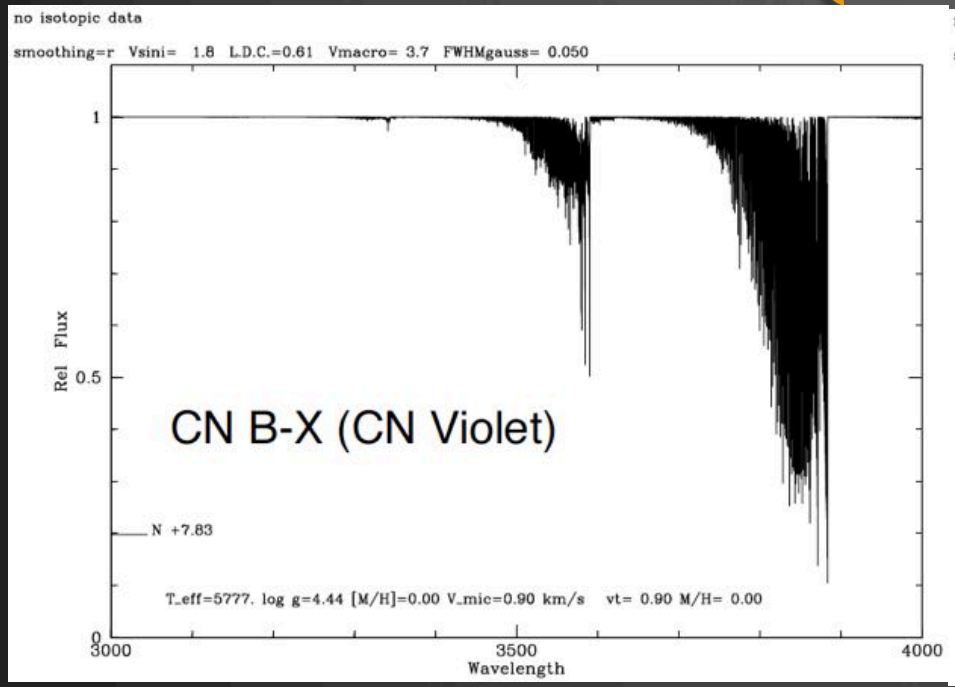
v_{macro} & v.sin(i)

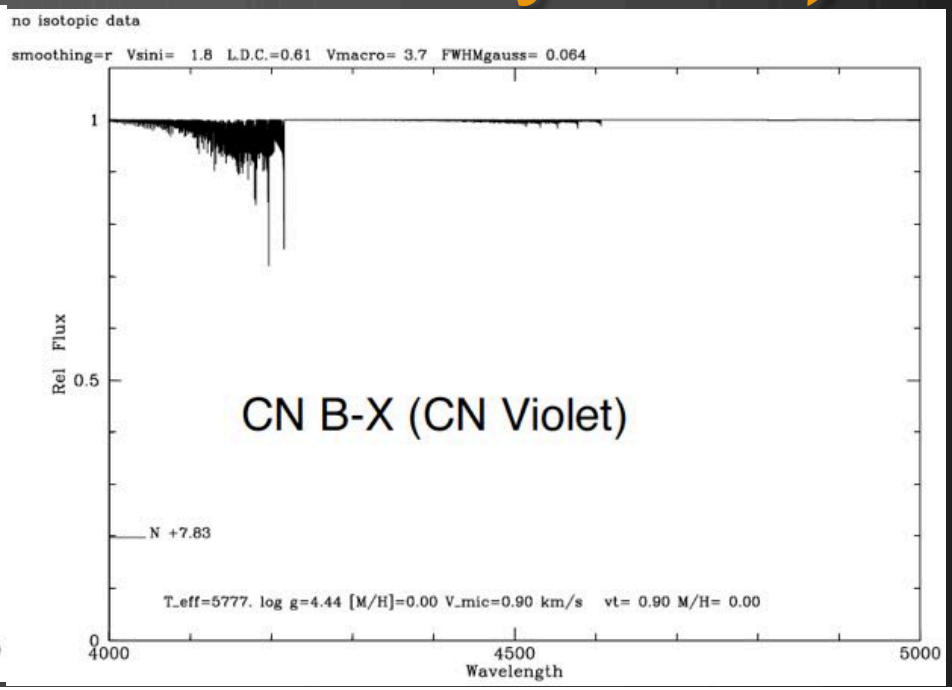
$$v_{macro} = v_{macro,\odot} - 0.0070\,T_{eff} + 9.2422x10^{-7}\,T_{eff}^{2} - 1.81(\log g - 4.44) + 9.95$$

Santos et al. (2016)



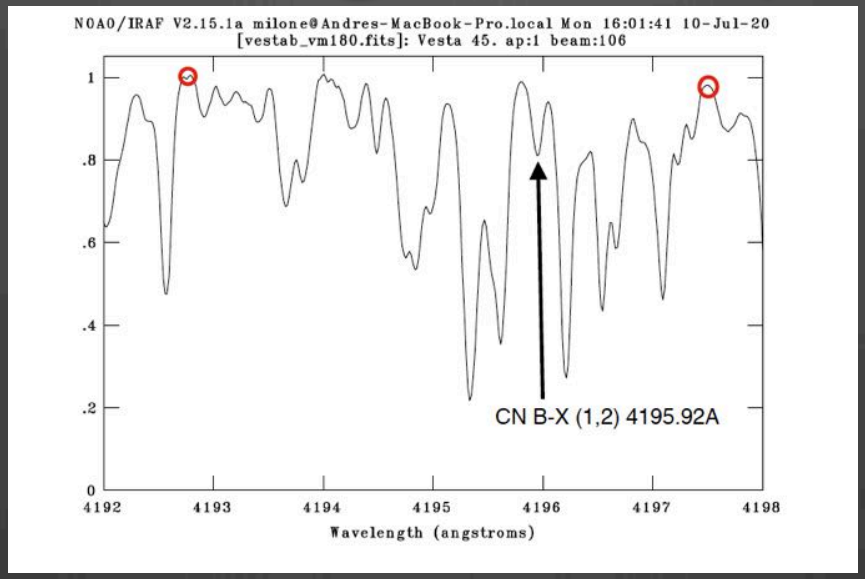
CN B-X lines (CN Violet System)

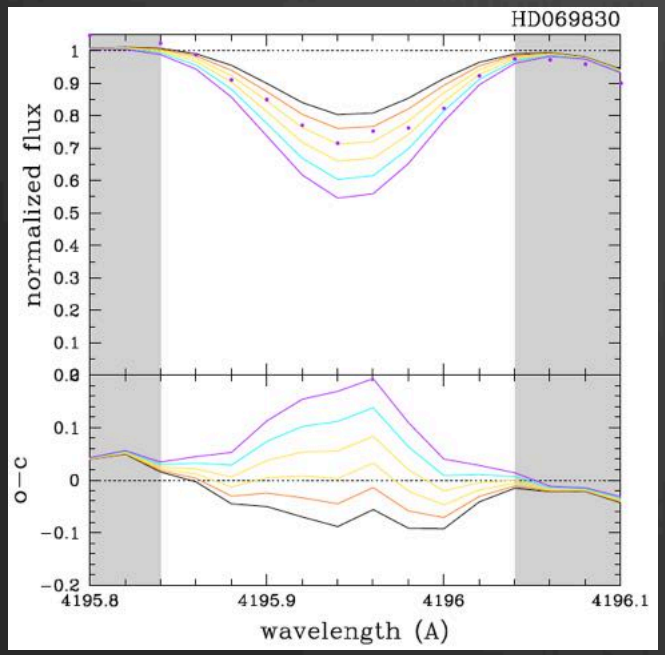


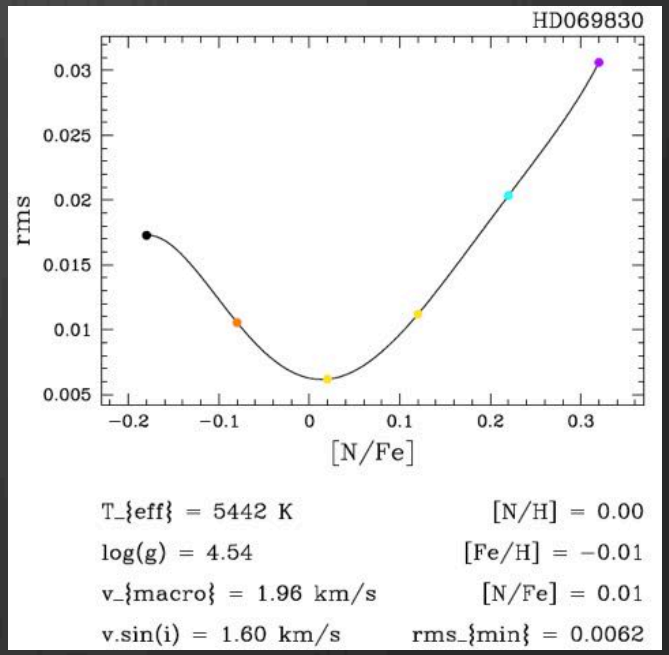


Line (Å)	Vibrational band (v',v")	Spectral range (Å)	Blue Continuum point (Å)	Red Continuum point (Å)
3841.72	(5,5)	3839-3869	———	3866.63
3851.26	(2,2)	3839-3869	———	3866.64
3880.35	(0,0)	3874-3904	———	3883.92
3880.70	(0,0)	3874-3904	———	3883.92
3881.01	(0,0)	3874-3904	———	3883.92
3881.60	(0,0)	3874-3904	———	3883.92
4195.92	(1,2)	4180-4210	4192.74	4197.49

CN B-X: a single line (λ 4195Å)







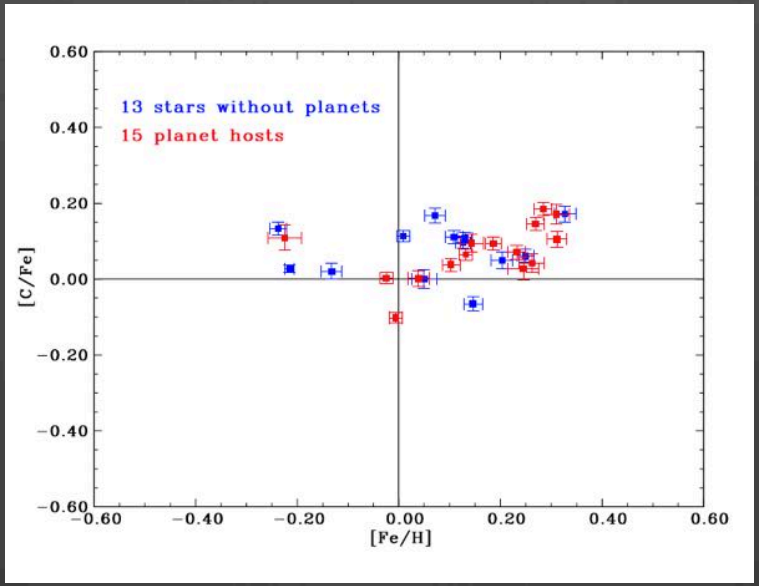
error in [N/H]

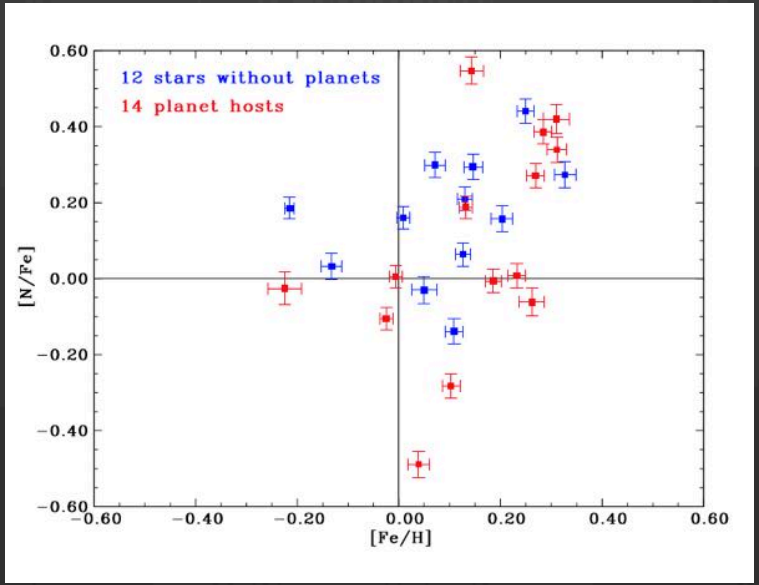
- $[N/H]_{CN}$ --> 0.027 dex !
  - due to spectral synthesis and parameters errors
  - HD016141 as “average” star
    - line: CN B-X λ 4195Å

$$\mathrm{error}[N/H]_{CNj} = \mathrm{sqrt}(e[N/H]^2_{Teff} + e[N/H]^2_{\log g} + e[N/H]^2_{[Fe/H]} + e[N/H]^2_{synthesis})$$

$$\mathrm{error}[N/H]_{CNj} = \mathrm{sqrt}(0.02^2 + 0.008^2 + 0.013^2 + 0.01^2) = 0.027\,\mathrm{dex}$$

Results: [X/Fe] vs. [Fe/H]





Conclusions & Perspectives

- a list of CH A-X, C_2 D-A and CN B-X lines at the blue and green regions
  - ***However, more CN lines and additional NH lines are requested… (e.g. CN B-X 4215Å)***
- high precision of [C/H] and [N/H] based on these molecular lines
  - ***e[C/H]=0.004 dex & e[N/H]=0.027 dex !***
- no statistical difference in [C,N/H] between solar analogues with and without giant planets (15 and 13 respectively)
  - ***However, C and N abundances may be different…need for greater samples…***
- homogeneously redetermine the photospheric parameters to fine tune the spectral synthesis of molecular features and improve the final results…