

# Oxygen abundance determinations in cool giant and supergiant stars.


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**Ukraine**



# Importance of oxygen

- **Oxygen is the most abundant element in our Universe (after H and He).**
- **Oxygen is the base of the life on our Earth.**
- **As a part of $O_3$ molecule oxygen is a good protector of our life.**
- **As a part of $H_2O$, SiO, OH, CO and other molecules, oxygen forms maser sources that give us possibility to investigate different objects in our Universe and its large structure.**
- **As alpha-process element it forms one of the most important criteria - [O/Fe] in GChD models.**
- **And finally,**

**due to oxygen I have got very nice possibility to visit Canary island.**

**My thanks to oxygen and organizers of conference**

**OXYGEN 2012 !**

**Special thanks to:**

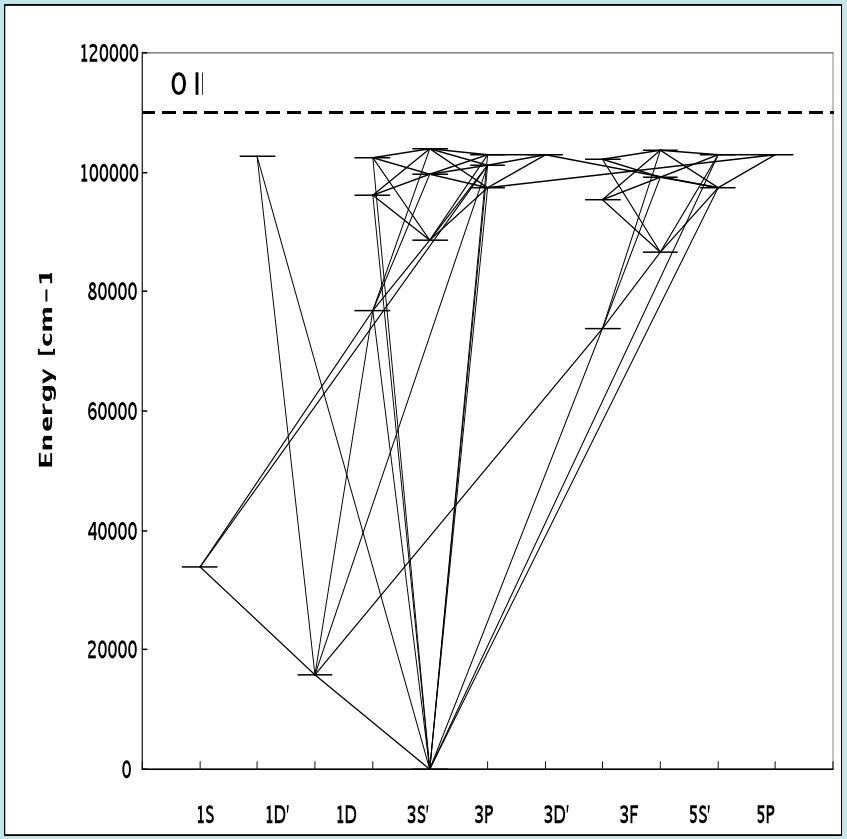
**Grazyna Stasinska, Sergio Simon-Diaz and Jorge Garcia-Rojas!**

# Available oxygen lines in cool stars

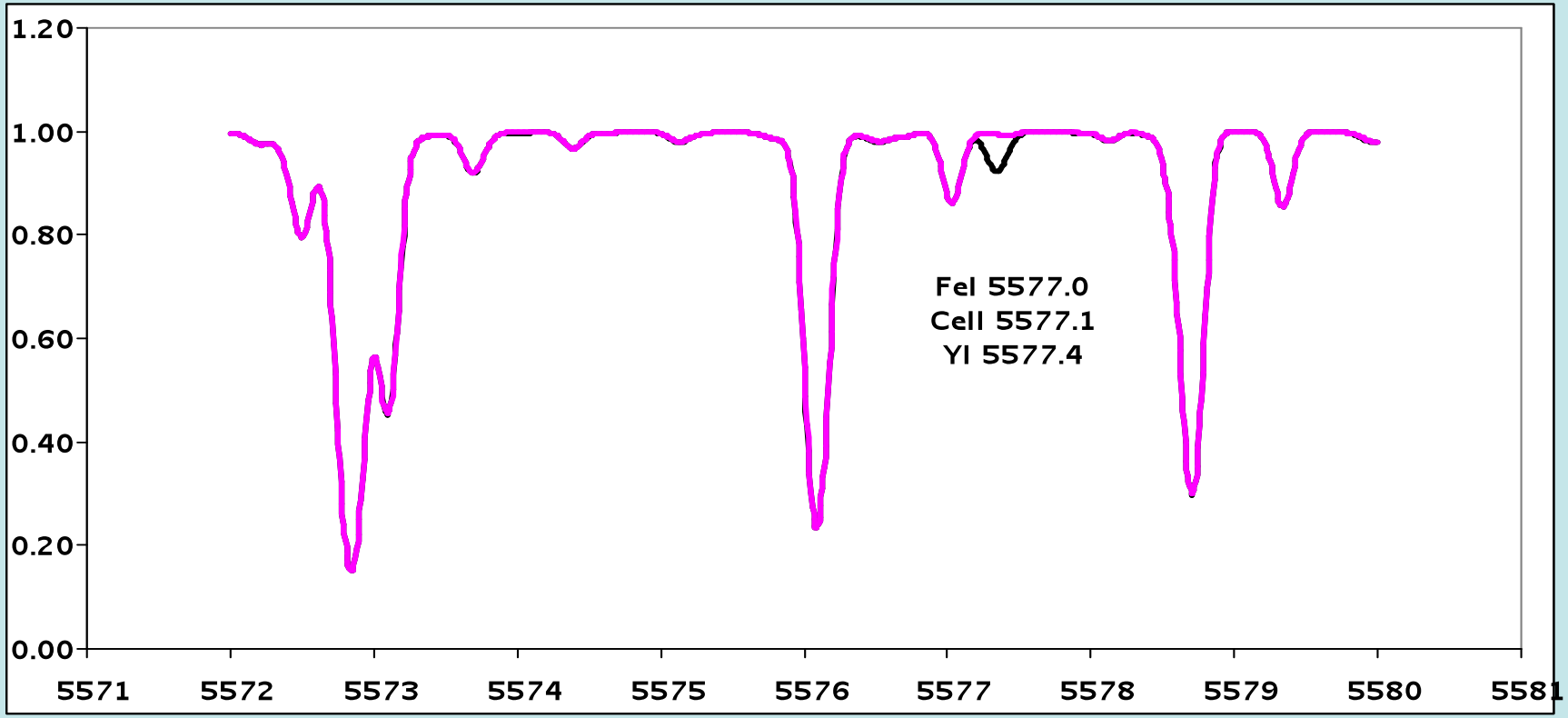
Spectrum of neutral oxygen in the visual and IR part has only several available for analysis lines.

All of them are in the green and red part of the spectrum. I will mention only:
triplet 8446.24 Å, 8446.35 Å, 8446.75 Å
triplet 7771.94 Å, 7774.16 Å, 7775.38 Å
triplet 6155.97 Å, 6156.76 Å, 6158.17 Å
three forbidden lines: 5577.34 Å, 6300.30 Å and 6363.77 Å.
(Almost nobody uses 5577 Å line in analysis)

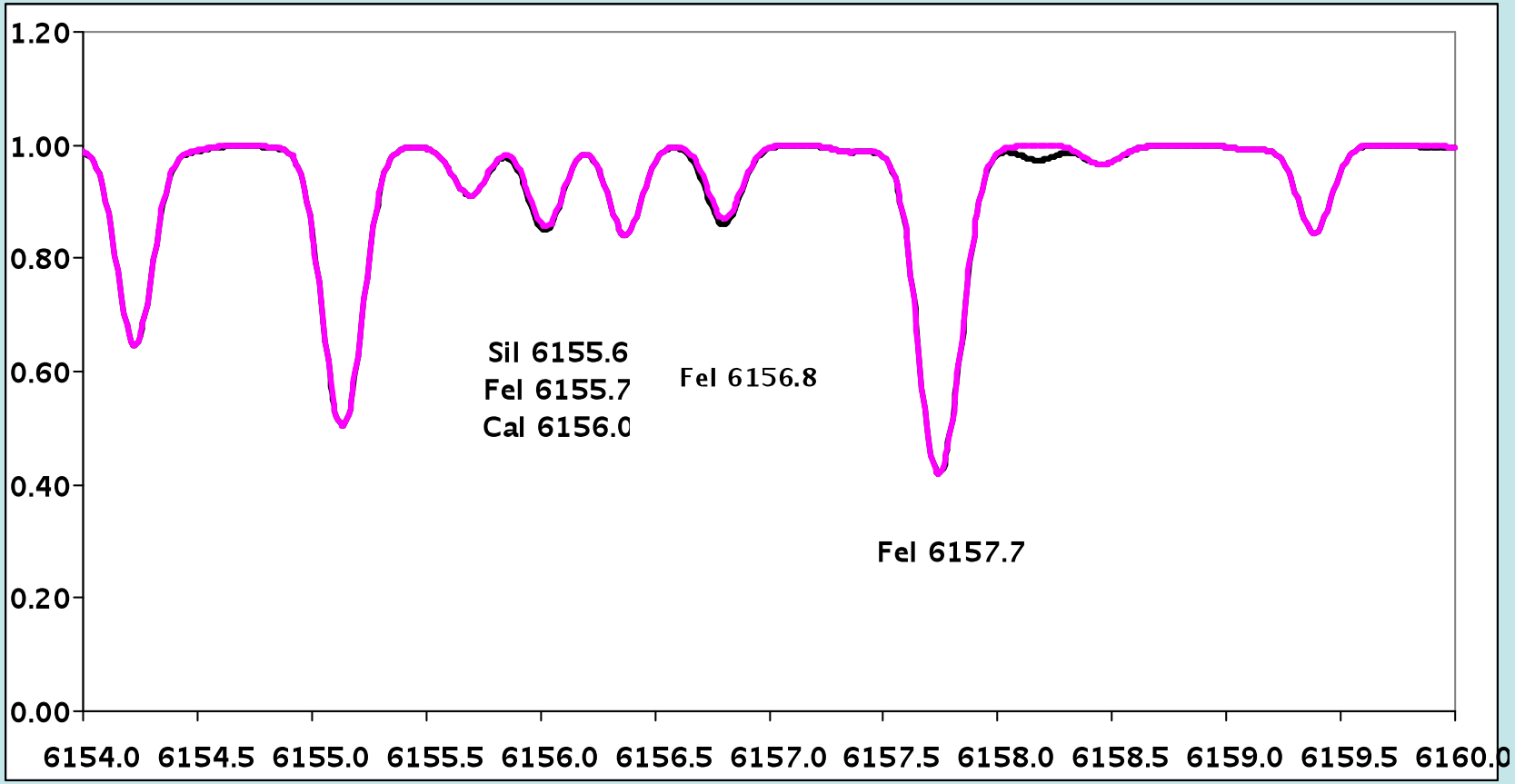
The rest of the lines are situated in the far UV or IR spectral parts.



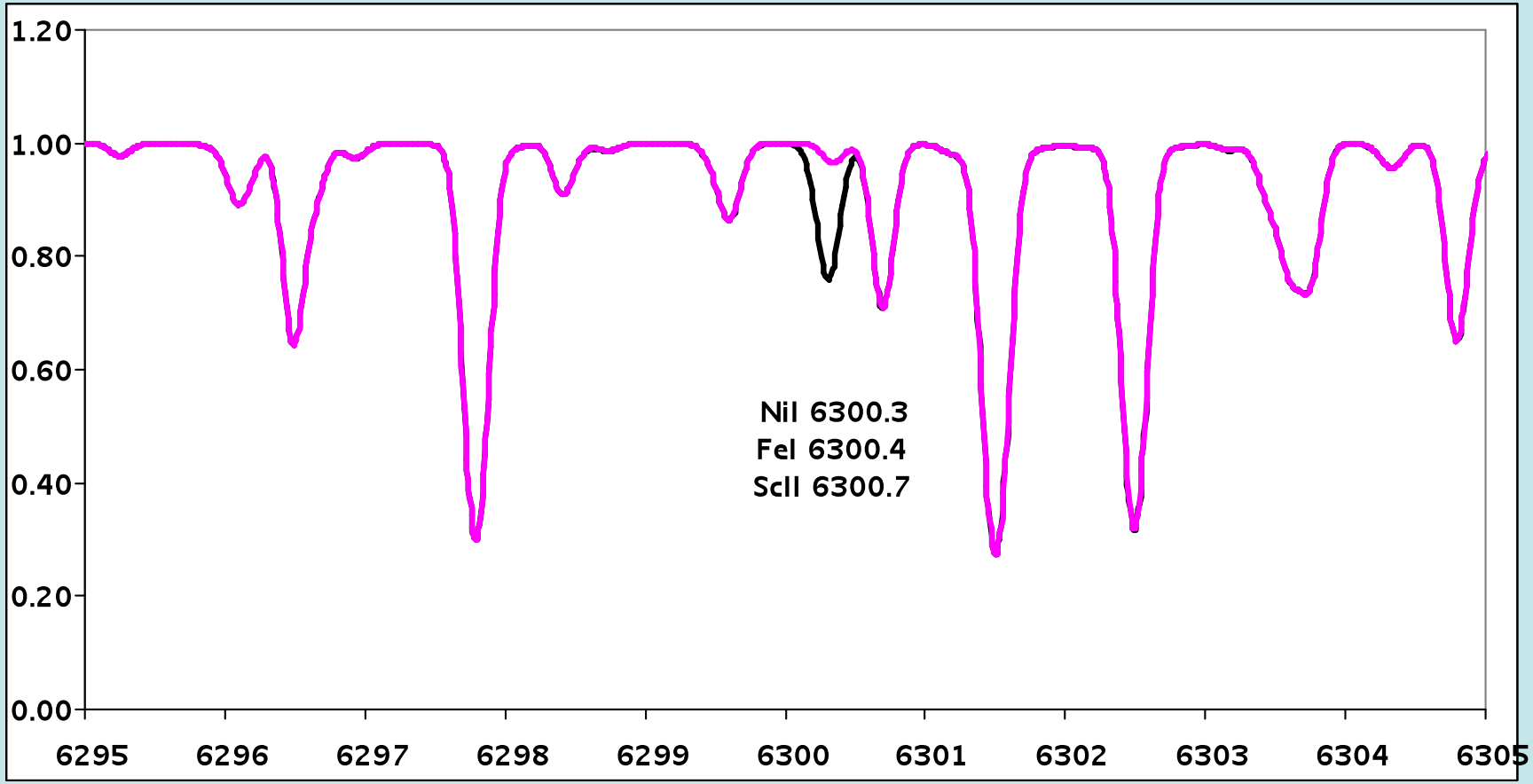
# Blending lines at Teff = 5000 K, logg = 2.0 (VALData-base)



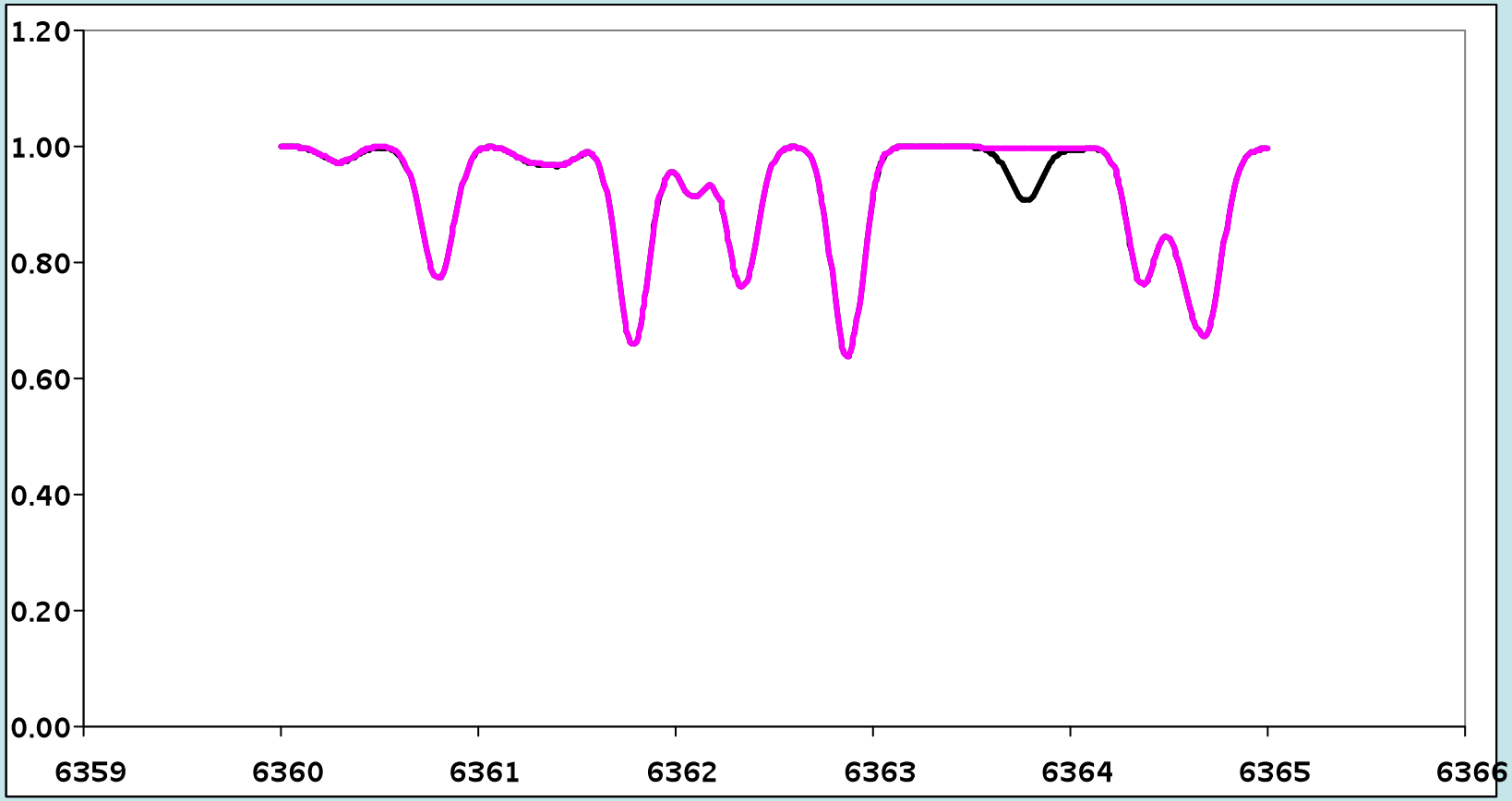
# Oscillator strengths of blending lines are not reliable!



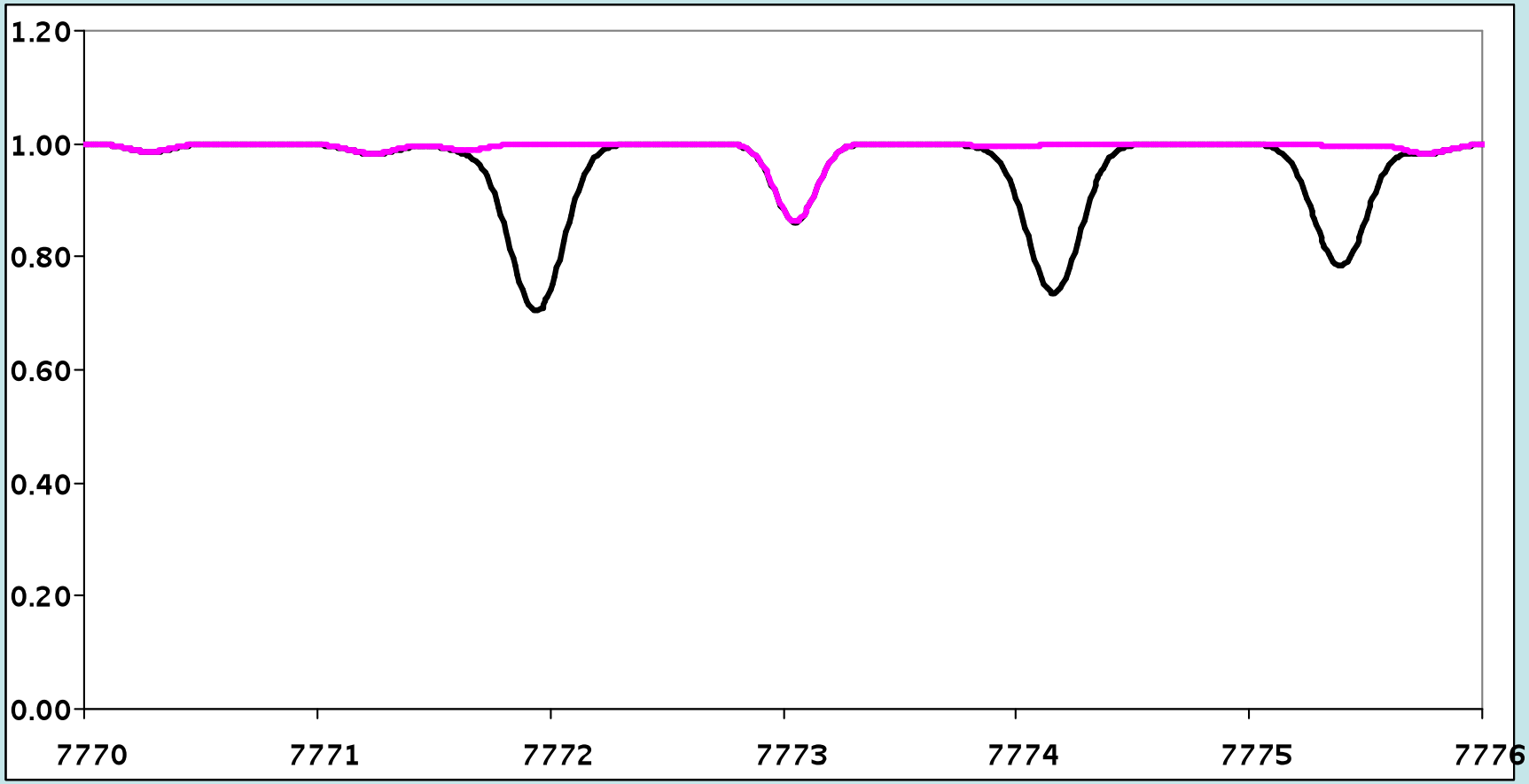
# Telluric lines can be a problem.



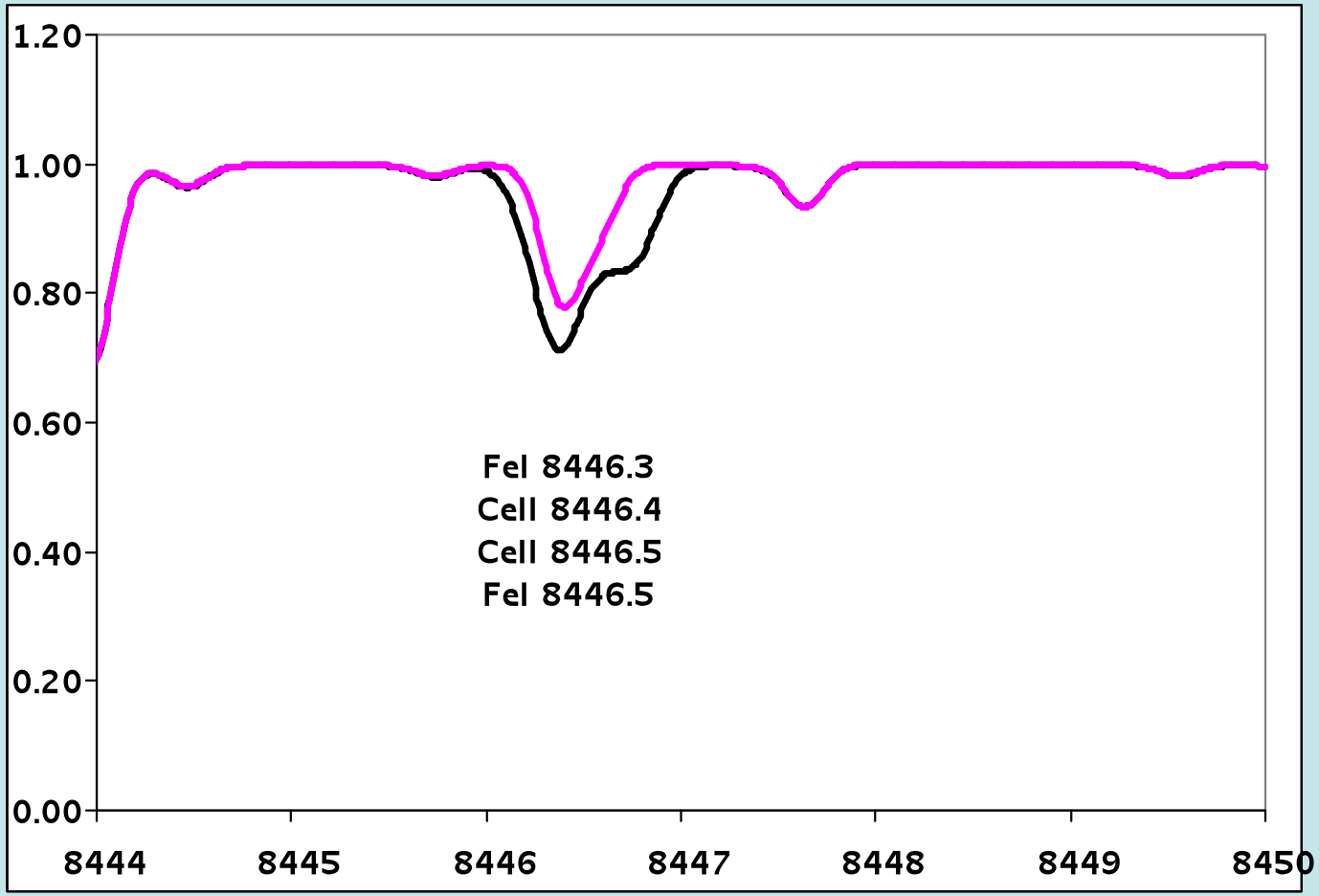
# The same as for 6363 A line.



# Thanks to the Nature these lines are very clean!



# Oscillator strengths of blending lines are not reliable!



# Very instructive example of Hyades
## (Schuler et al., 2006, ApJ 636, 432)

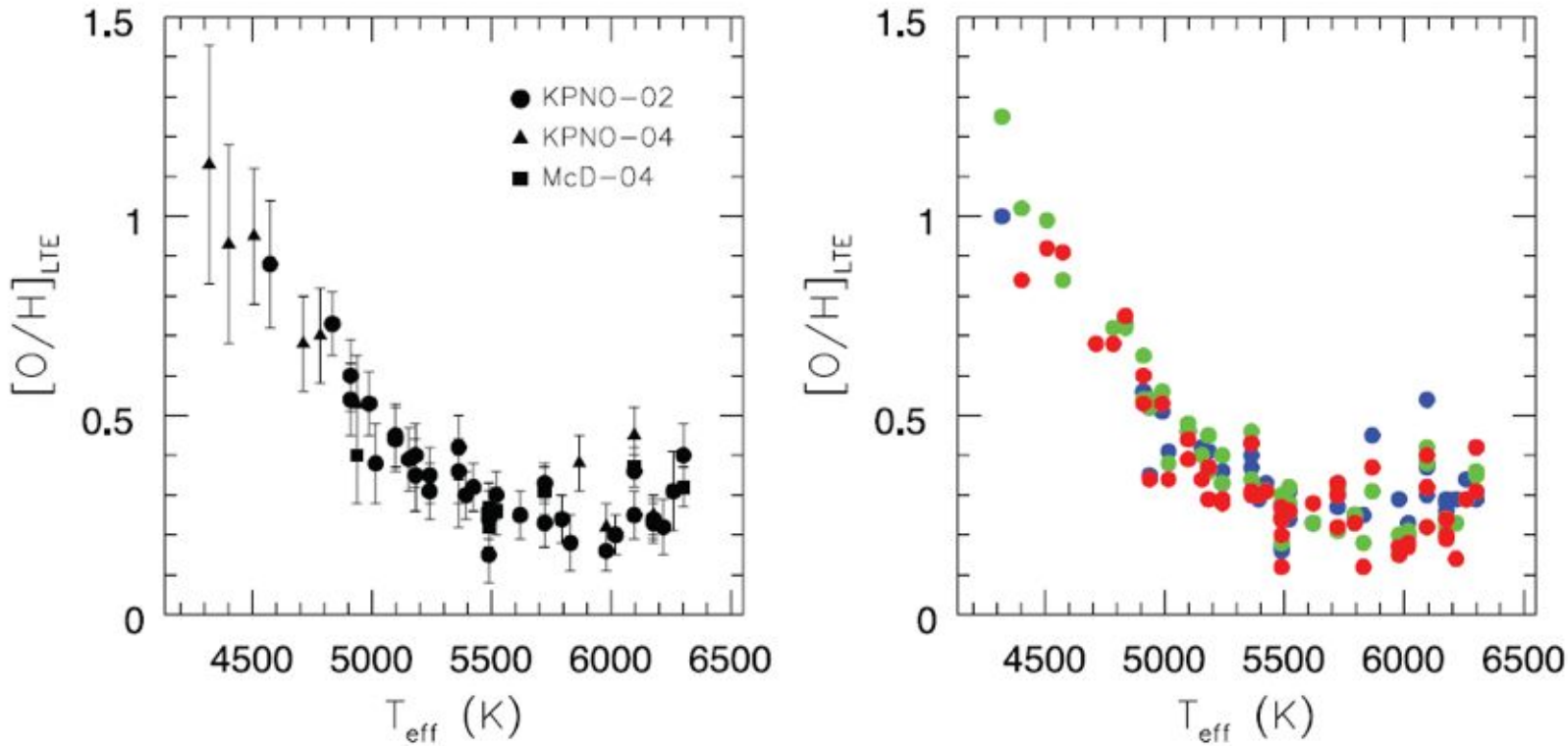



FIG. 3.—*Left*: Relative LTE O abundances vs. $T_{eff}$ for the combined Hyades data set. The points are again distinguished by the data set from which they are derived. The error bars represent the total internal abundance uncertainties. *Right*: Line-by-line relative LTE O abundances vs. $T_{eff}$ for the combined Hyades data set. Abundances derived from the $\lambda\lambda$7772, 7774, and 7775 lines are given in blue, green, and red, respectively.

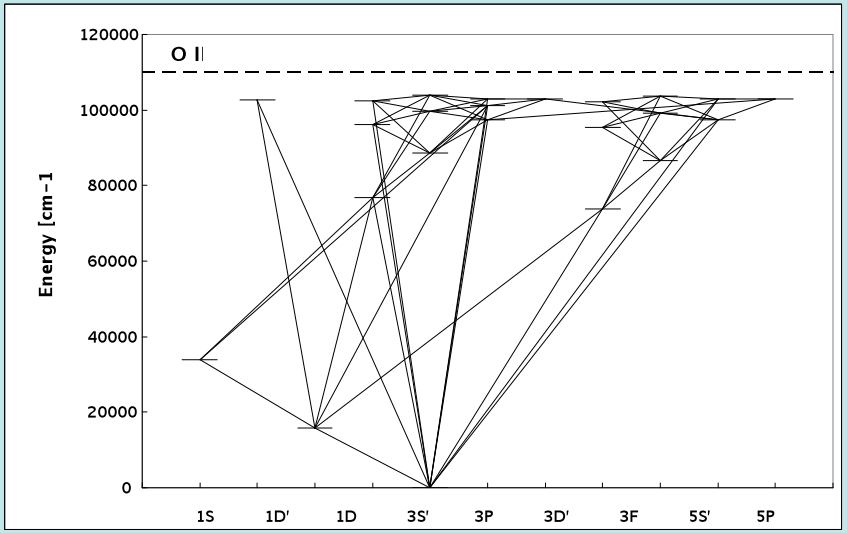
# Very short history of the NLTE calculations

- Seldmayr (1974): 6 levels / 7 lines atomic model
- Kiselman (1991): 16 levels / 22 lines atomic model
- Takeda et al. (1998, 2000, 2003)
- Tomkin et al. (1992): 15 levels / 22 lines atomic model
- Mishenina et al. (2000): 75 levels / 46 lines atomic model
- Carretta et al. (2000): 13 levels / 28 lines atomic model
- Nissen et al. (2002): 22 levels/43 lines atomic model
- Very instructive paper: Fabian, Asplund, Barklem, Carlsson, Kiselman (2009): 54 levels

LTE analyses of atomic oxygen lines and the lines of O containing molecules are very numerous. No possibility to describe them here.

# Atomic model of oxygen

- Our model includes in a detailed consideration 23 terms of OI and ground level of OII. Additional 48 terms of neutral oxygen, 9 terms of OII, 5 terms of OIII and ground level of OIV were included in order to keep the condition of the particles number conservation. Altogether 58 bound-bound transitions were included in the detailed analysis.
- Photo-ionizations cross-sections are from TOPBASE.
- Collision rates between the first seven levels are from Barklem (2007, A&A 462, 781). For the rest allowed transition we used van Regemorter formula, for the forbidden transition – Allen formula.
- Collision b-f rates were calculated using Seaton formula. Specifically, for the collisions with hydrogen atoms we used Steenbock and Holweger formula with correcting factor 1/3.



# Method

- NLTE MULTI profiles of OI lines

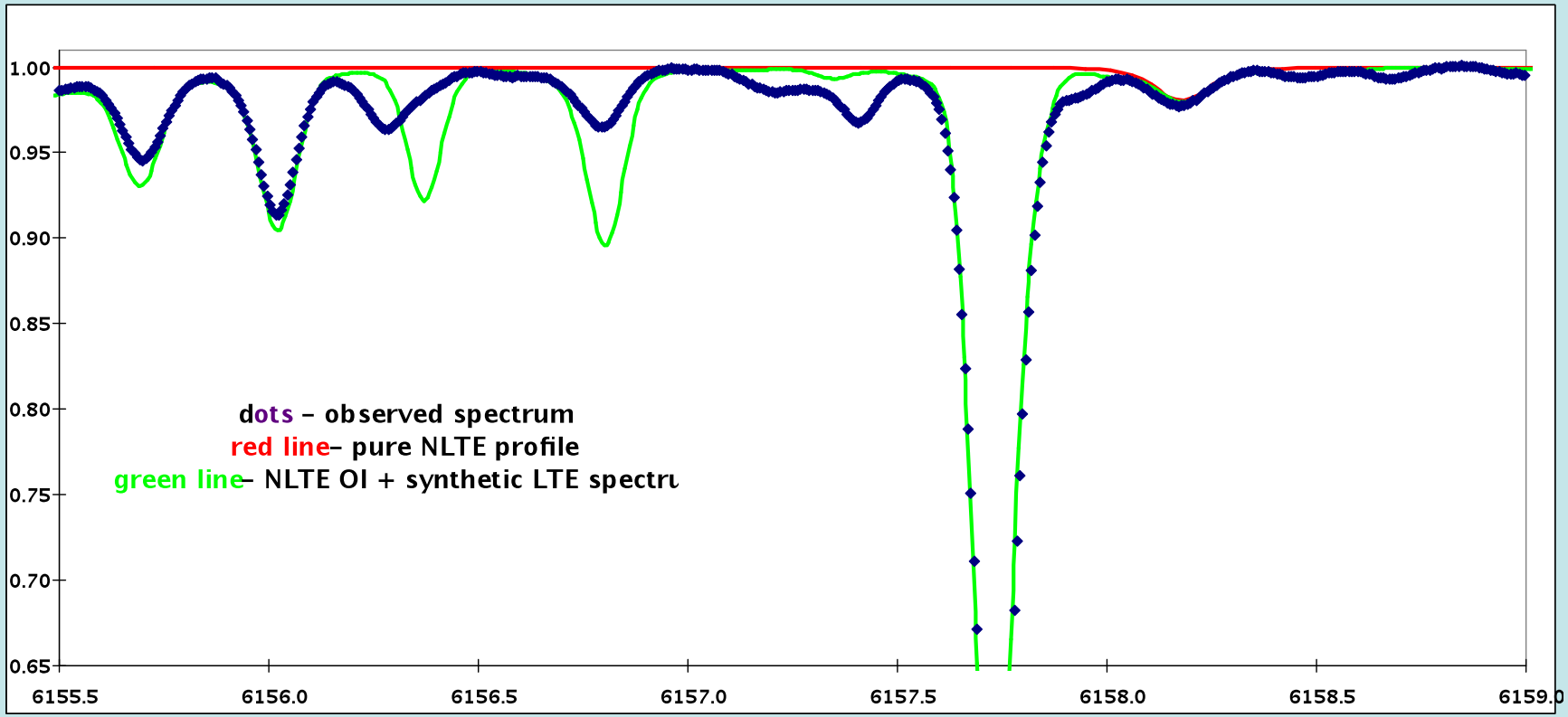
- b-factors ($S_{ul} \approx b_u/b_l B_{ul}$) for OI levels of interest

$$S = \frac{n_u A_{ul}}{(n_l B_{lu} - n_u B_{ul})} = \frac{n_u}{n_u}\frac{A_{ul}}{B_{ul}}\frac{1}{(\frac{n_l}{n_u}\frac{B_{lu}}{B_{ul}} - 1)} = \frac{2h\nu^3}{c^2}\frac{1}{(\frac{n_l}{n_u}\frac{g_u}{g_l} - 1)} = [\frac{g_u}{g_l} = \frac{n_u^*}{n_l^*}\exp(h\nu/kT)] \approx$$

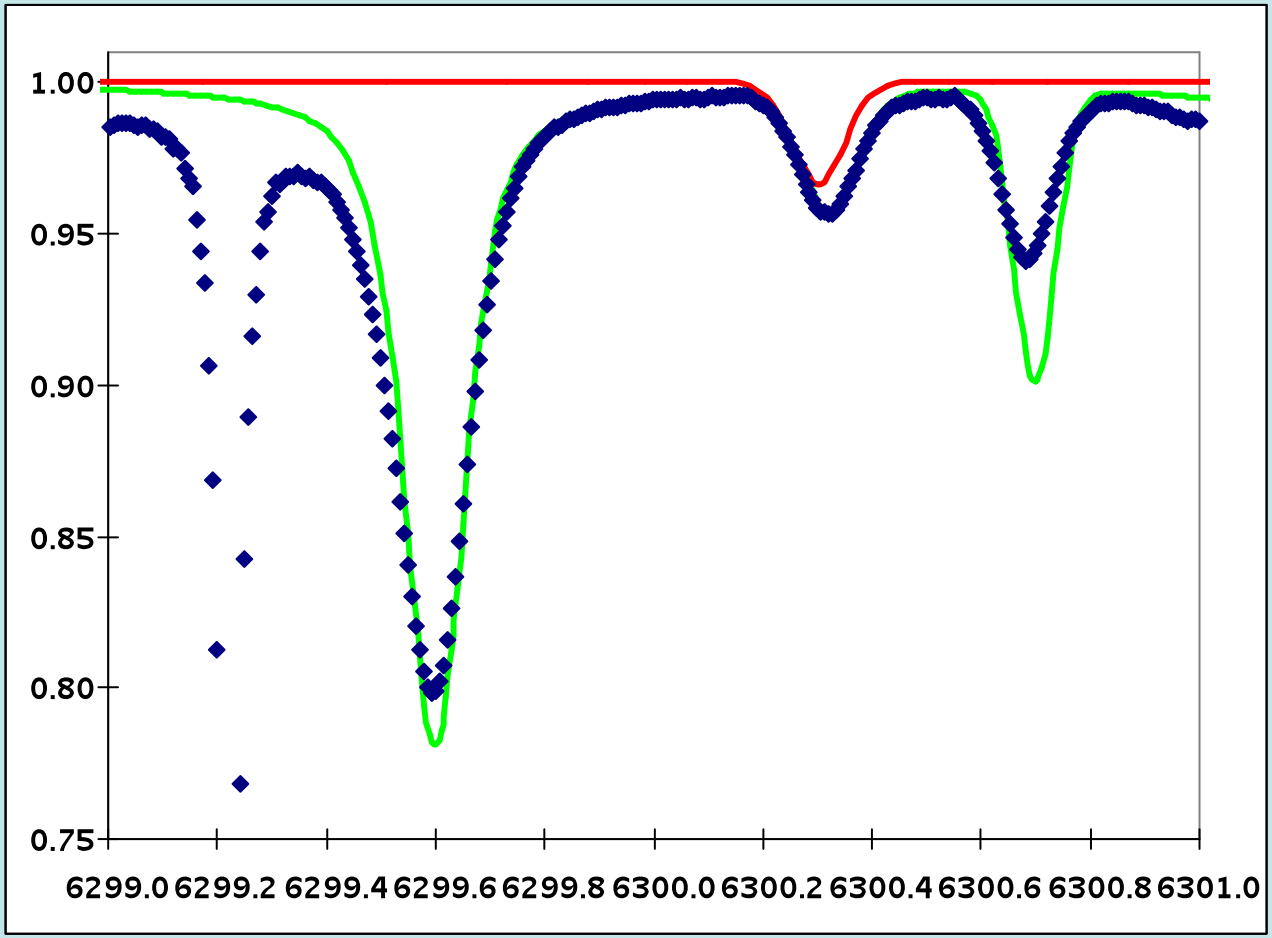
$$\frac{n_u}{n_l}\frac{n_l^*}{n_u^*}\frac{2h\nu^3}{c^2}\exp(-\frac{h\nu}{kT}) = \frac{b_u}{b_l}B(T)$$

- b-factors for these levels are included in LTE synthetic code accounting all the blending lines from VALData-base.

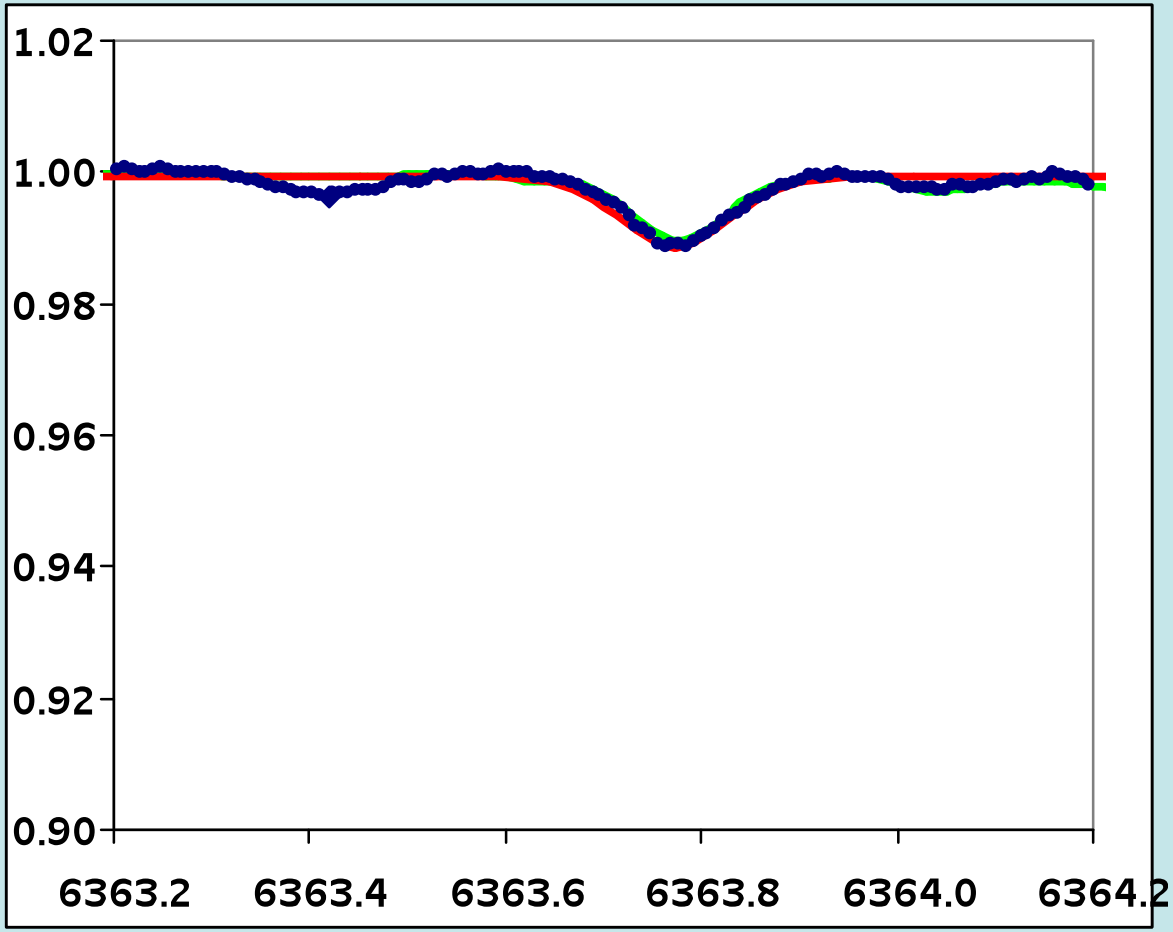
# Test calculations: Sun (Kurucz et al. 1984 spectrum) logε(O)=8.71



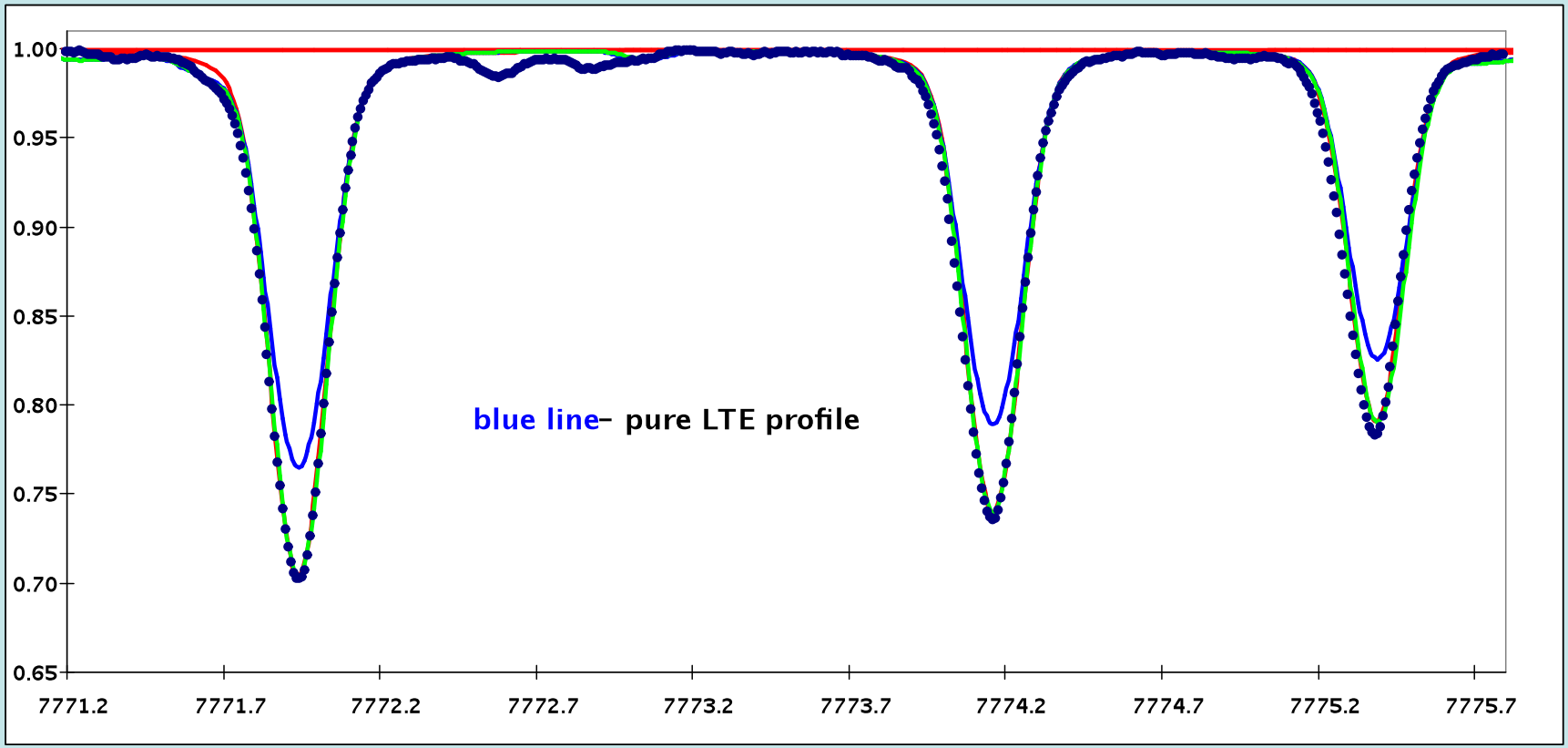
# Test calculations: Sun



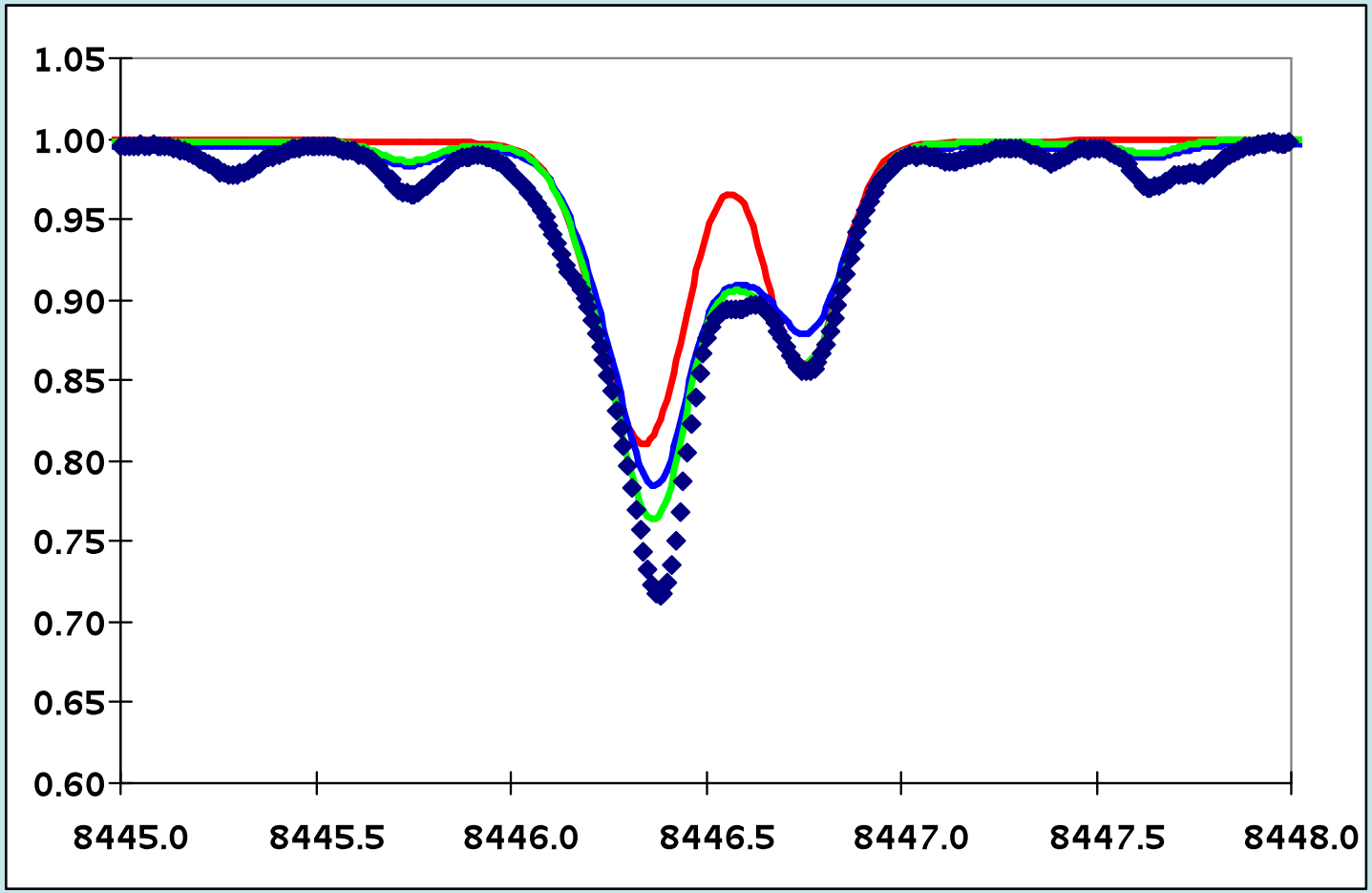
# Test calculations: Sun



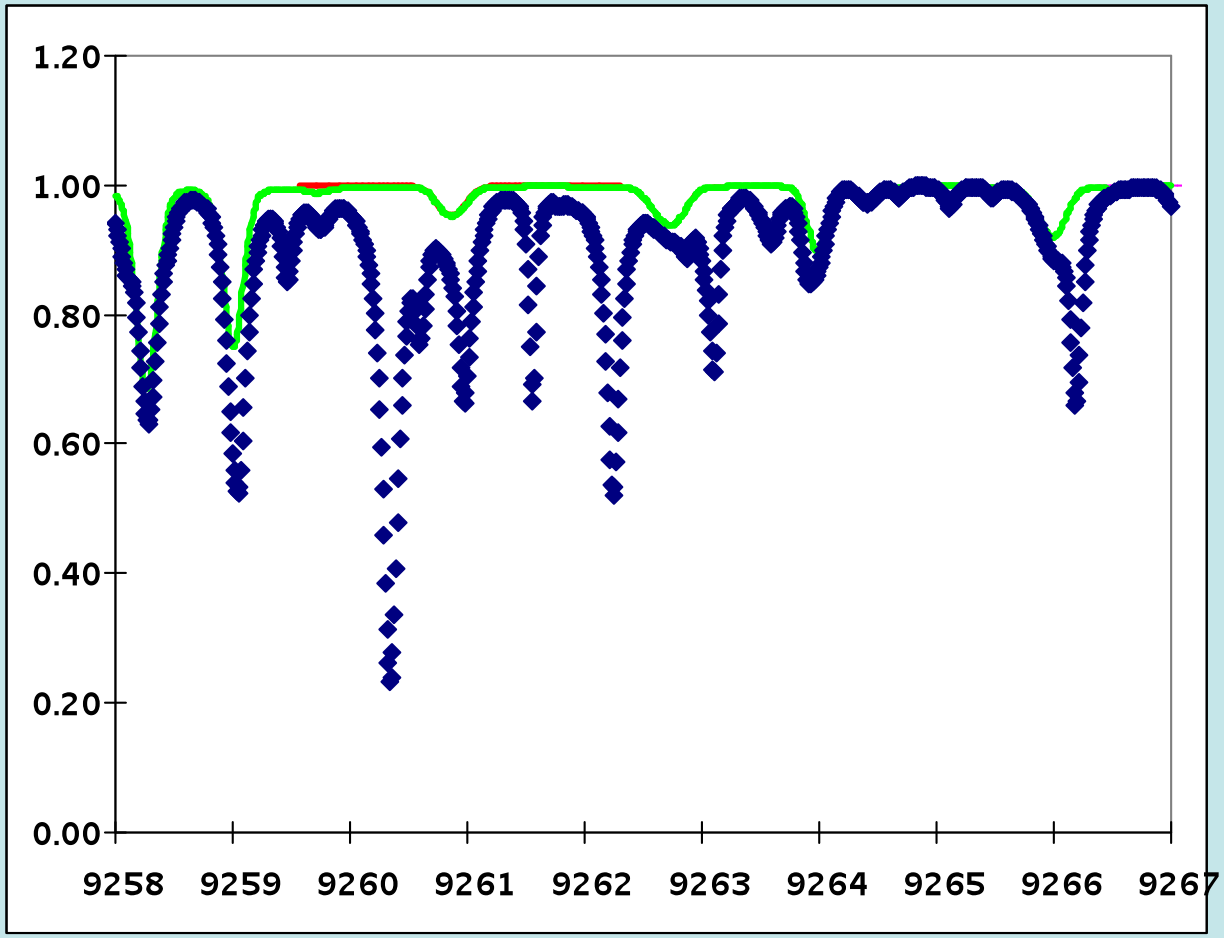
# Test calculations: Sun



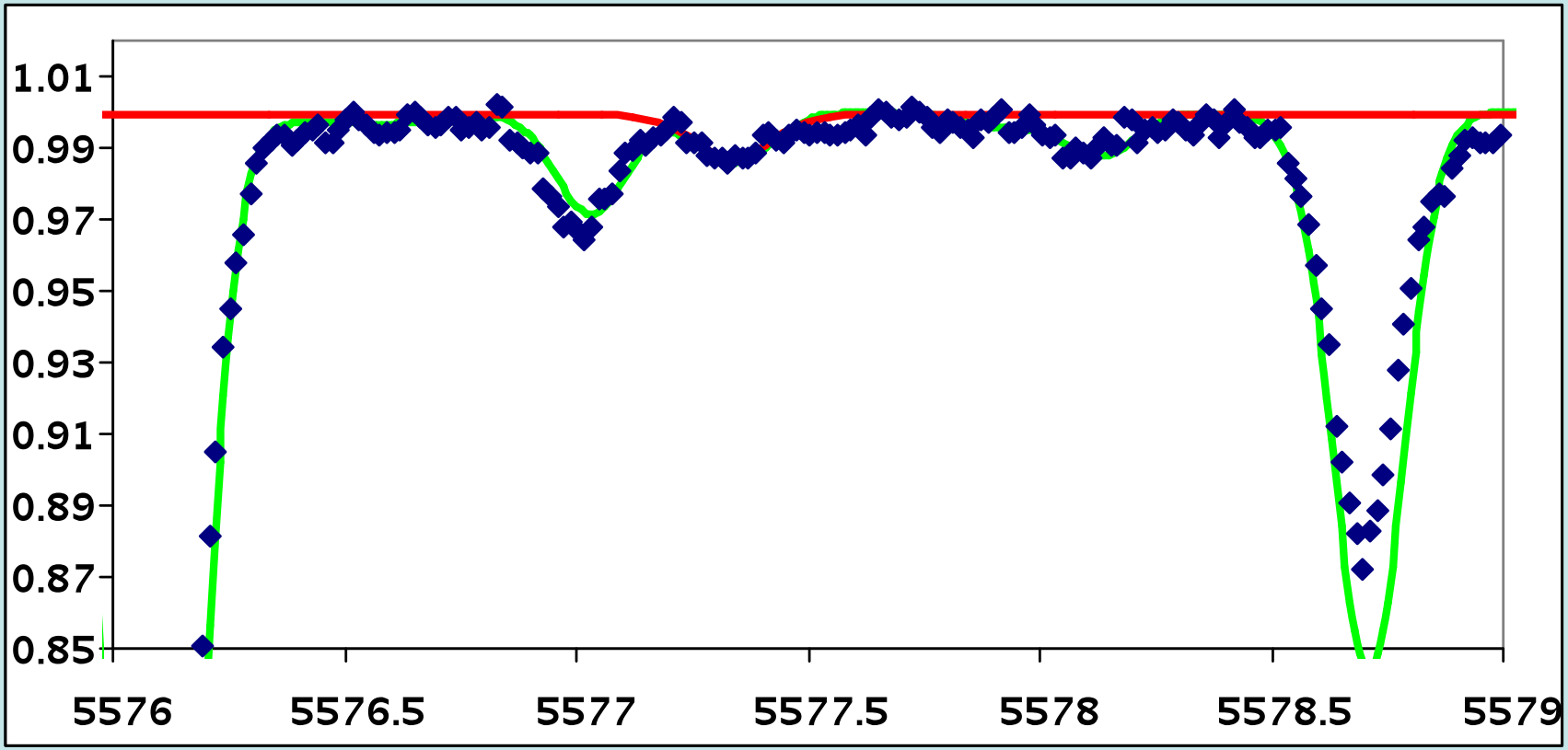
# Test calculations: Sun



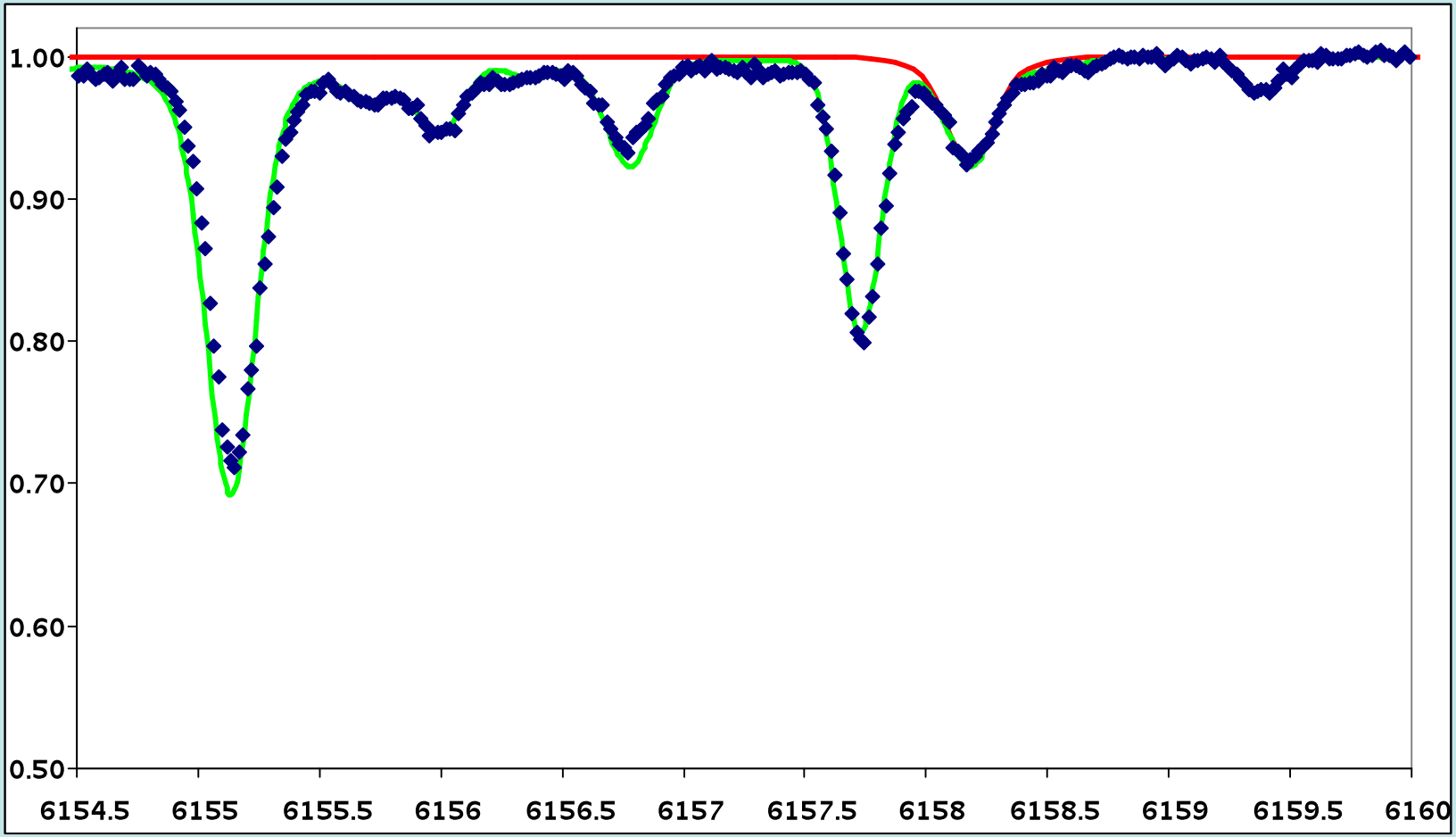
# Test calculations: Sun



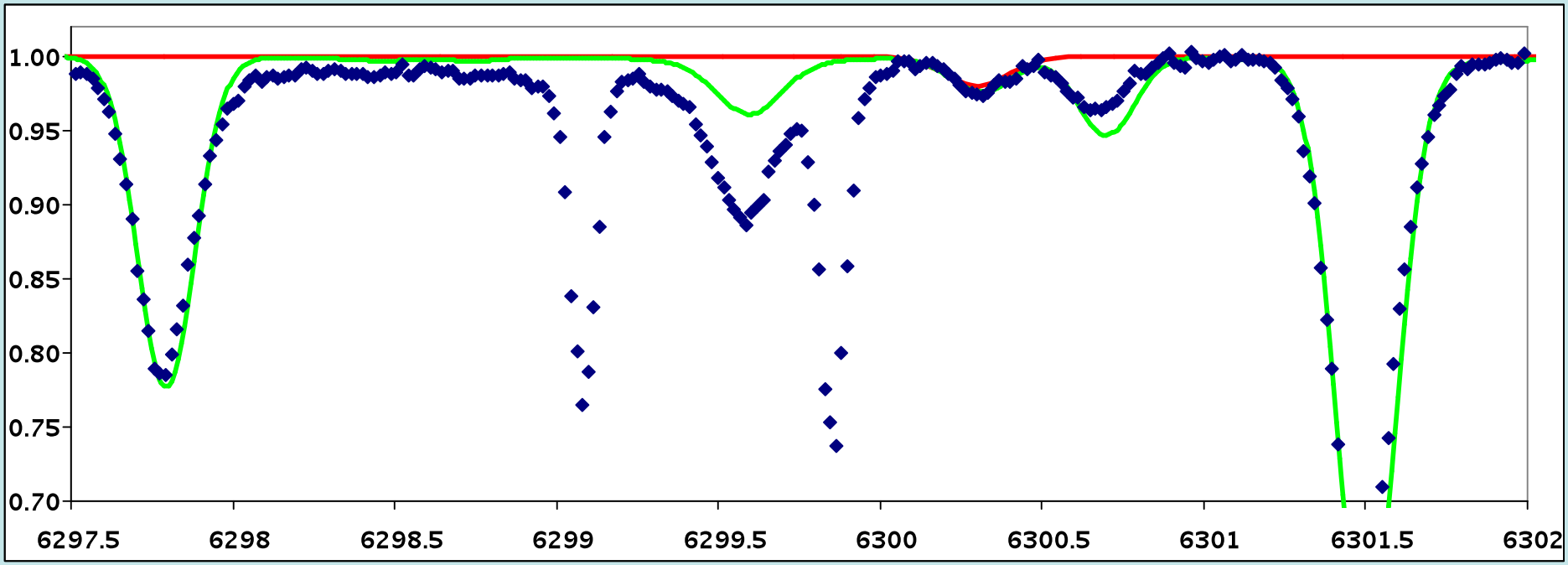
# Test calculations: Procyon (VLT archive spectrum) Teff=6600 K, logg = 4.0 logε(O) = 8.81



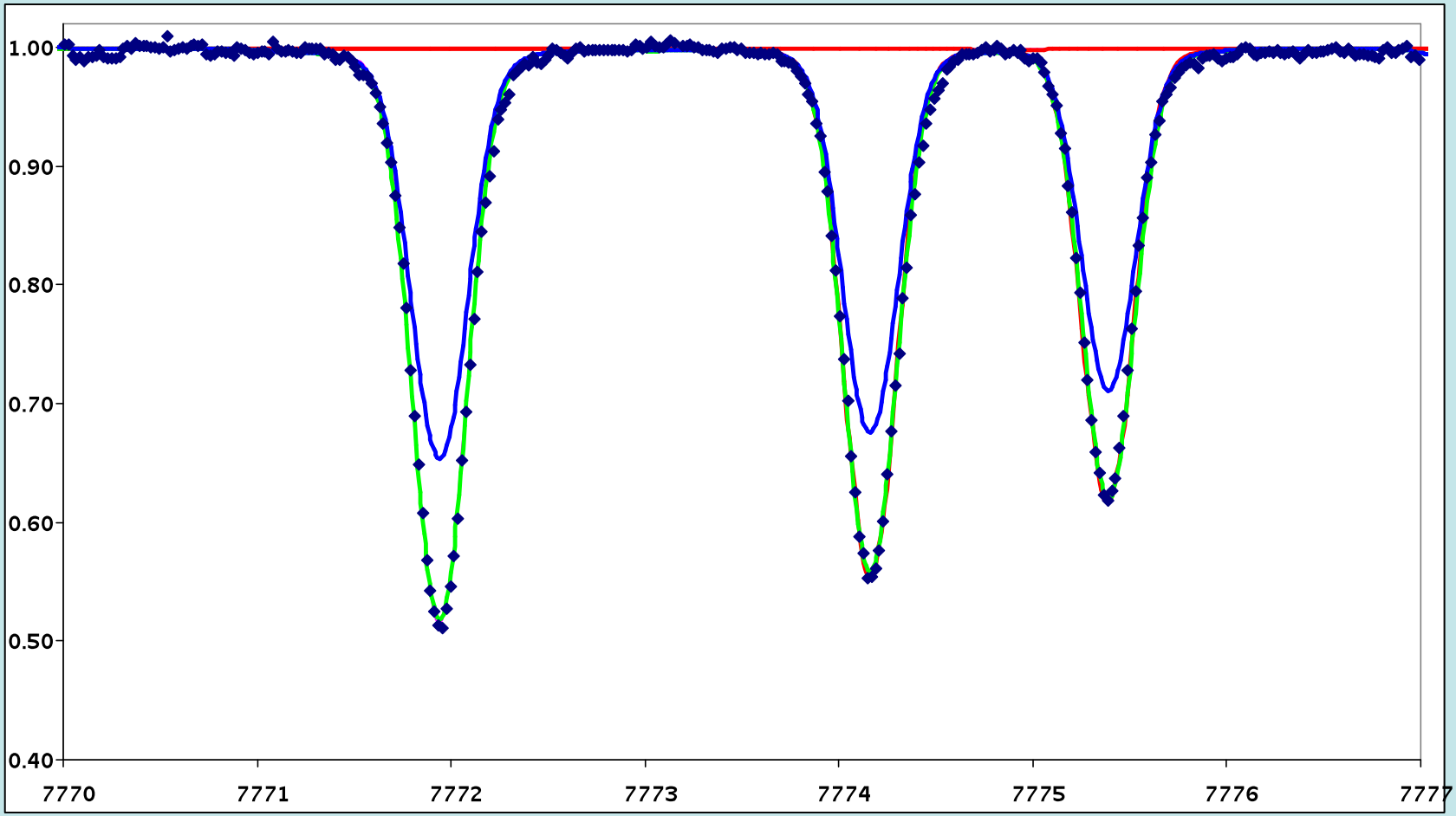
# Test calculations: Procyon



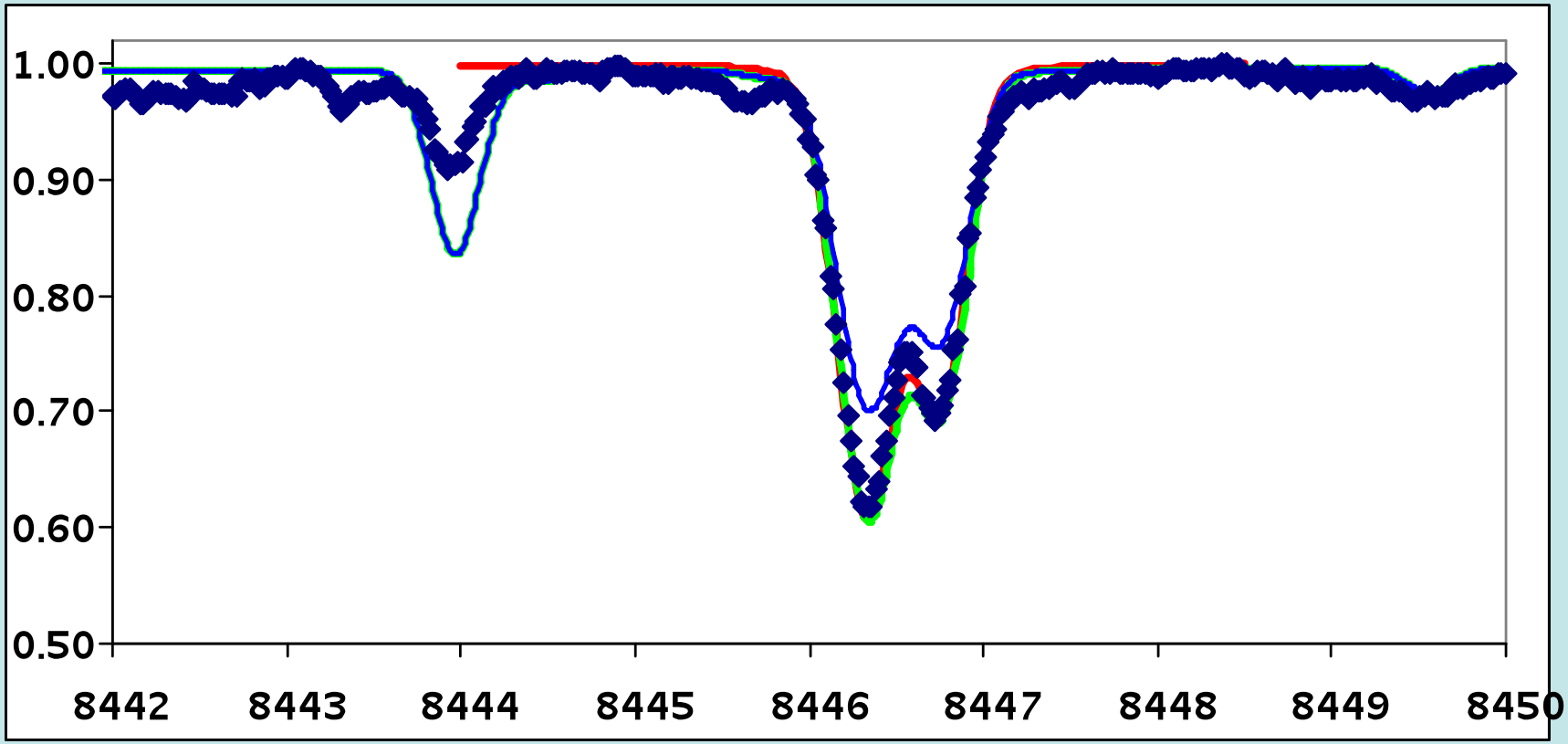
# Test calculations: Procyon



# Test calculations: Procyon



# Test calculations: Procyon



# Test calculations: conclusions

**One can conclude that all oxygen lines are quite well reproduced with our adopted OI atomic model in our test spectra.**

# Oxygen lines in giants and super-giants: examples for real (not ideal) spectra. Evolution with Teff.

**Cepheid AG Cru:**

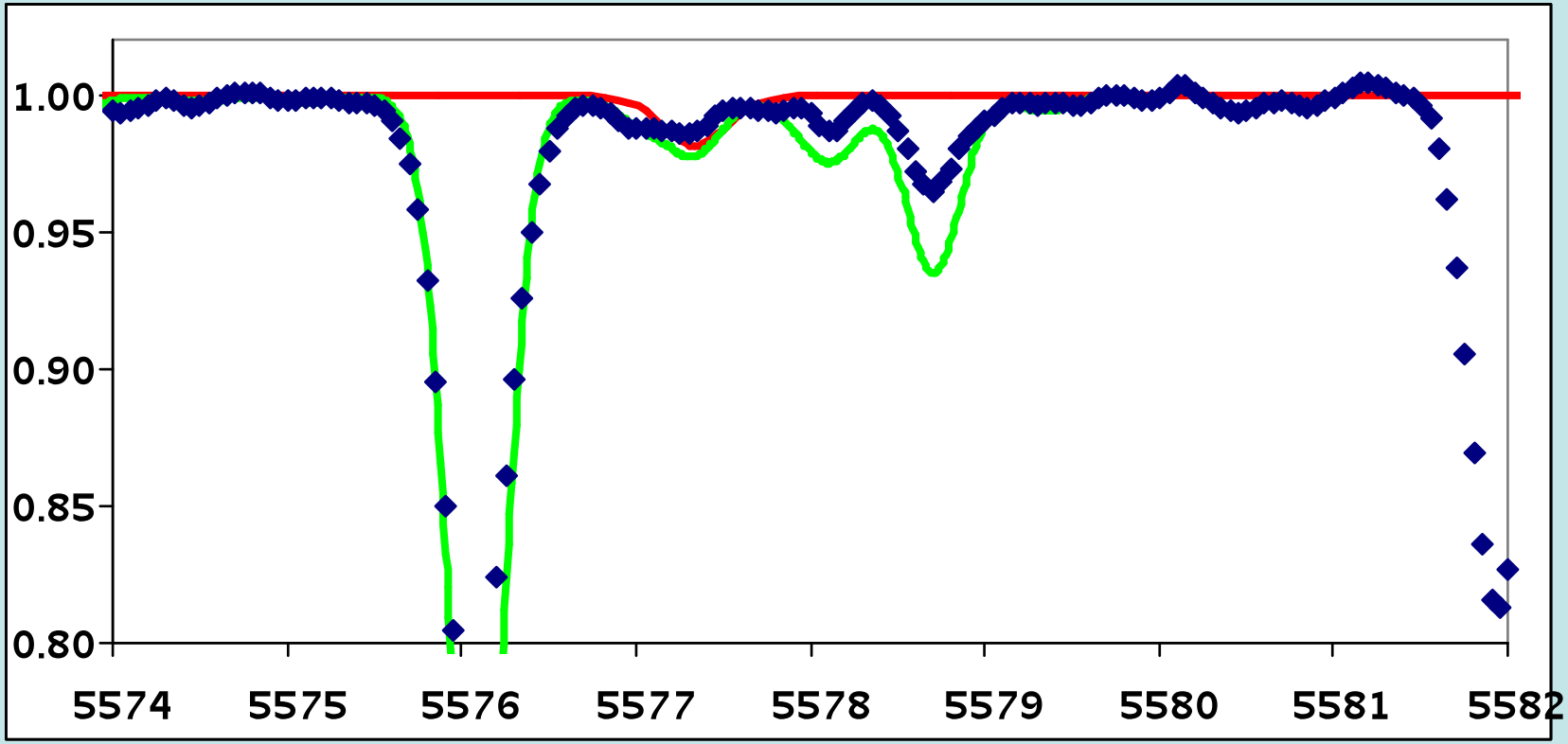
**Teff = 6628 K, logg=2.2**

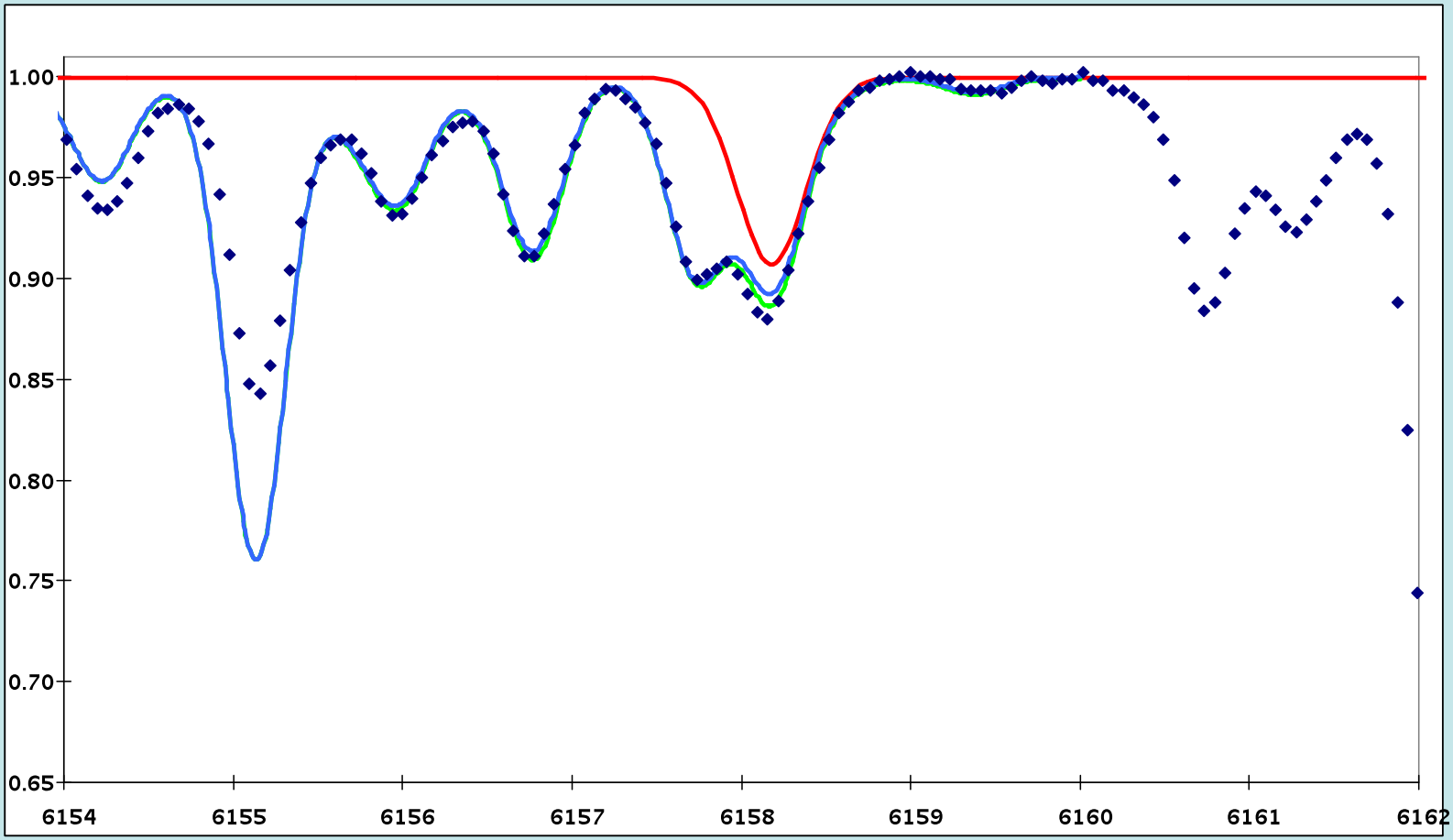
**$\log\varepsilon(O) = 8.69$**

**ESO MPG 220 cm FEROS**

**R ≈ 48000**

# The stellar 5577 OI line is distorted by the green aurora component




1.00
0.95
0.90
0.85
0.80
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0.65
6154
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6160
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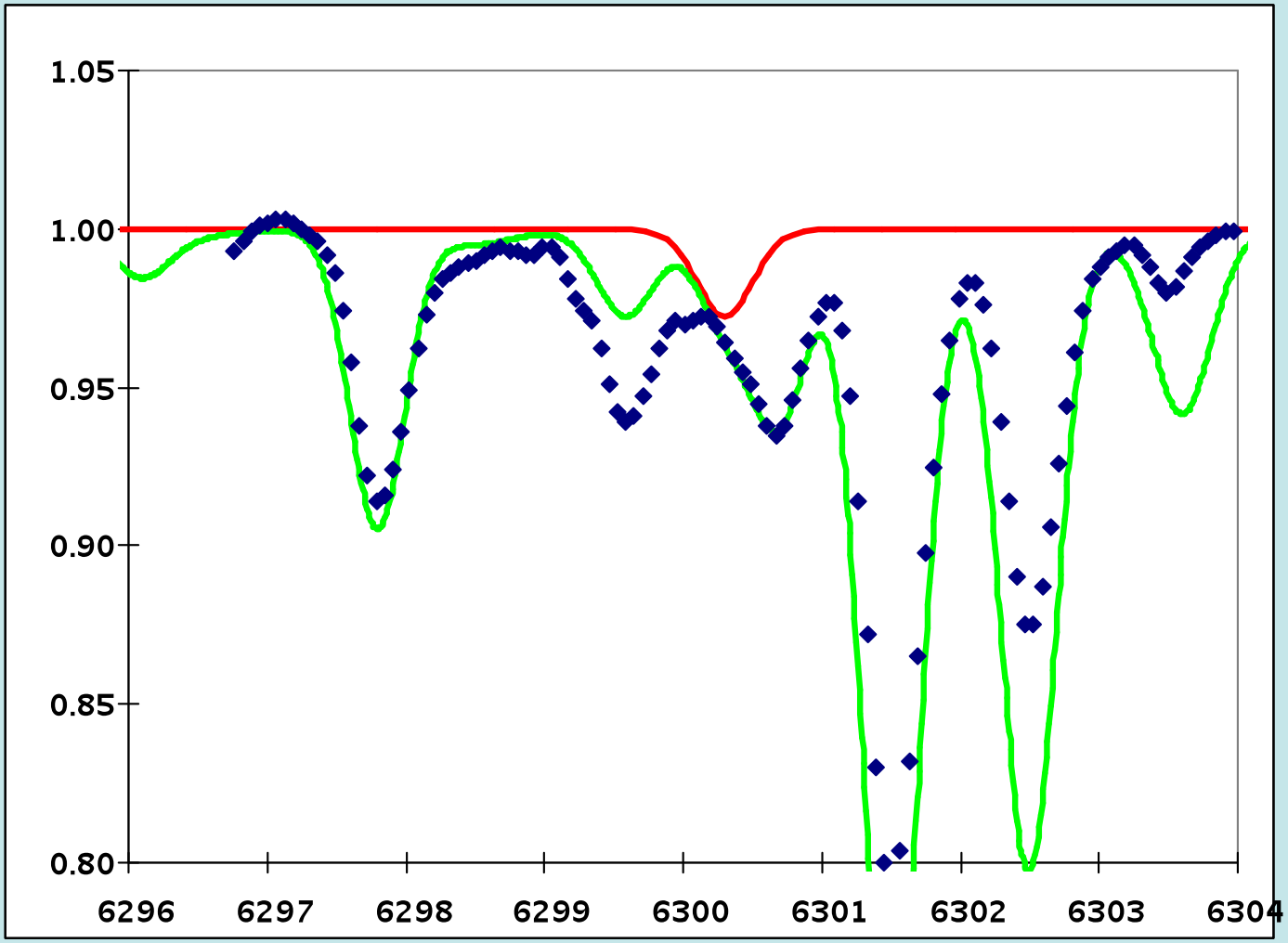
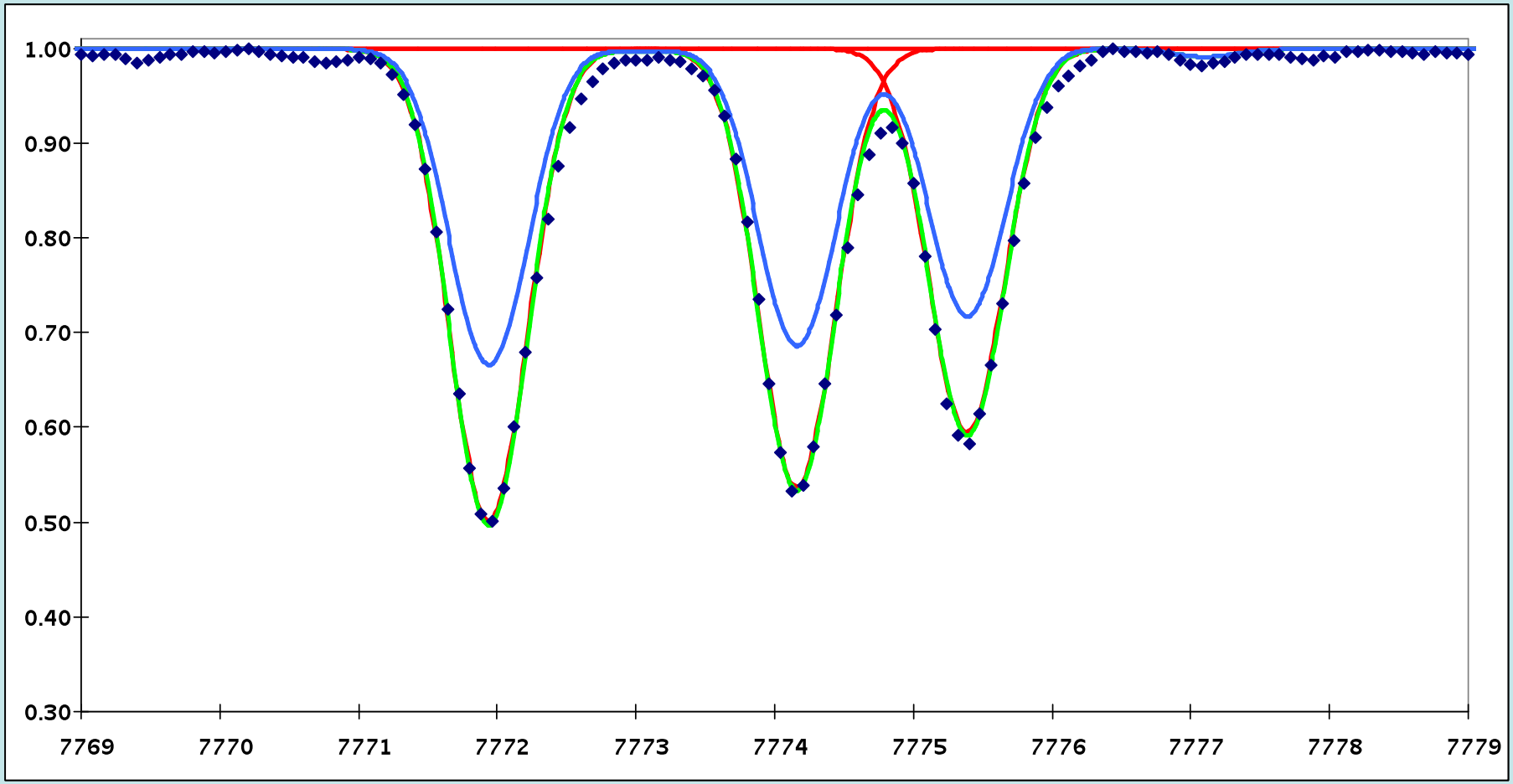
6162

# Telluric lines are removed

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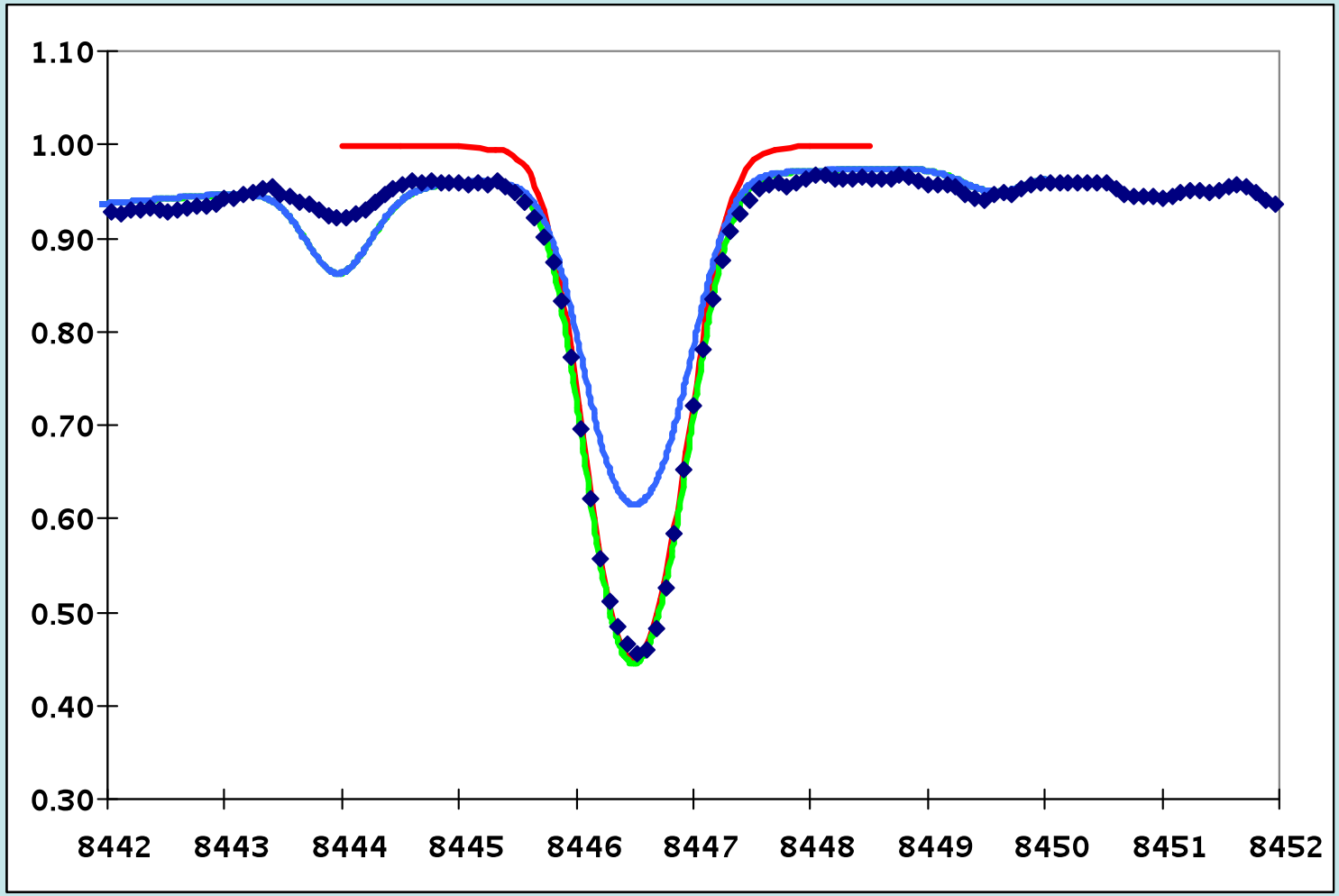
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8442
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8450
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8452

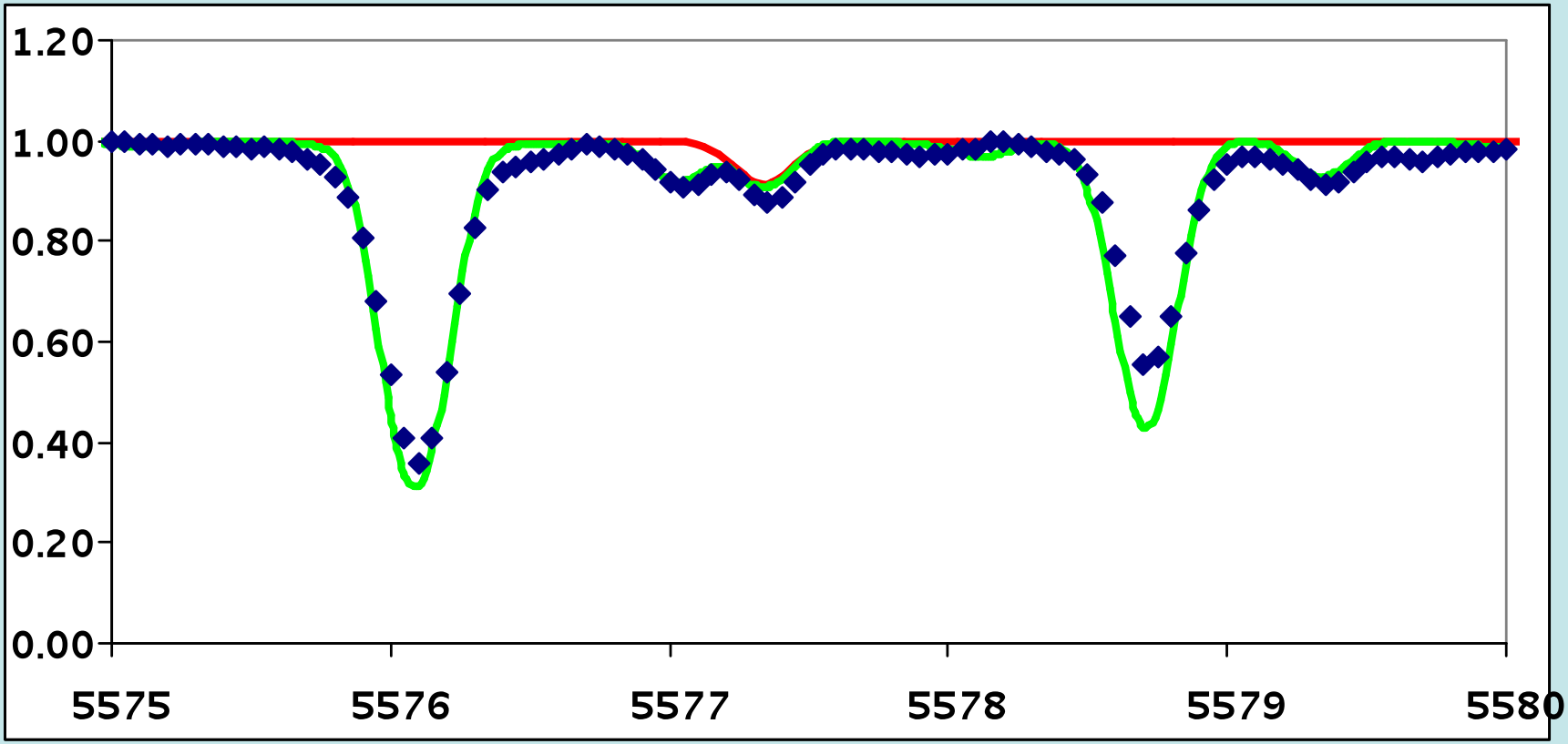
**Cepheid U Nor:**

**Teff = 5426 K, logg=1.4**

**$\log\varepsilon(O) = 8.72$**

**ESO MPG 220 cm FEROS**

**R ≈ 48000**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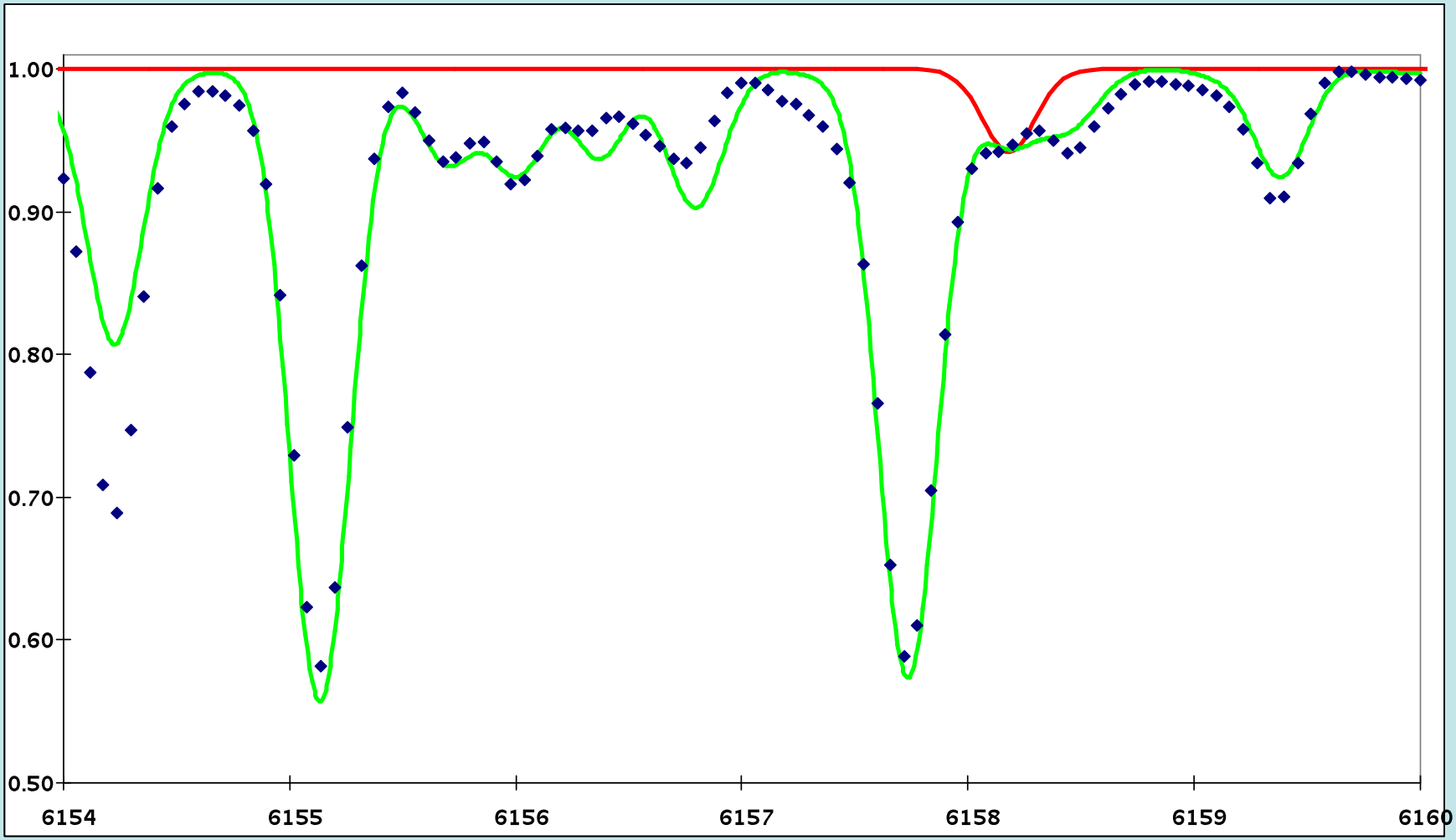
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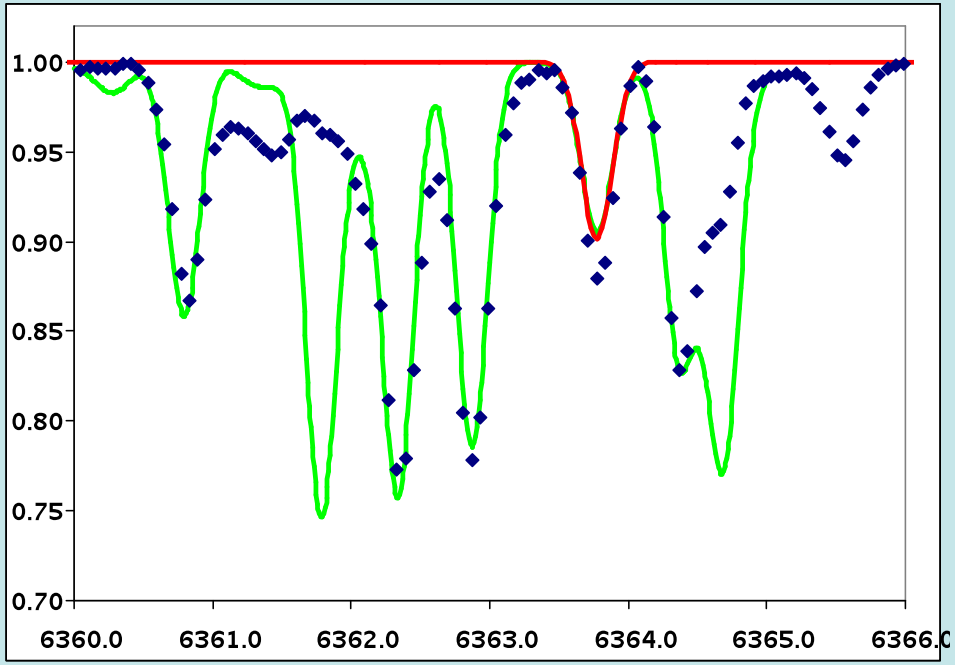
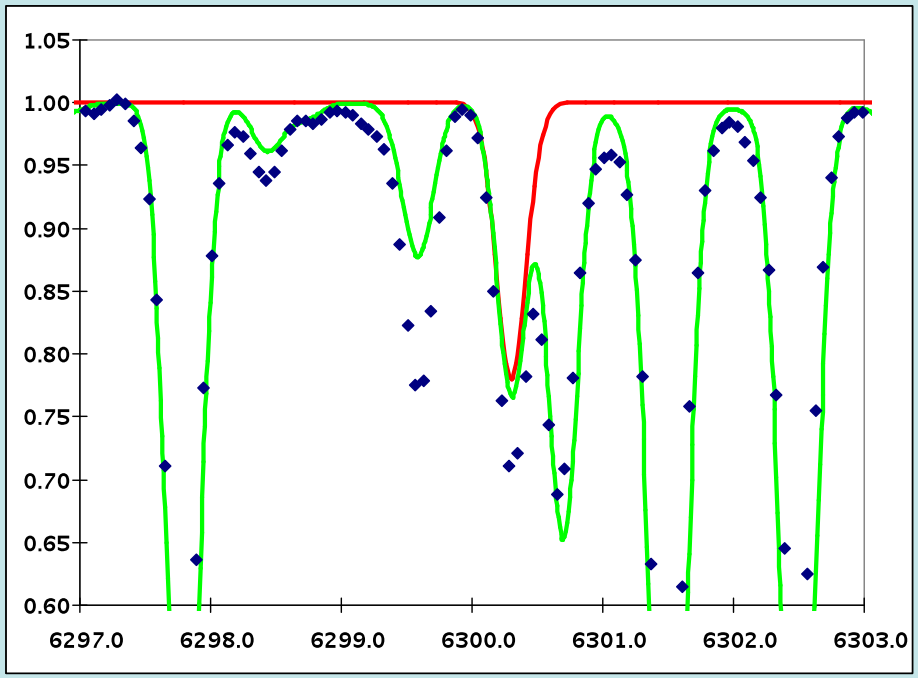
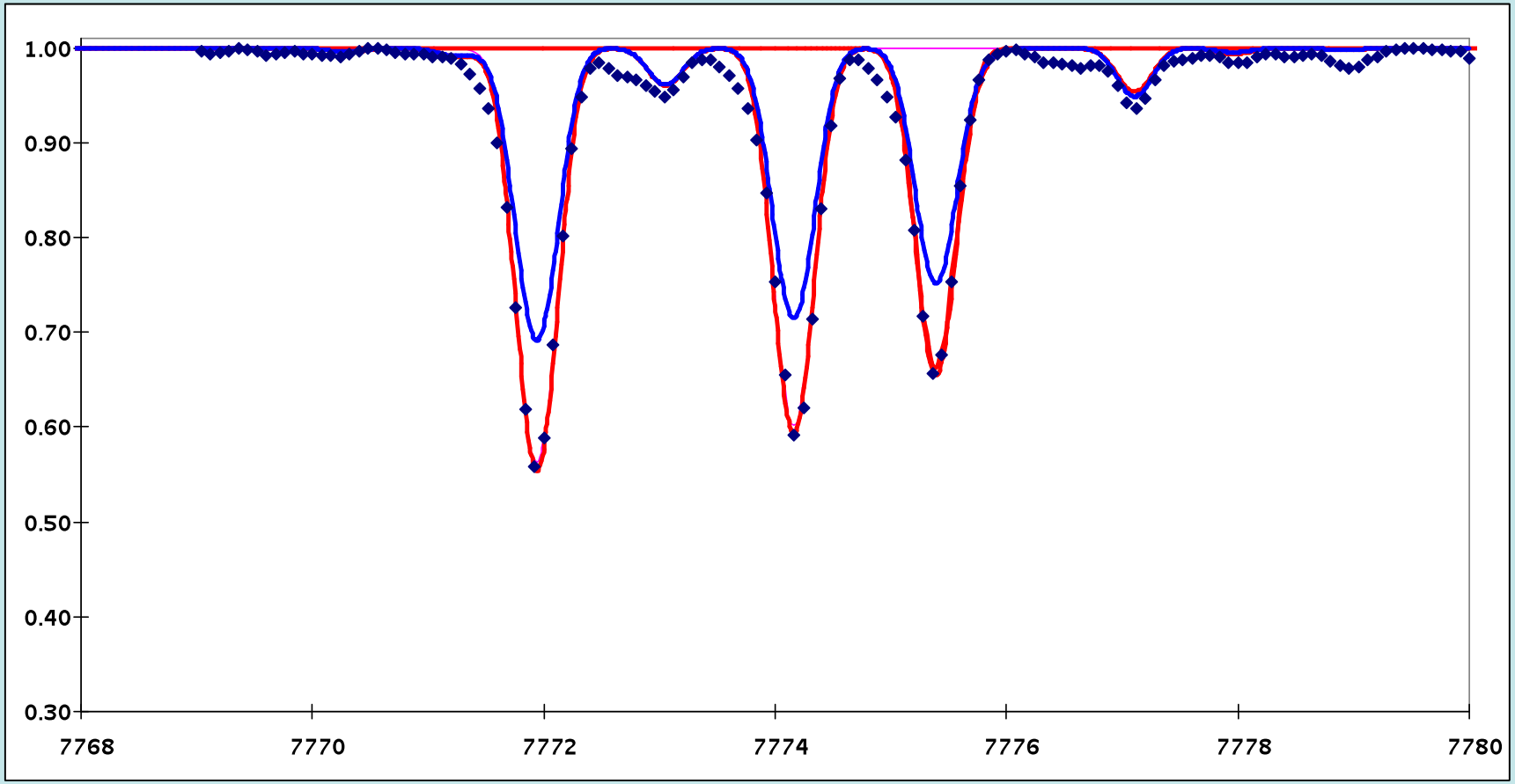



# Telluric lines are removed

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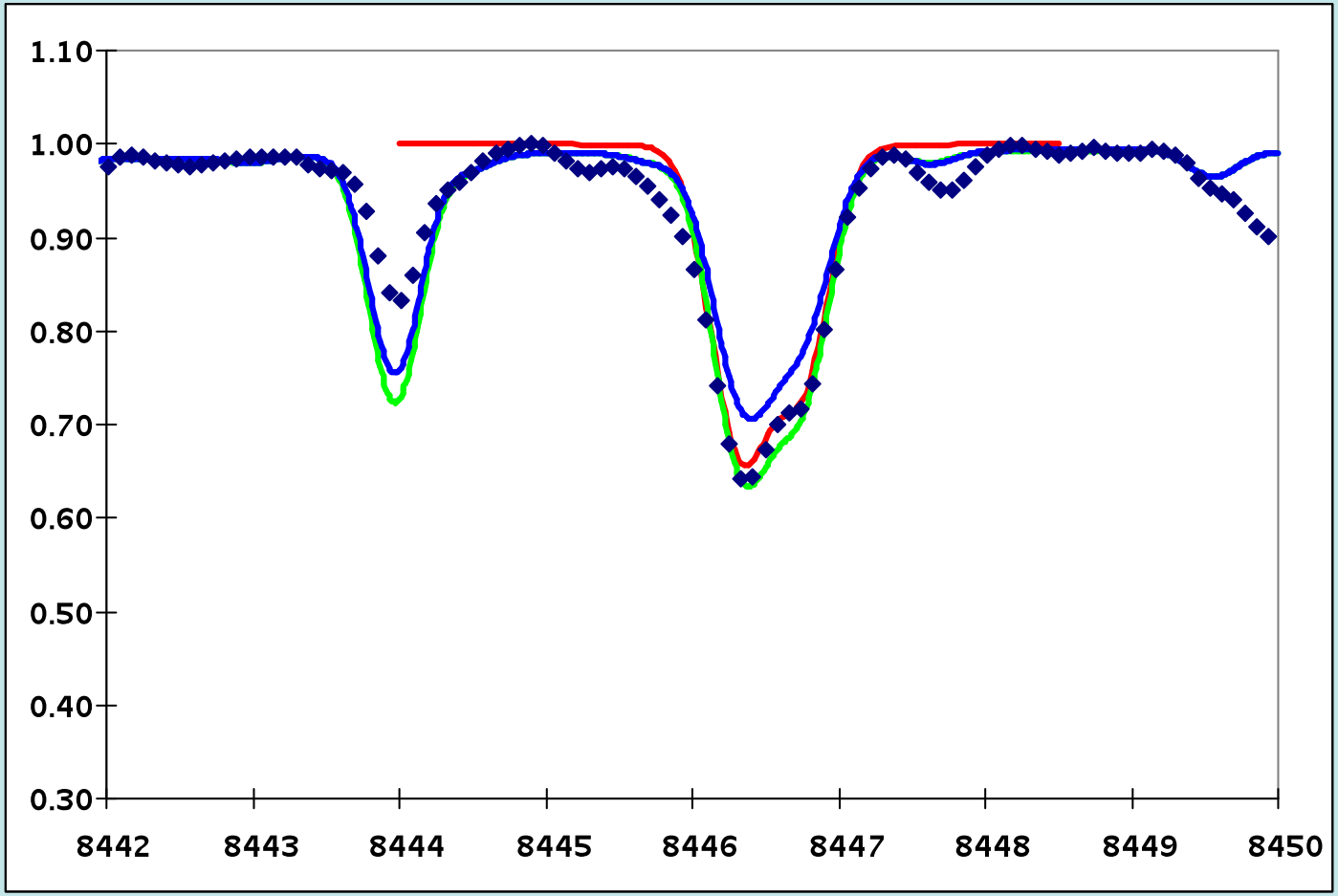
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8442
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8450

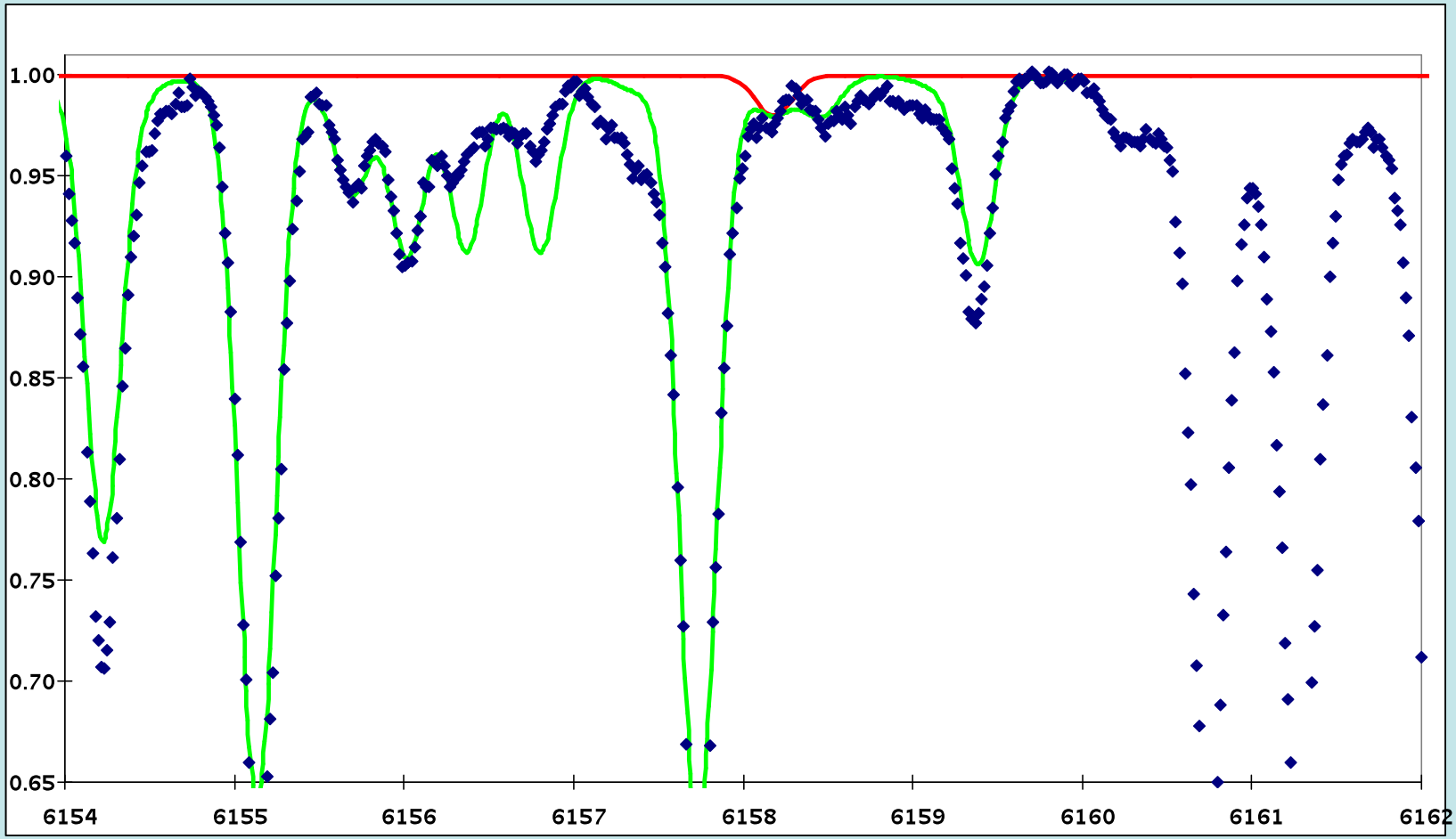
**Bright giant HD109379:**

**Teff = 5144 K, logg=2.3**

**$\log\varepsilon(O) = 8.65$**

**ESO VLT UVES**

**$R \approx 80\ 000$**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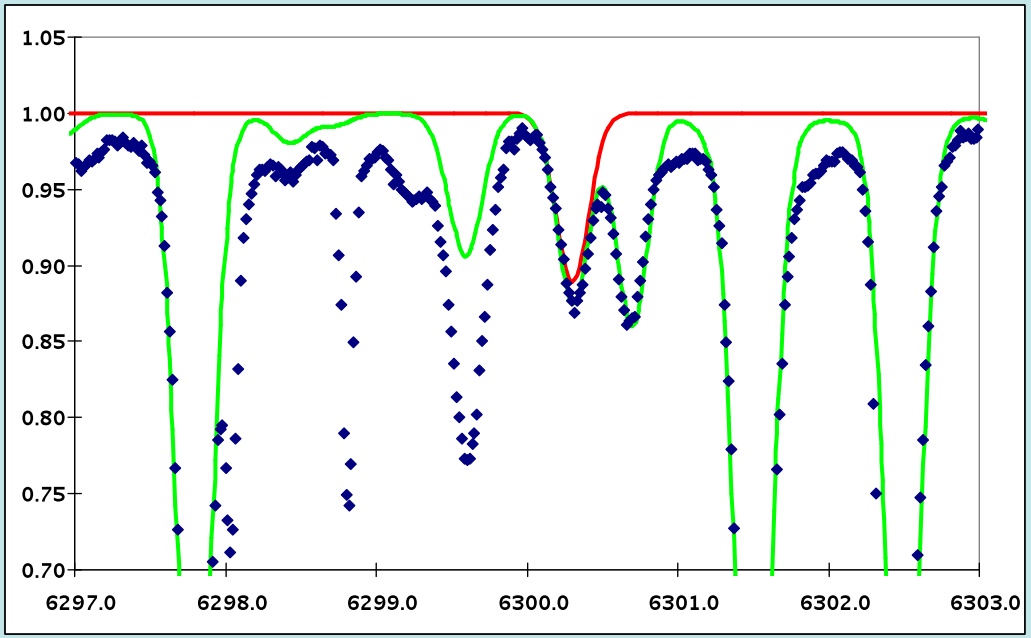
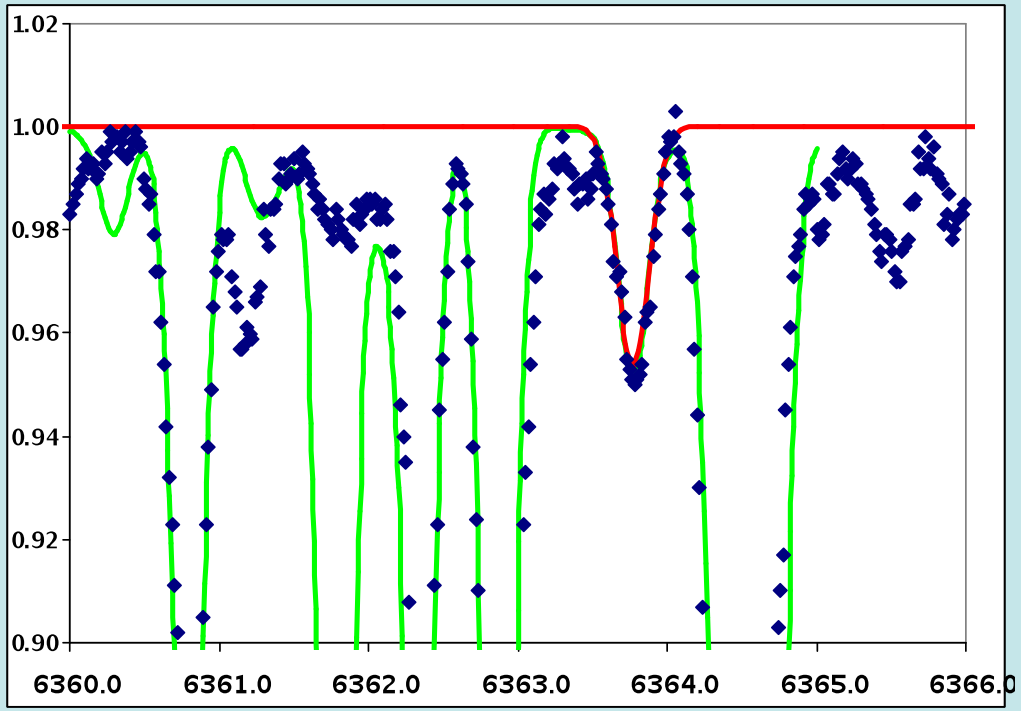
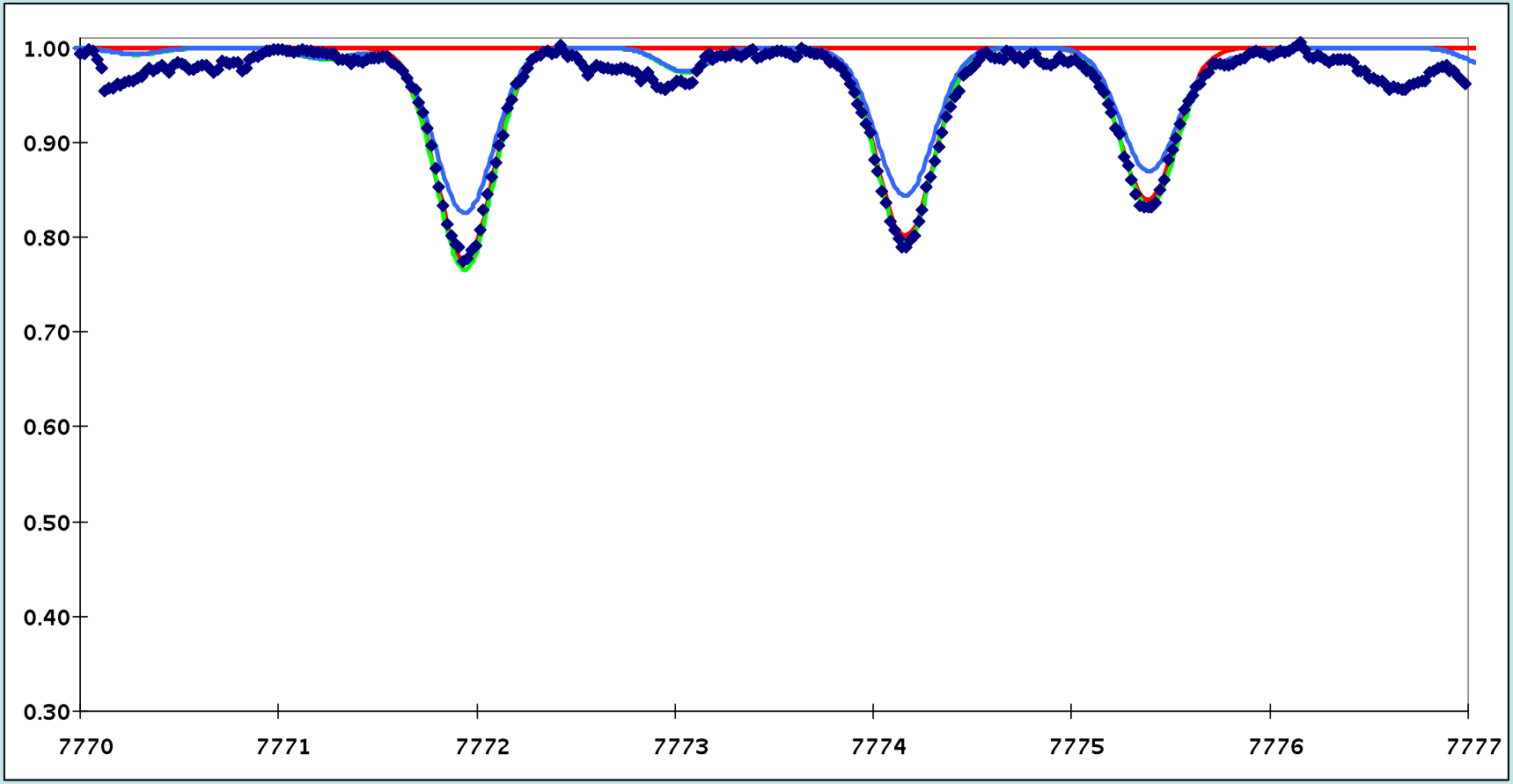



**Telluric lines are not removed**

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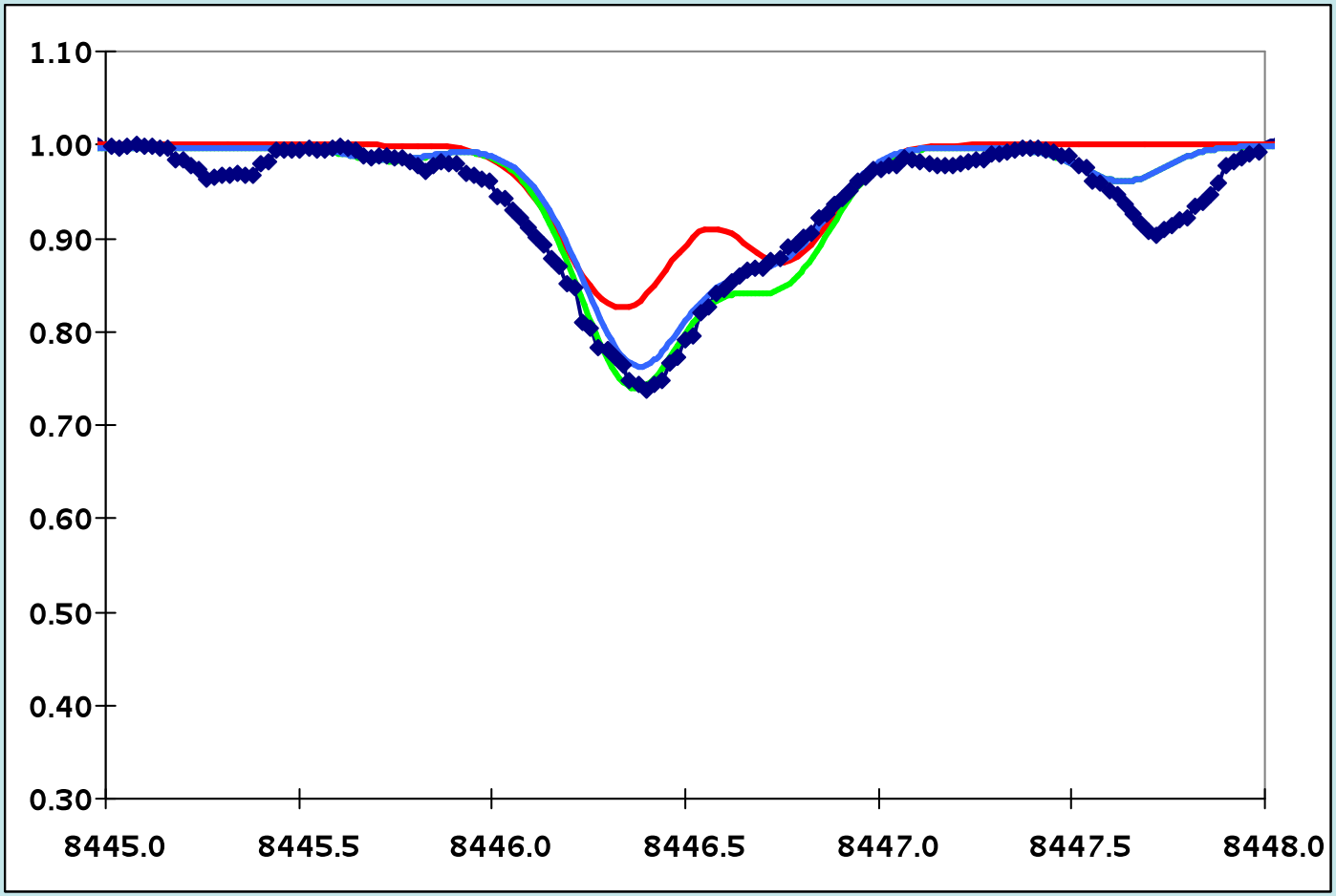
1.10
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0.80
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0.60
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0.40
0.30
8445.0
8445.5
8446.0
8446.5
8447.0
8447.5
8448.0

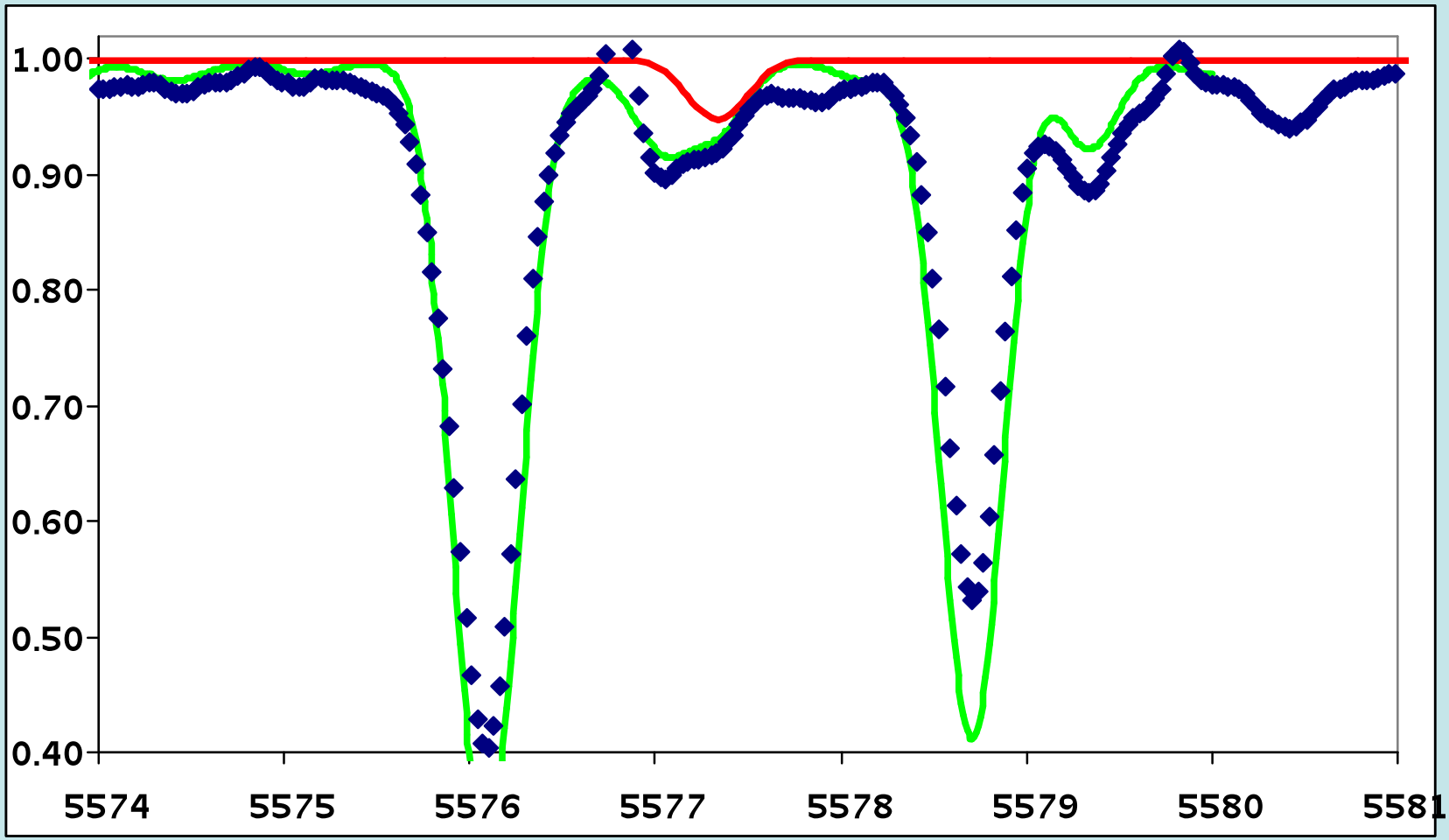
**Cepheid SV Mon:**

**Teff = 4924 K, logg=1.1**

**logε(O) = 8.56**

**ESO 152 cm FEROS**

**R ≈ 48000**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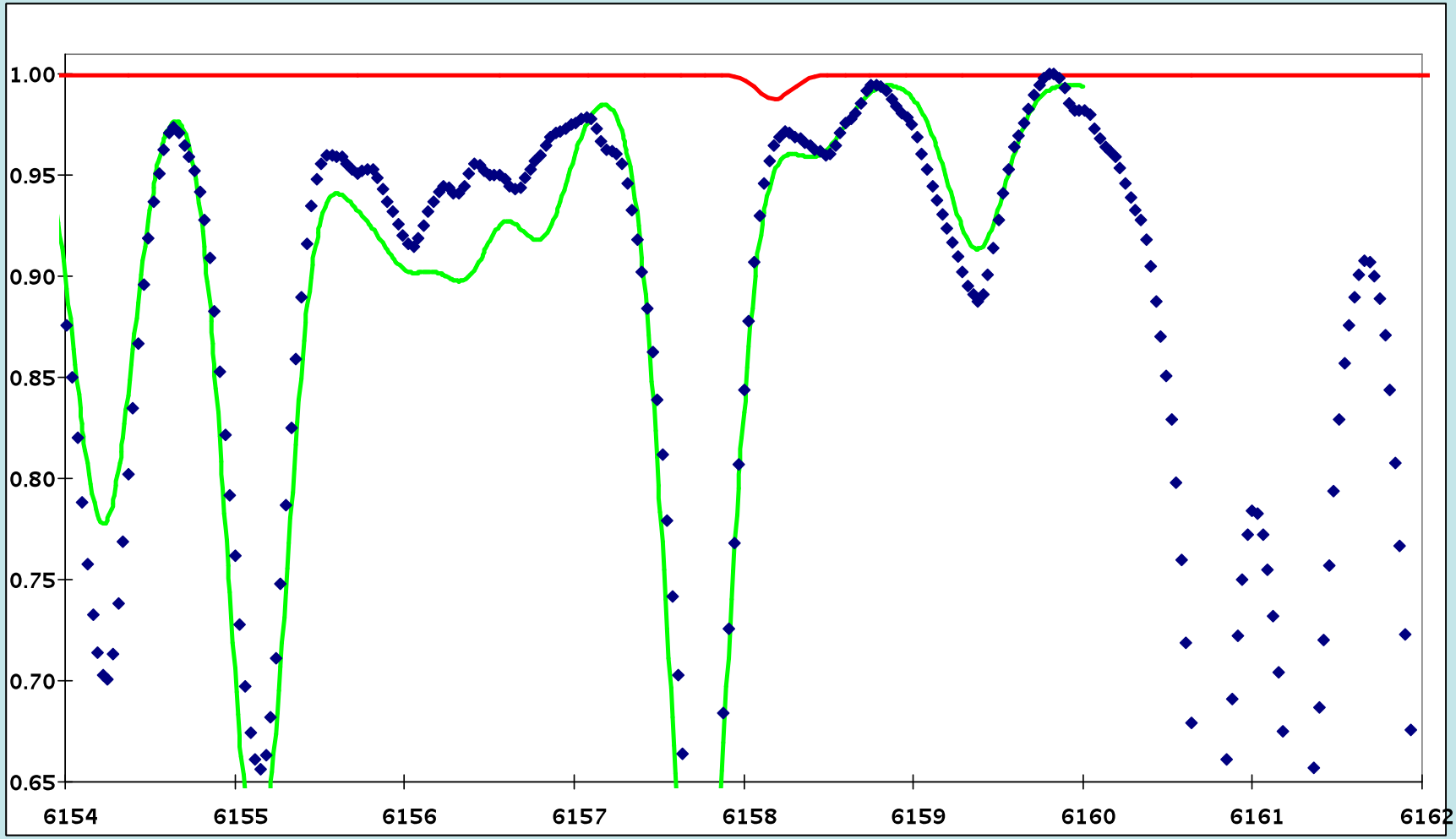
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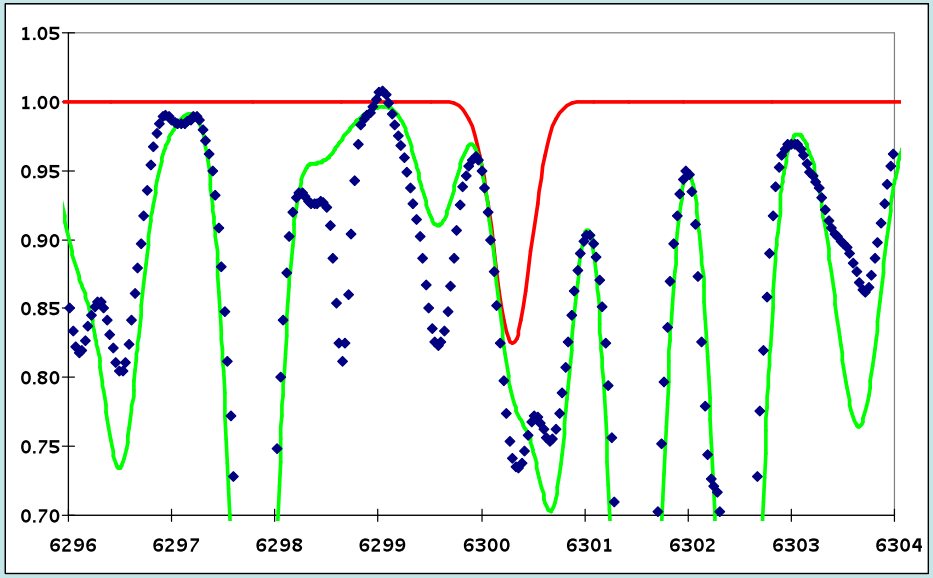
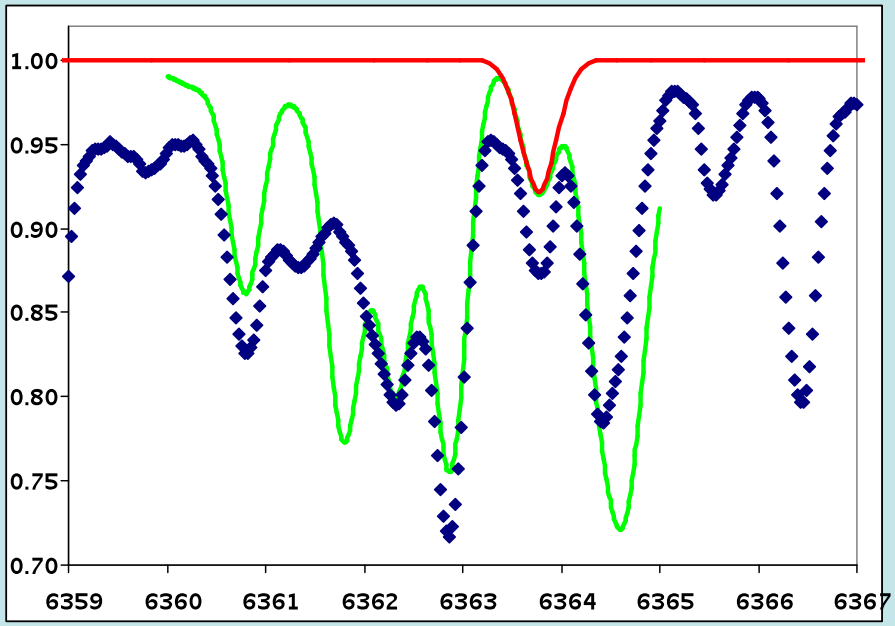
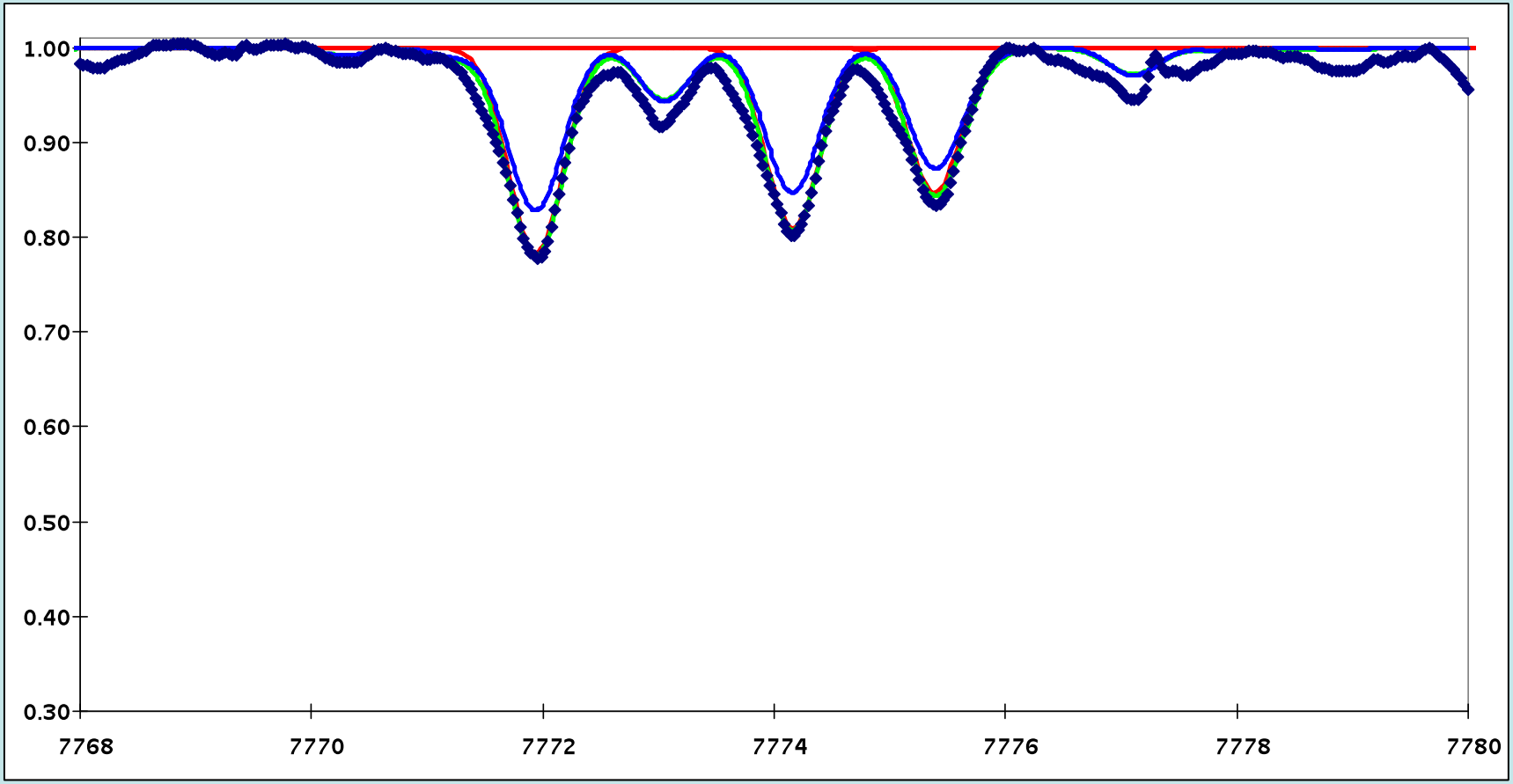



**Telluric lines are not removed**
**The fit is very bad**

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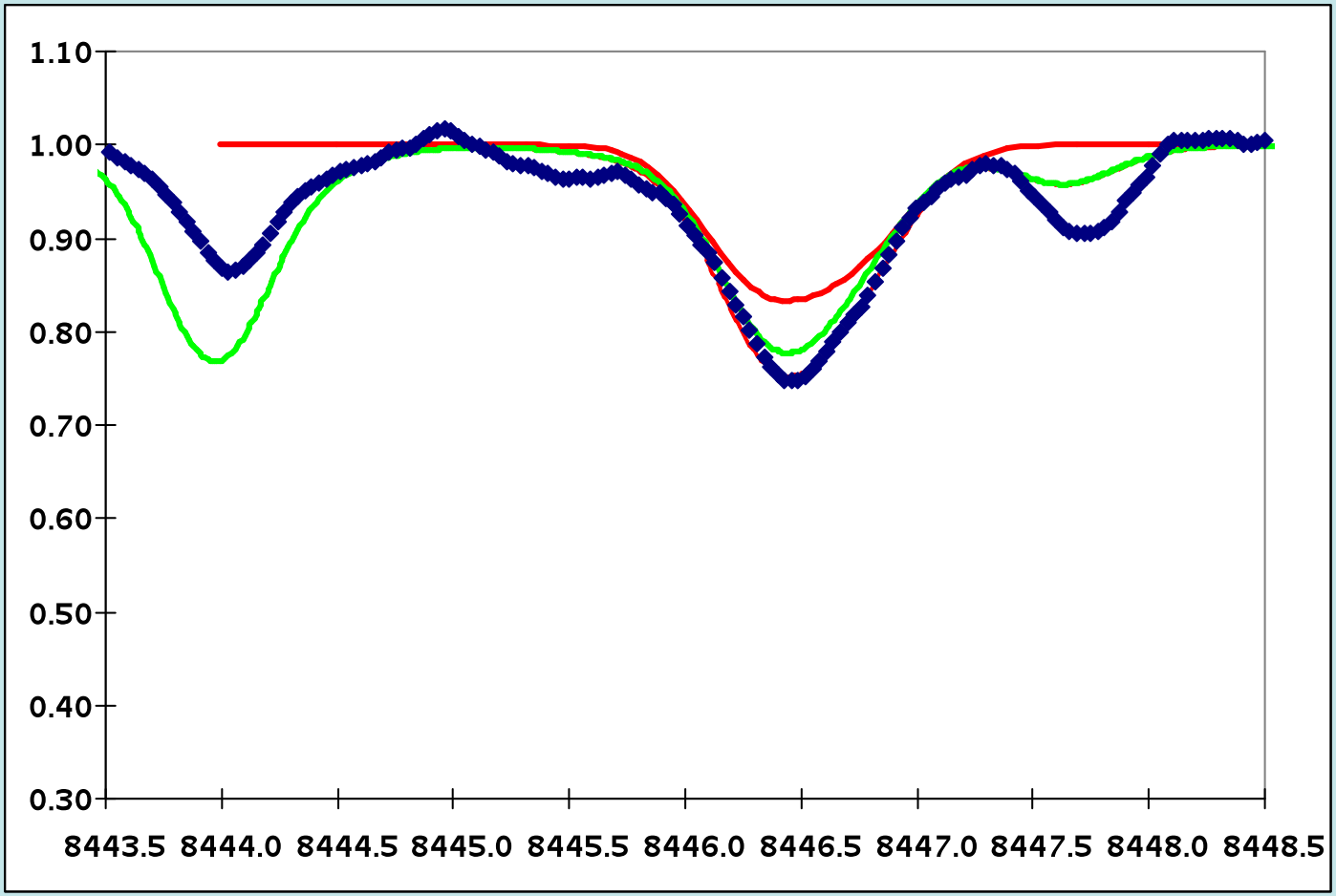
7778
7780


1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
8443.5
8444.0
8444.5
8445.0
8445.5
8446.0
8446.5
8447.0
8447.5
8448.0
8448.5

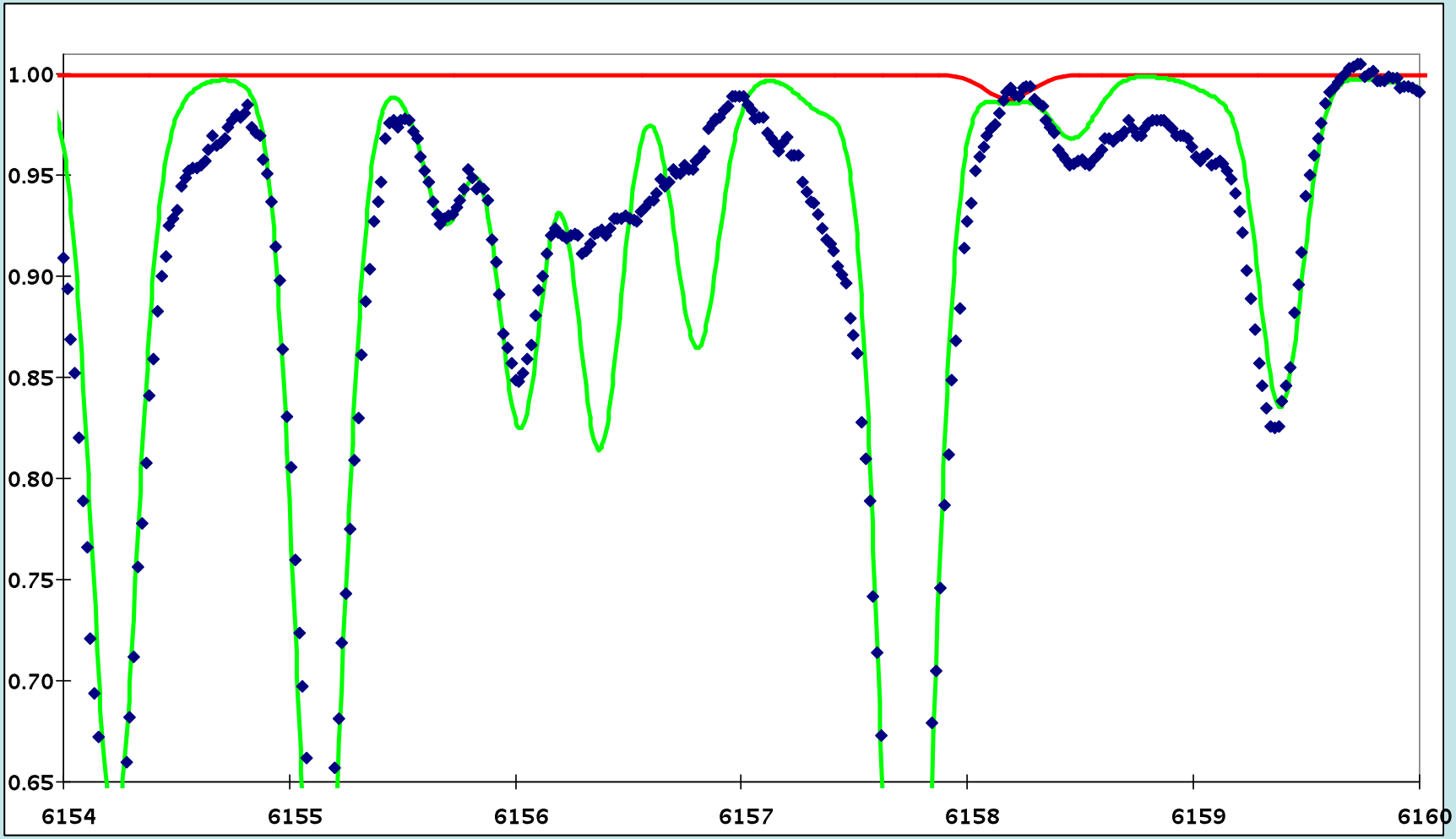
**Non-variable supergiant HD117440:**

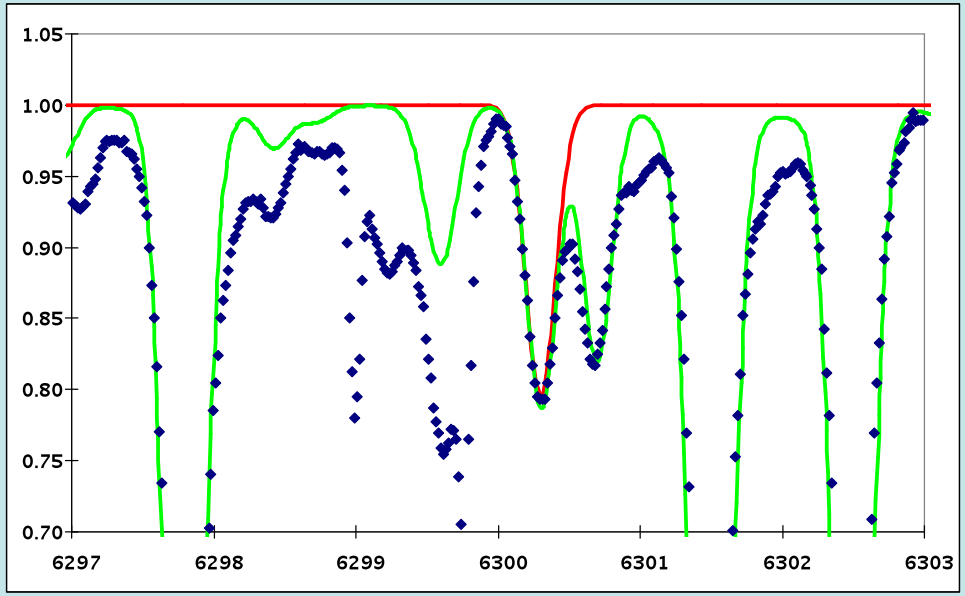
**Teff = 4741K, logg=1.9**

**logε(O) = 8.71**

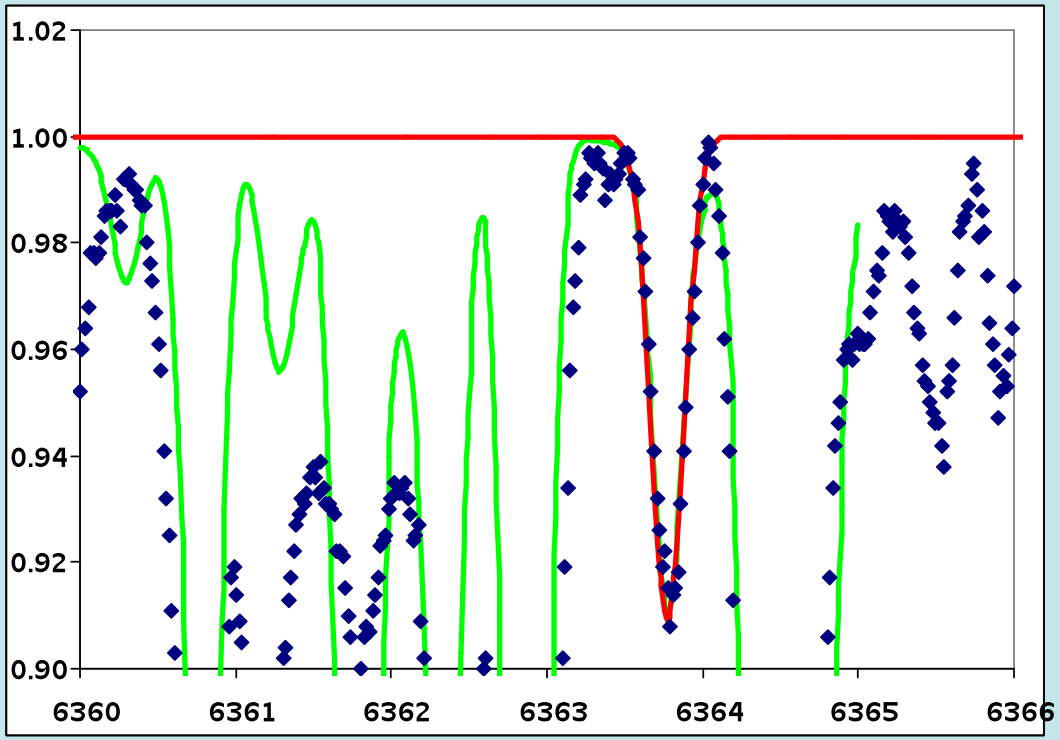
**ESO VLT UVES**

**R ≈ 80 000**

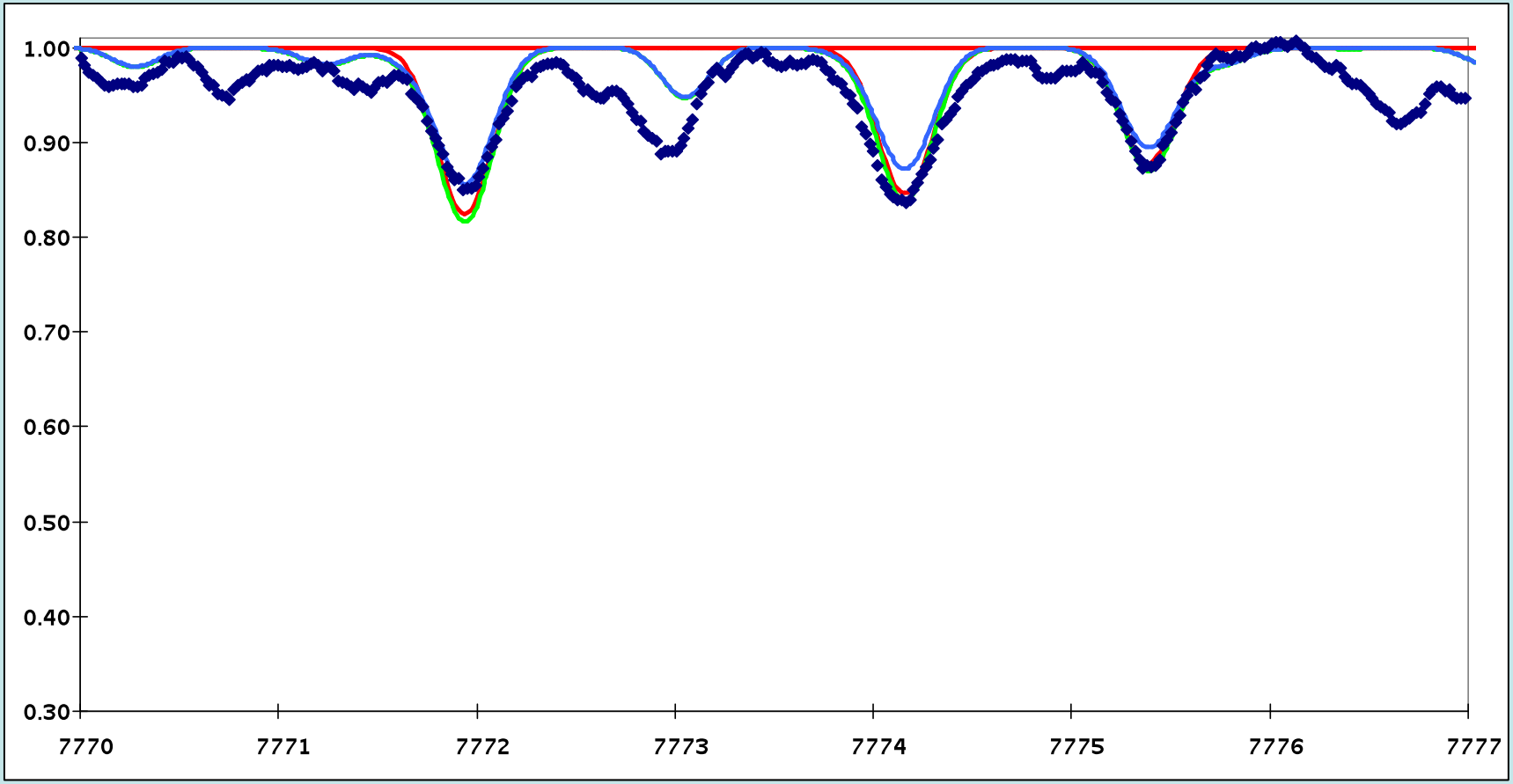

1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
6154
6155
6156
6157
6158
6159
6160




**Telluric lines are not removed**



# At this temperature CN may affect triplet



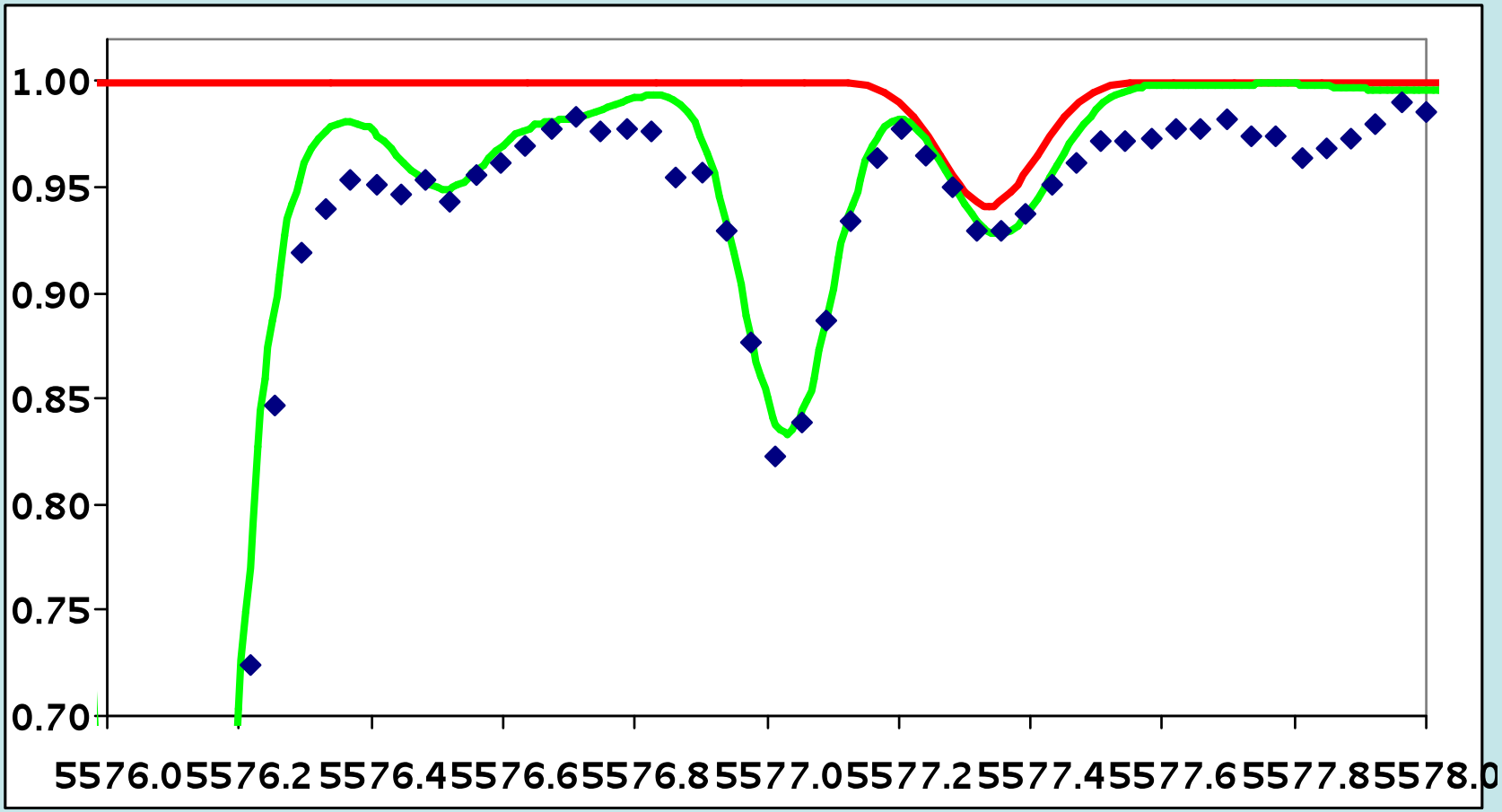
# Bright giant VW Dra

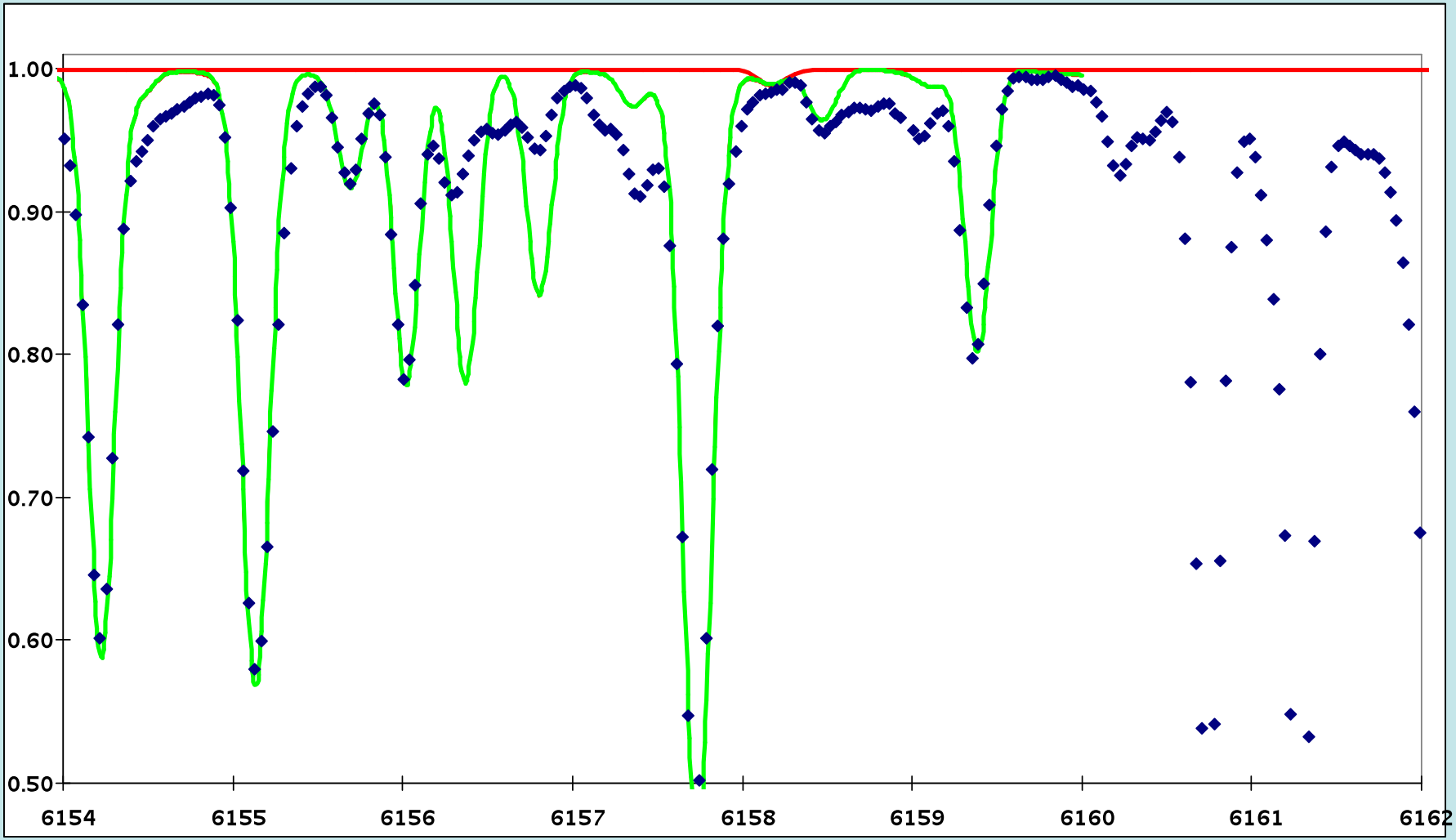
**Teff = 4660K, logg=2.0**

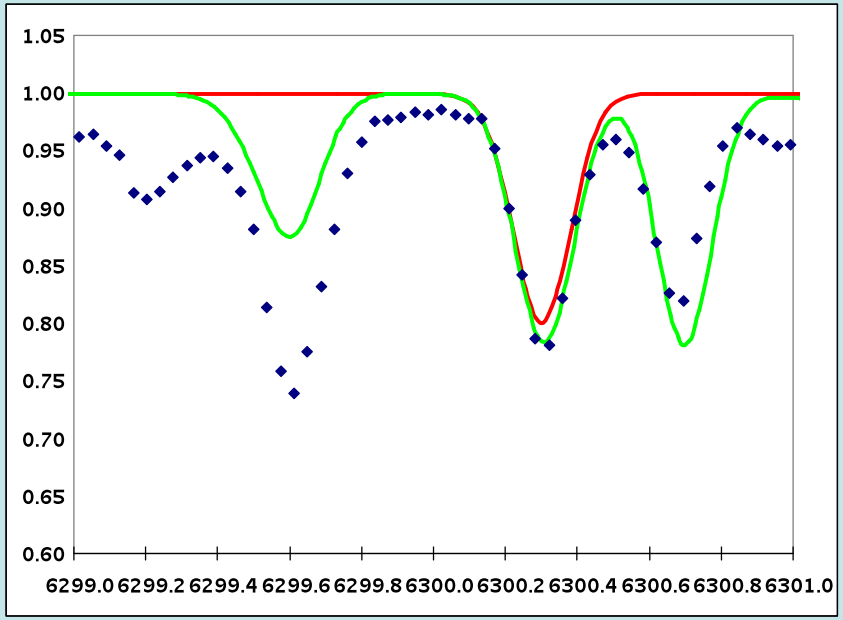
**logε(O) = 8.71**

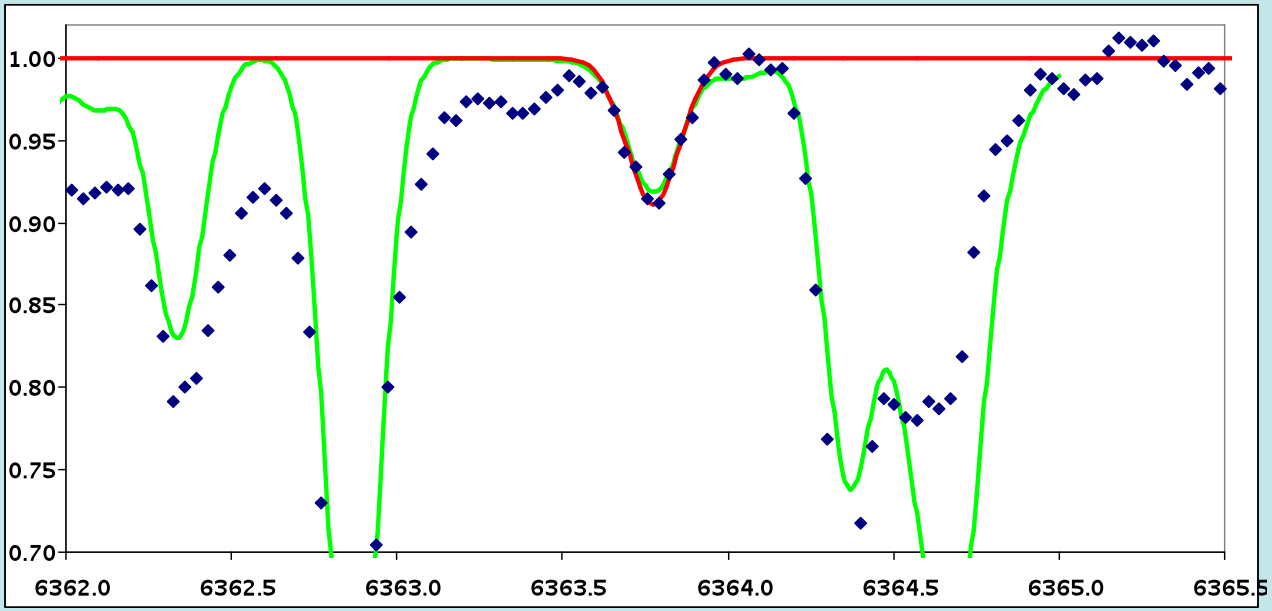
**CFHT 360 cm ESPaDOnS**

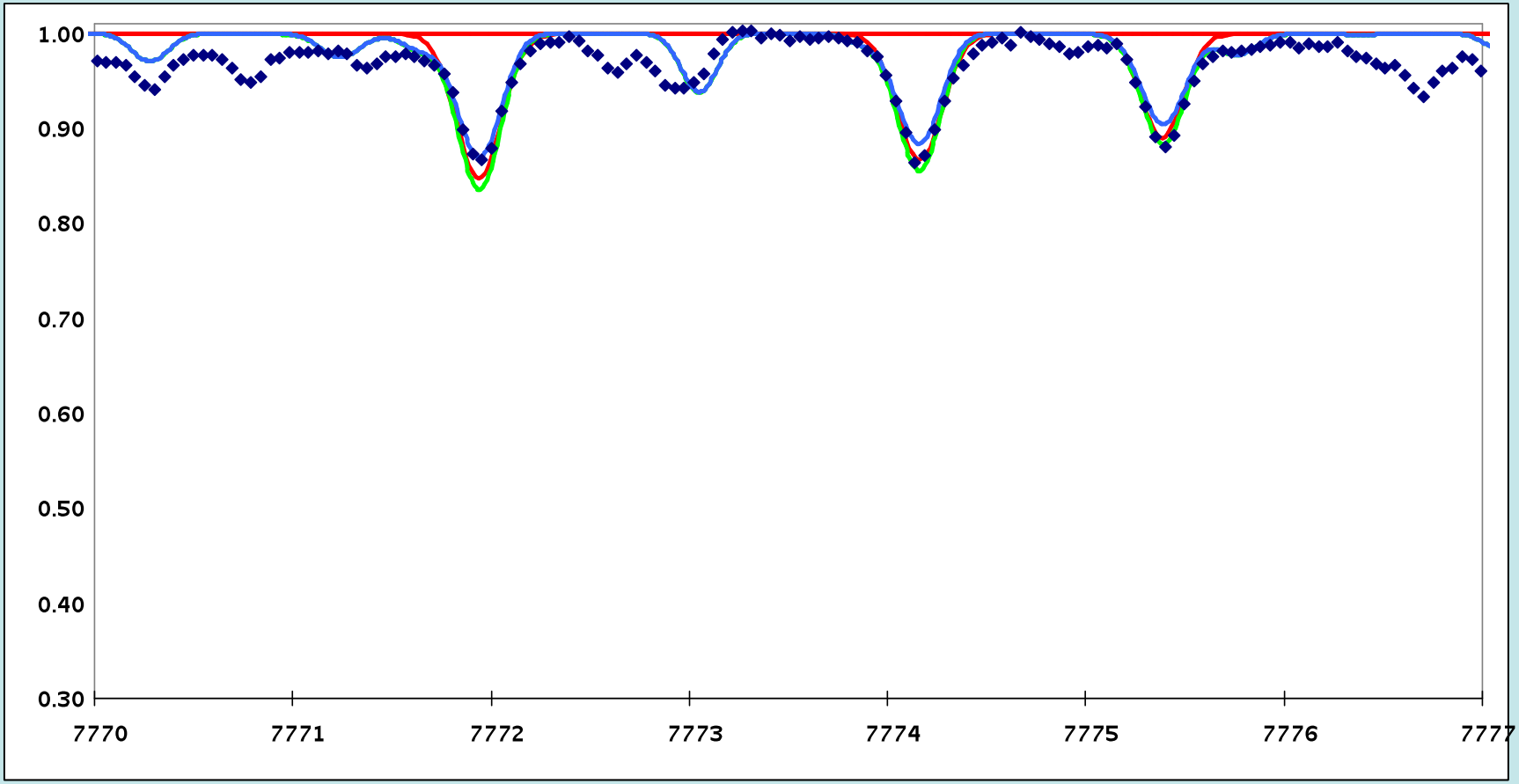
**R ≈ 80000**


1.00
0.95
0.90
0.85
0.80
0.75
0.70
5576.0
5576.2
5576.4
5576.6
5576.8
5577.0
5577.2
5577.4
5577.6
5577.8
5578.0


1.00
0.90
0.80
0.70
0.60
0.50
6154
6155
6156
6157
6158
6159
6160
6161
6162

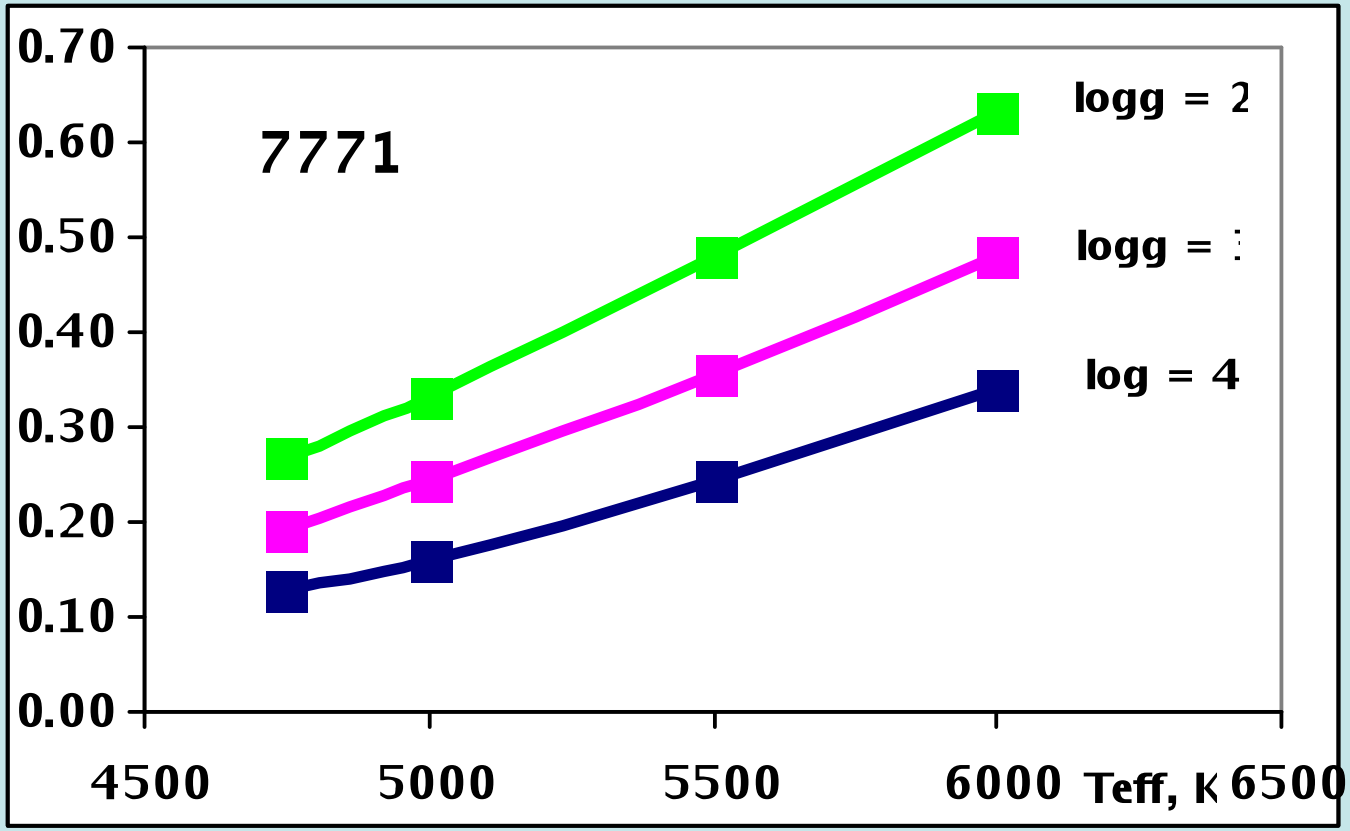

1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
6299.0 6299.2 6299.4 6299.6 6299.8 6300.0 6300.2 6300.4 6300.6 6300.8 6301.0


1.00
0.95
0.90
0.85
0.80
0.75
0.70
6362.0 6362.5 6363.0 6363.5 6364.0 6364.5 6365.0 6365.5


1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
7770
7771
7772
7773
7774
7775
7776
7777

# NLTE correction bevaviour for different oxygen lines

# NLTE grid
# (LTE-NLTE)
# Dependence on effective temperature



# Very instructive example of Hyades
## (Schuler et al., 2006, ApJ 636, 432)

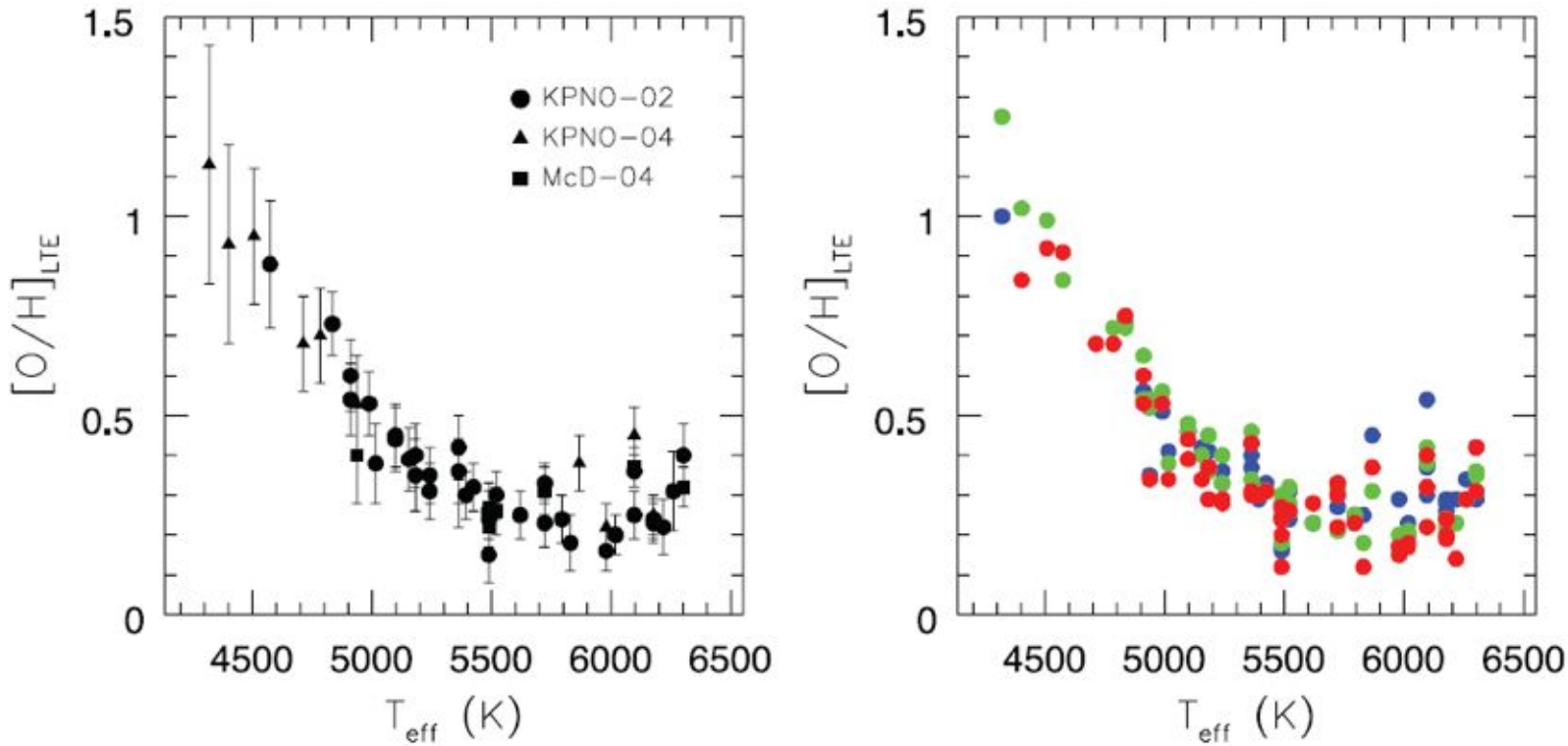
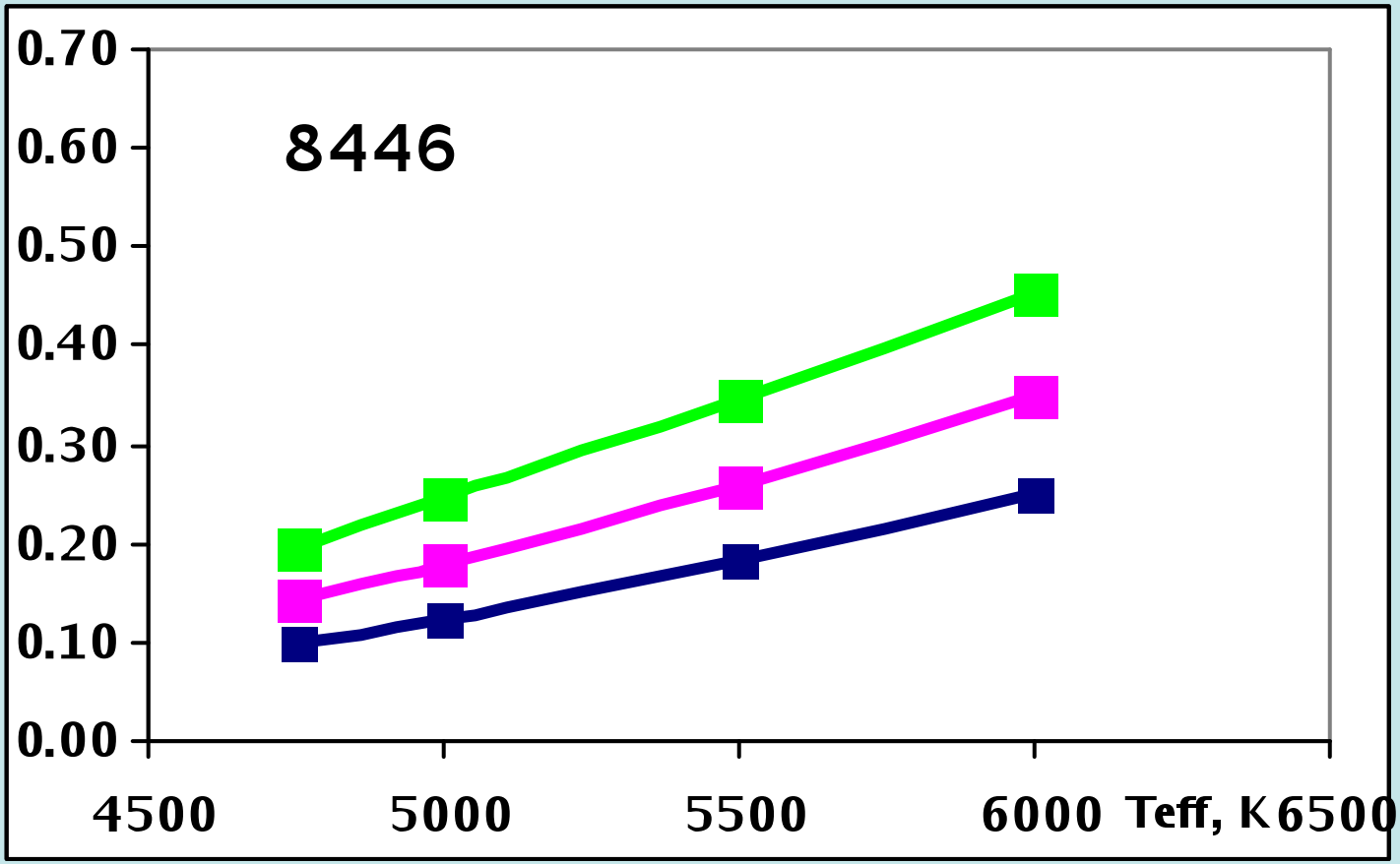
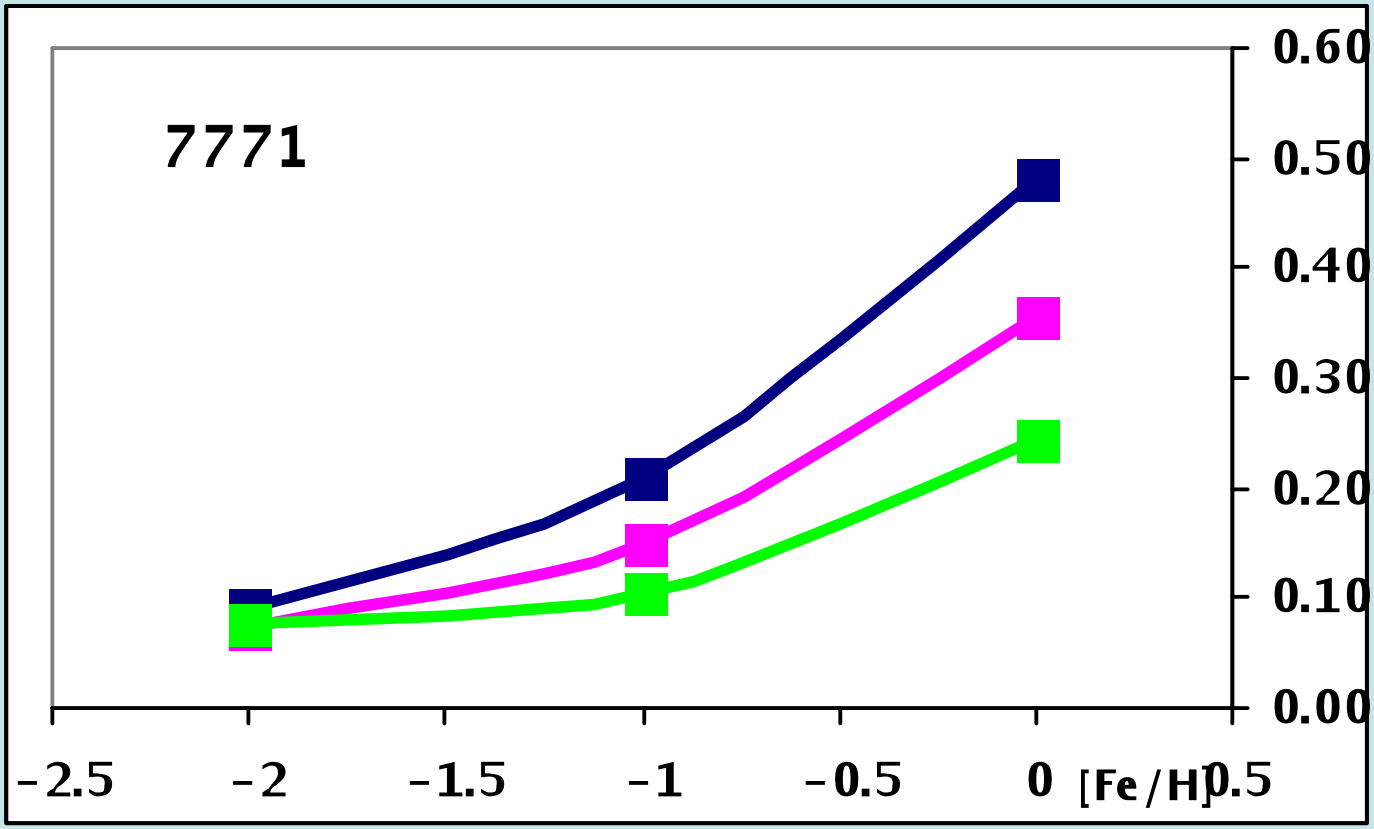



FIG. 3.—*Left*: Relative LTE O abundances vs. $T_{eff}$ for the combined Hyades data set. The points are again distinguished by the data set from which they are derived. The error bars represent the total internal abundance uncertainties. *Right*: Line-by-line relative LTE O abundances vs. $T_{eff}$ for the combined Hyades data set. Abundances derived from the $\lambda\lambda$7772, 7774, and 7775 lines are given in blue, green, and red, respectively.

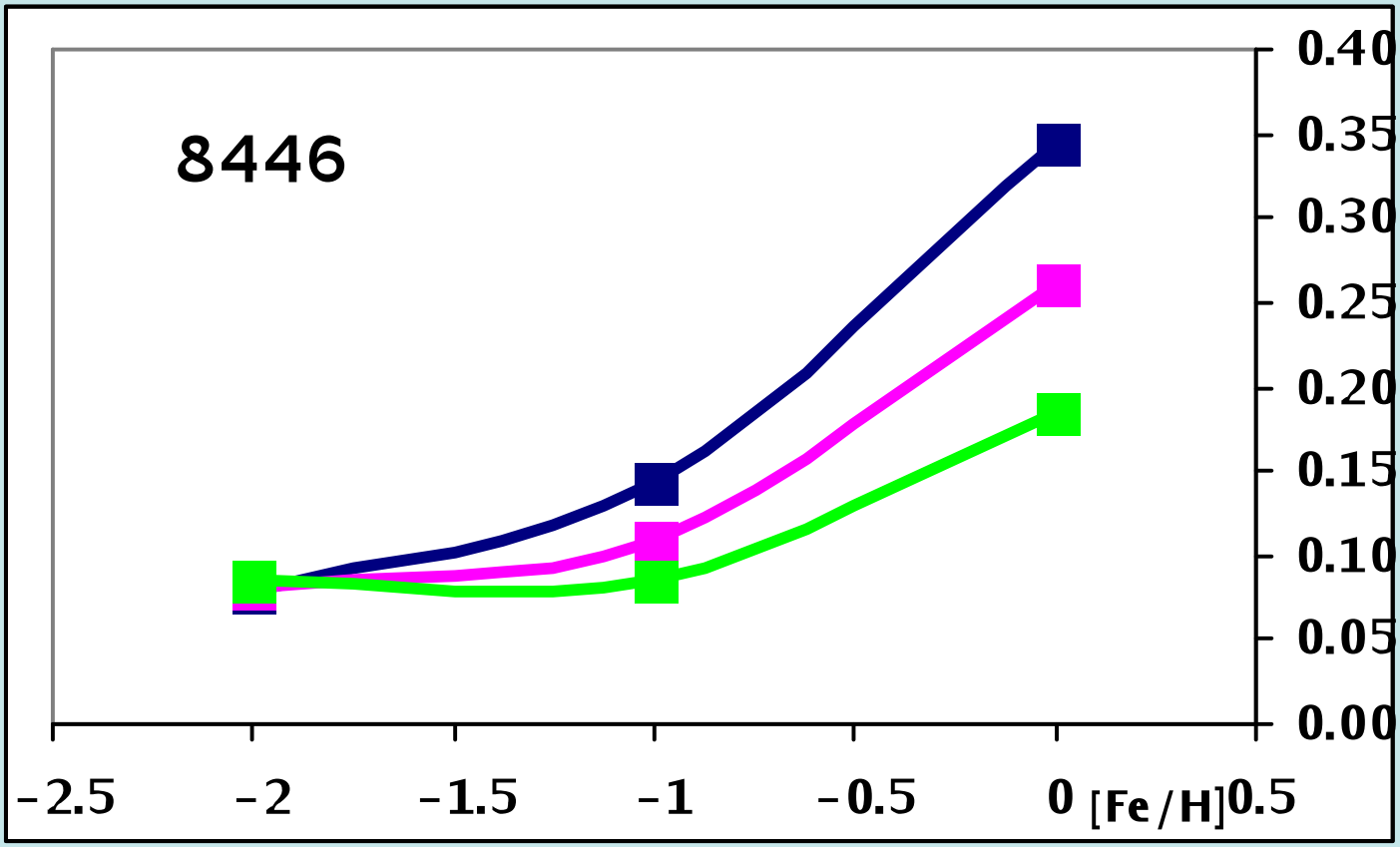
# Dependence on effective temperature



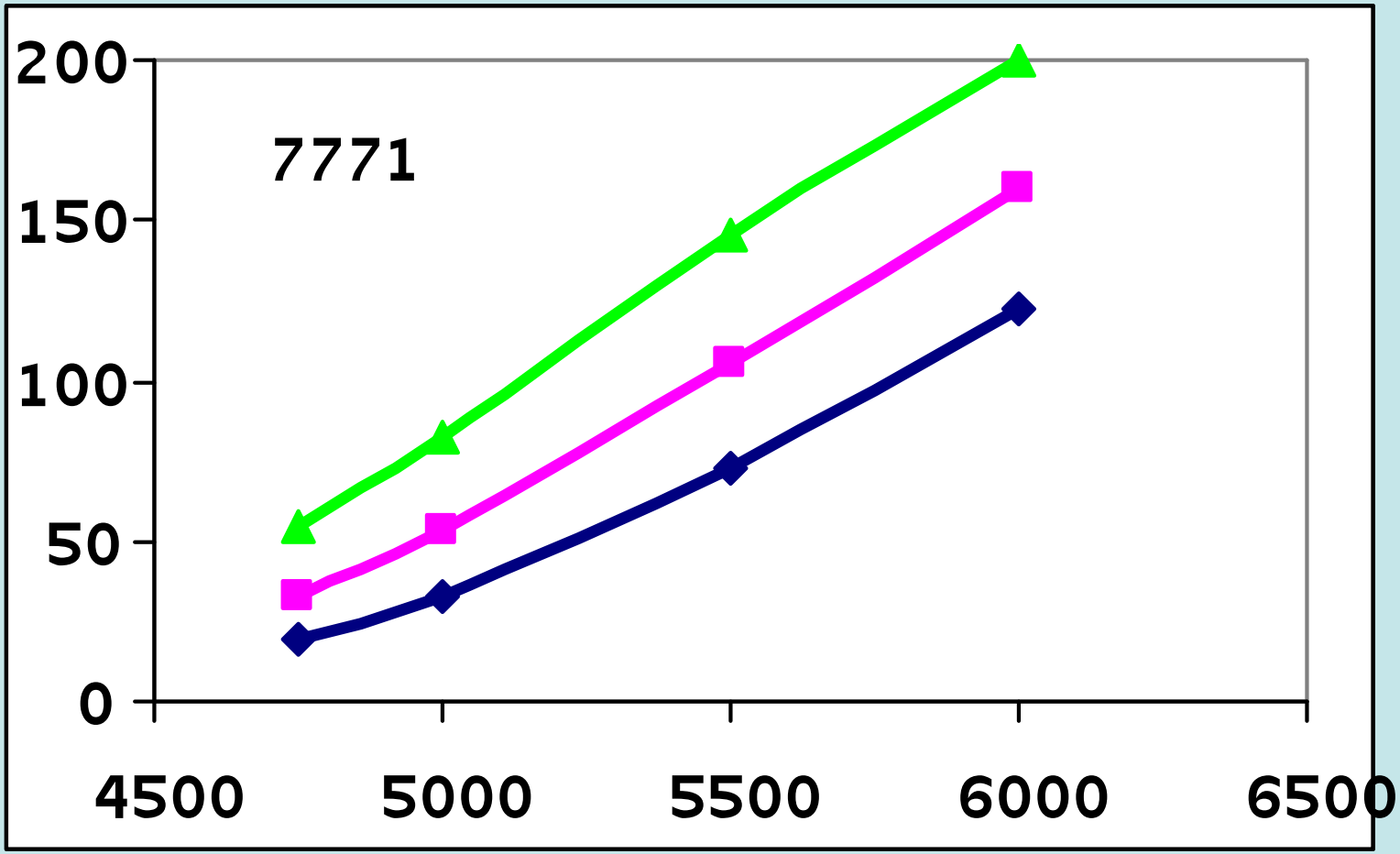
# Dependence on metallicity



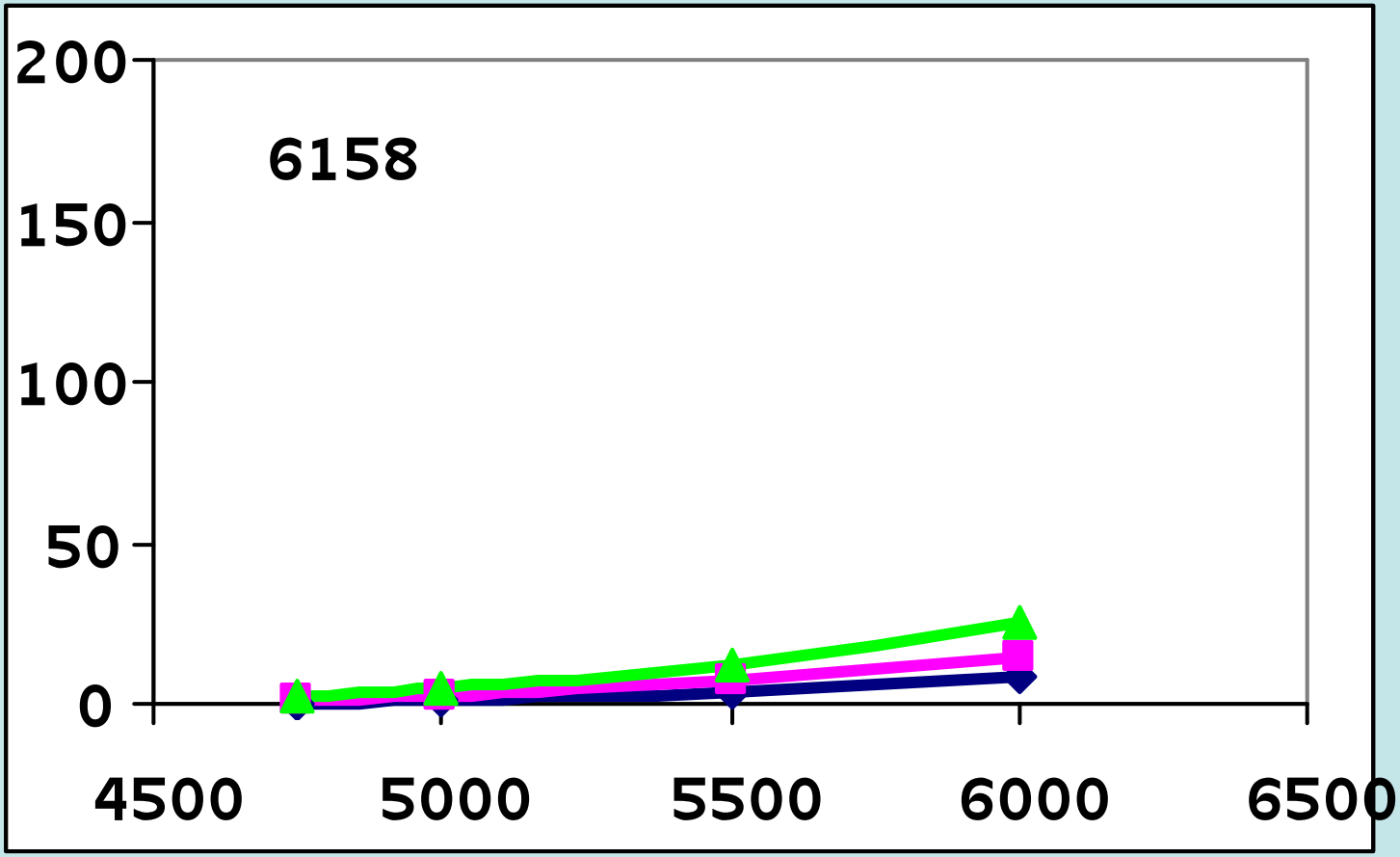
# Dependence on metallicity

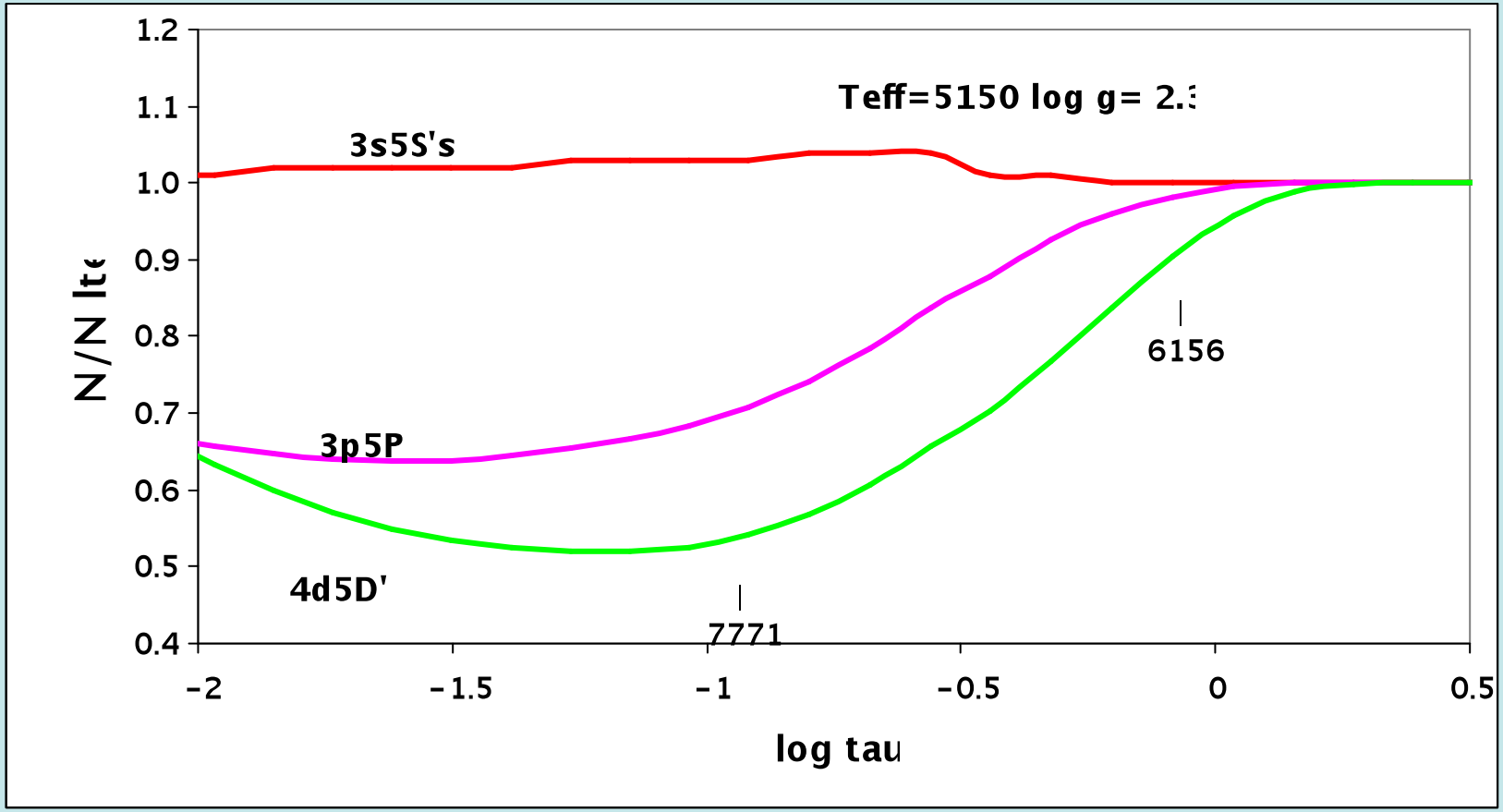


# Equivalent width (mA) as a function of Teff (K)



# Equivalent width (mA) as a function of Teff (K)




Teff=5150 log g= 2.3
3s5S's
3p5P
4d5D'
6156
7771
N/N lte
log tau
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
-2
-1.5
-1
-0.5
0
0.5

# CONCLUSION 1

- The line 5577 A could be significantly spoiled with an emission of the night sky.
- From triplet lines 6156-6158 A only 6158 A is more or less detectable in the giant/supergiant spectra. It cannot be reliably measured in the medium-to-high resolution spectra of the stars with $T_{eff}$ lower than about 5500-6000 K.
- 6300 A and 6363 A forbidden lines can hardly be detected in the spectra of stars with $T_{eff}$ higher than 5500 K.
- Moreover, these lines can be polluted with terrestrial absorptions. Another problem – correct continuum placement in this region dominated by terrestrial bands.

# CONCLUSION 2

Only 7771-7774 A triplet affords the most suitable opportunity to derive oxygen abundance in the cool stars because:

- its lines are quite strong (and thus easily detectable) over the wide range of the $T_{eff}$,
- those lines are practically not blended,
- they are reachable with many spectrographs available at present,

**but**

they require an application of the NLTE analysis in order to derive correct oxygen abundance.

# DO WE DERIVE RELIABLE OXYGEN ABUNDANCES IN COOL GIANT/SUPERGIANT STARS?

- At least 1D NLTE line profile analysis is required for 7771-7775 A triplet.
- For the stars cooler than 6000 K forbidden doublet lines are appropriate as LTE oxygen indicators, but if the spectra in 6300-6400 A are correctly reduced.
- For bright stars forbidden line 5577 A can produce rather reliable oxygen abundance.
- My personal opinion is that that our previous determinations of oxygen abundance in the giant/supergiant stars are accurate at the level of +/- 0.25 dex at best (to be very optimistic).

**Thank you for your attention!**

$$C_{ij} = 5.465 \cdot 10^{-11} N_e \sqrt{T_e} 14.5 f_{ij} \left( \frac{I_H}{E_0} \right) u_0 e^{-u_0} \max\left[ \overline{g}; 0.276 e^{u_0} E_1(u_0) \right]$$

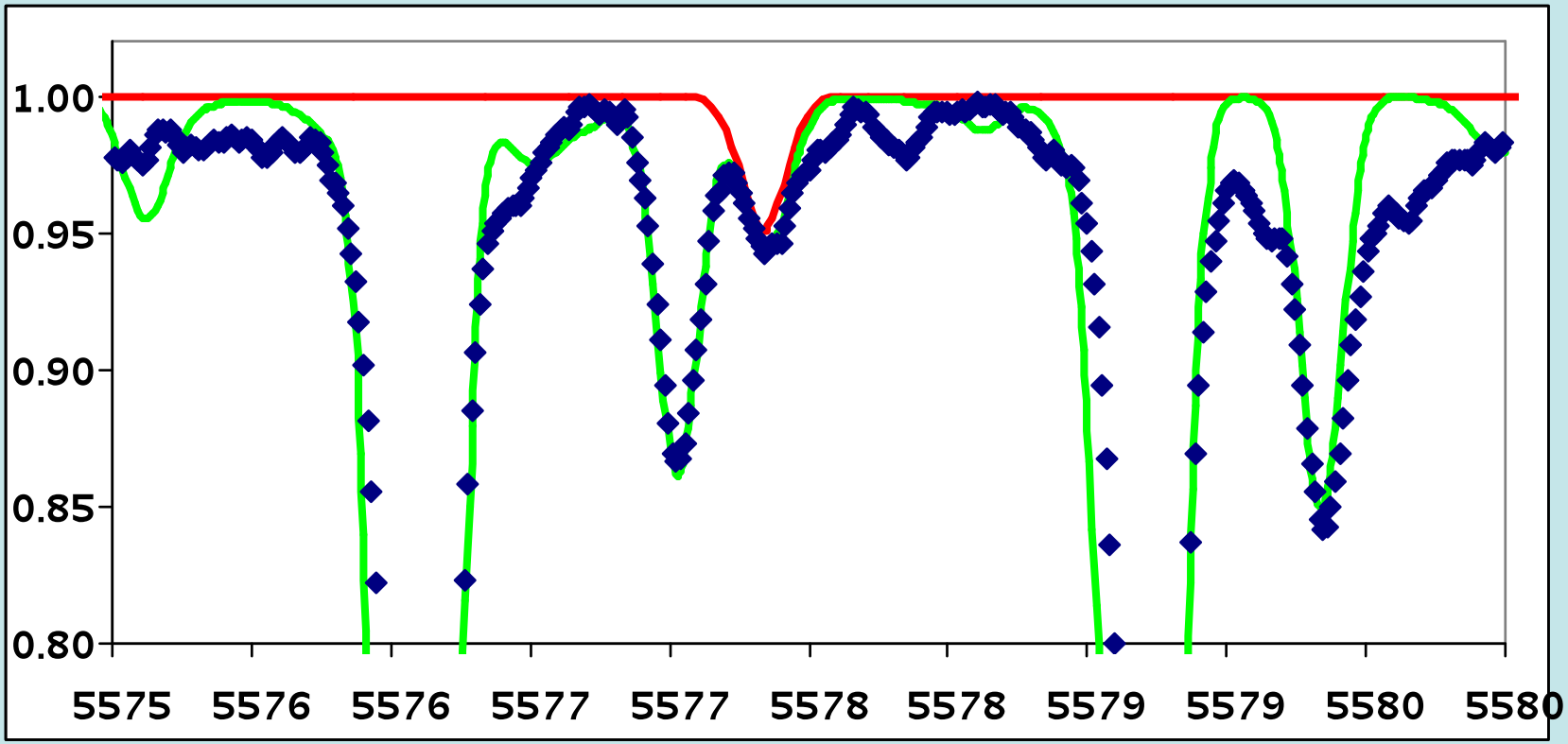
$$C_{ij} = 8.63 \cdot 10^{-6} N_e e^{-u_0} \Big/ \left( g_i \sqrt{T_e} \right)$$

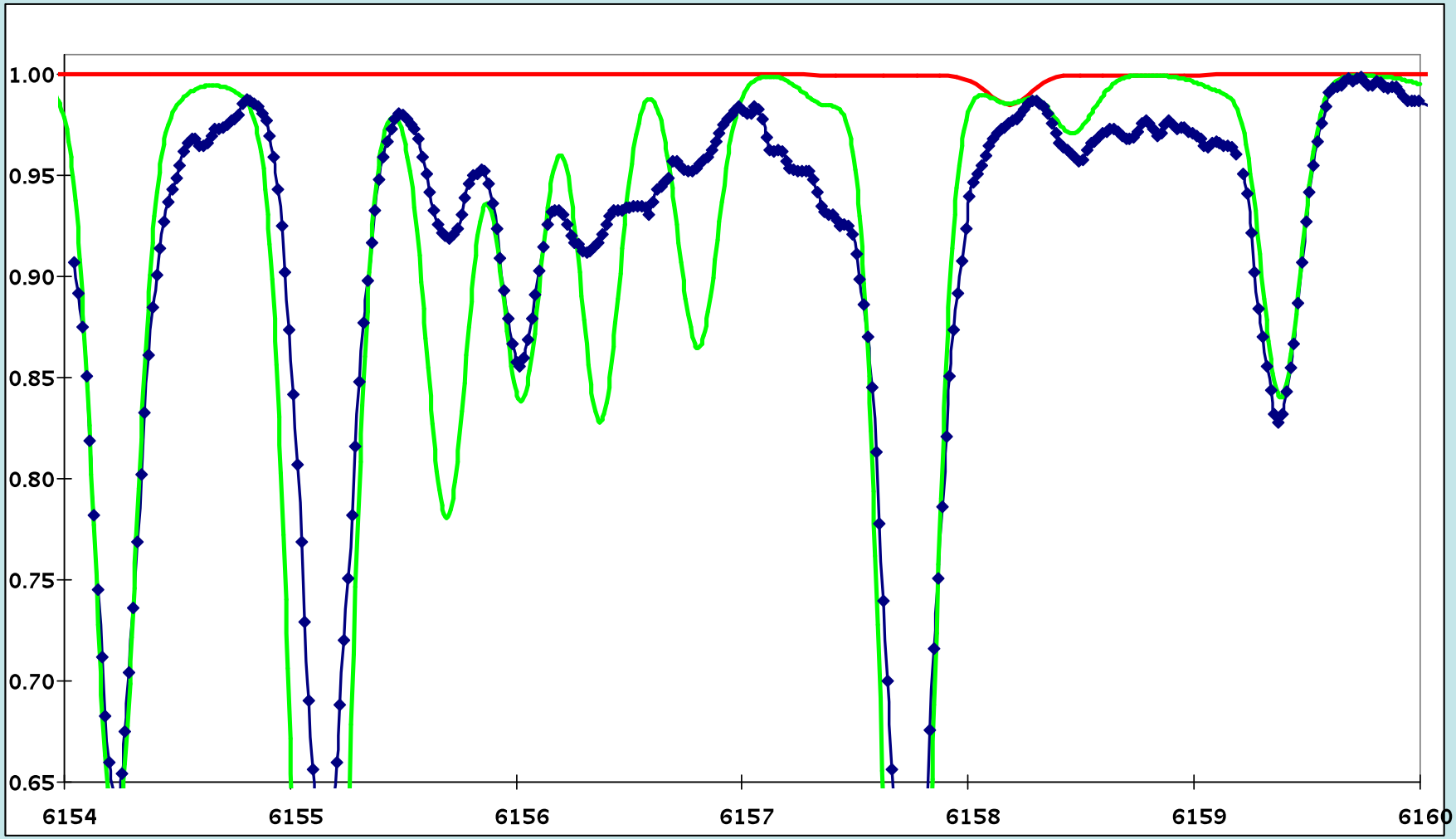
$$C_{ik} = 1.55 \cdot 10^{13} \frac{\alpha(\nu_0) \overline{g} N_e e^{-u_0}}{\sqrt{T_e} u_0}$$

$$C_{ij} = 16\pi a_0^2 \left( \frac{2kT}{\pi\mu} \right)^{1/2} \left( \frac{I_H}{E_j - E_i} \right) f_{ij} \frac{m_A}{m_H} \eta \left( 1 + \frac{2}{w} \right) \frac{e^{-w}}{1 + \left( \frac{2\eta}{w} \right)^2} k_h$$

$$w = \frac{E_j - E_i}{kT} \qquad \eta = \frac{m_e}{m_H + m_e} \qquad \mu = \frac{m_A m_H}{m_A + m_H}$$

**Beta Cap, K0 II**
**Teff = 4880, logg = 2.1**
**ESO VLT Program ID 076.B-0055(A).**
**R ≈ 80000**
**Spectrum reduced by Irina Yegorova (ESO)**

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0.85
0.80
0.75
0.70
0.65
6154
6155
6156
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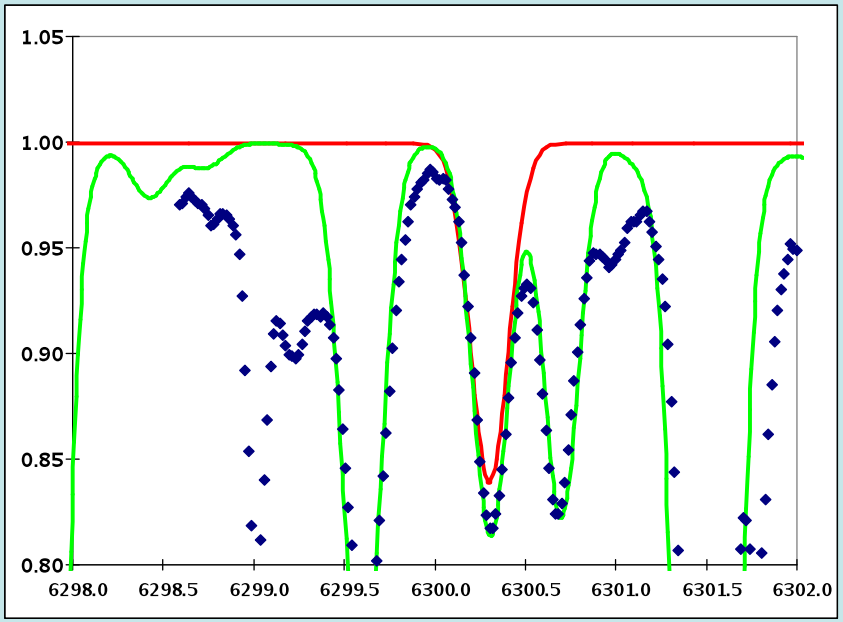
6158
6159
6160


1.05
1.00
0.95
0.90
0.85
0.80
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6298.5
6299.0
6299.5
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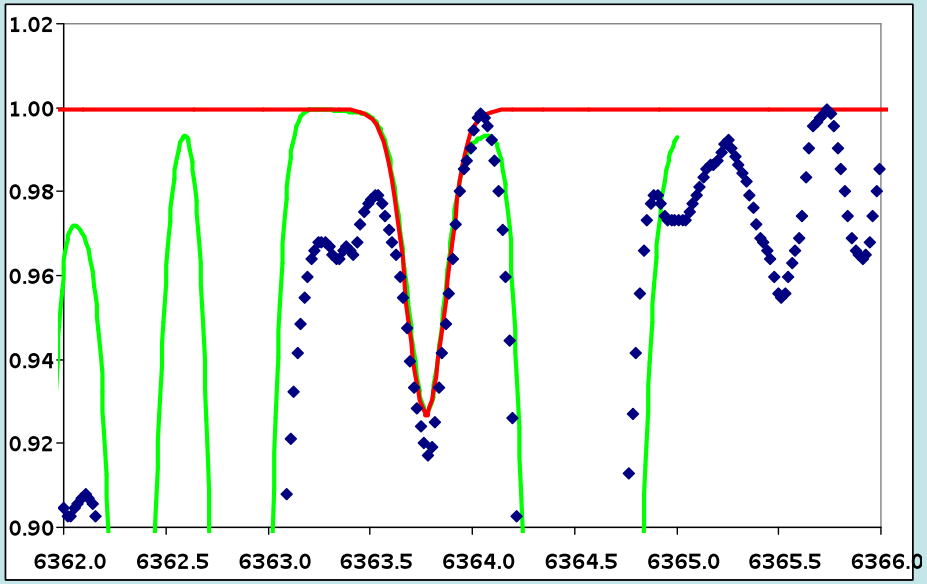
6300.5
6301.0
6301.5
6302.0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1.00
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0.96
0.94
0.92
0.90
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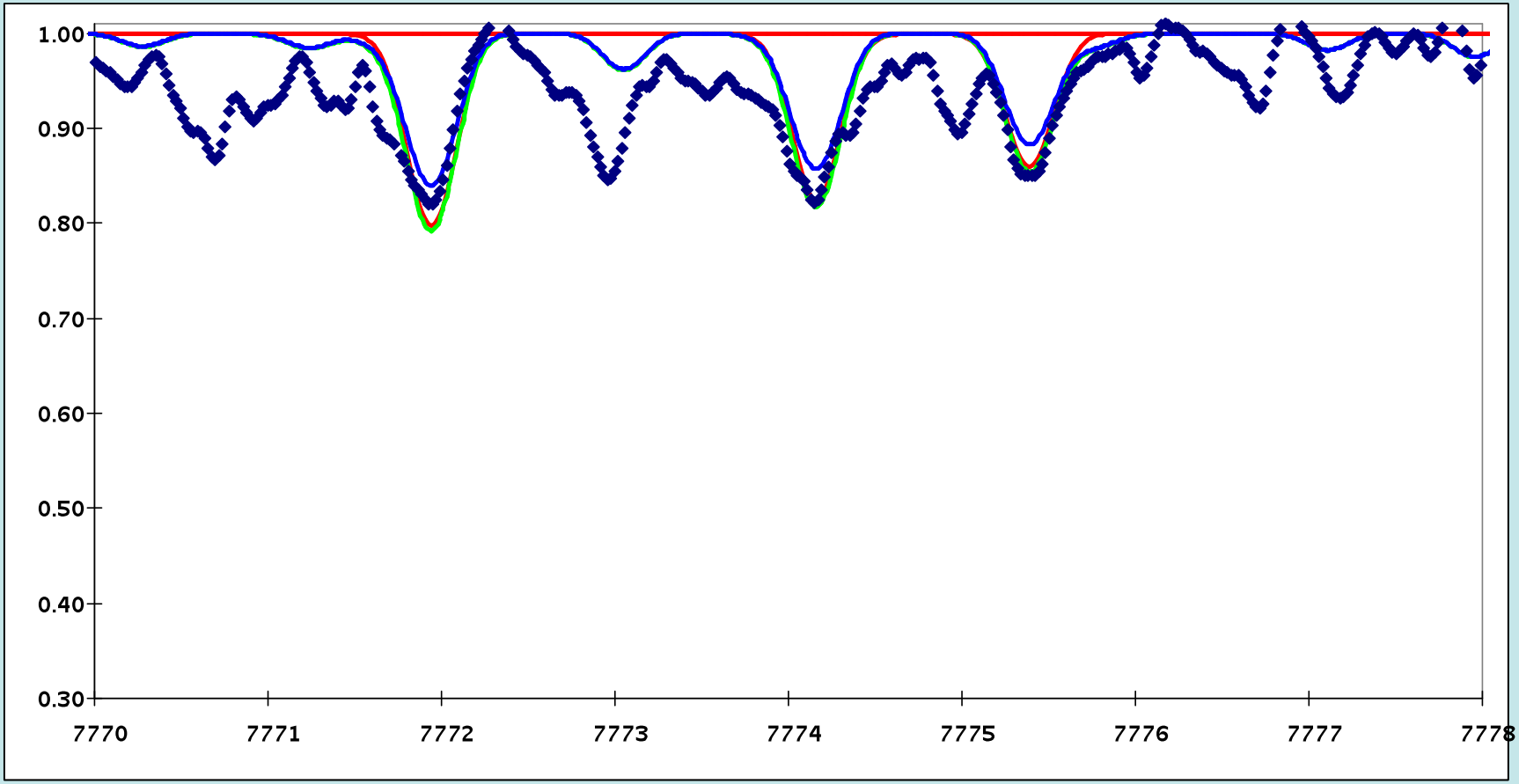
6363.0
6363.5
6364.0
6364.5
6365.0
6365.5
6366.0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0.90
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0.60
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7771
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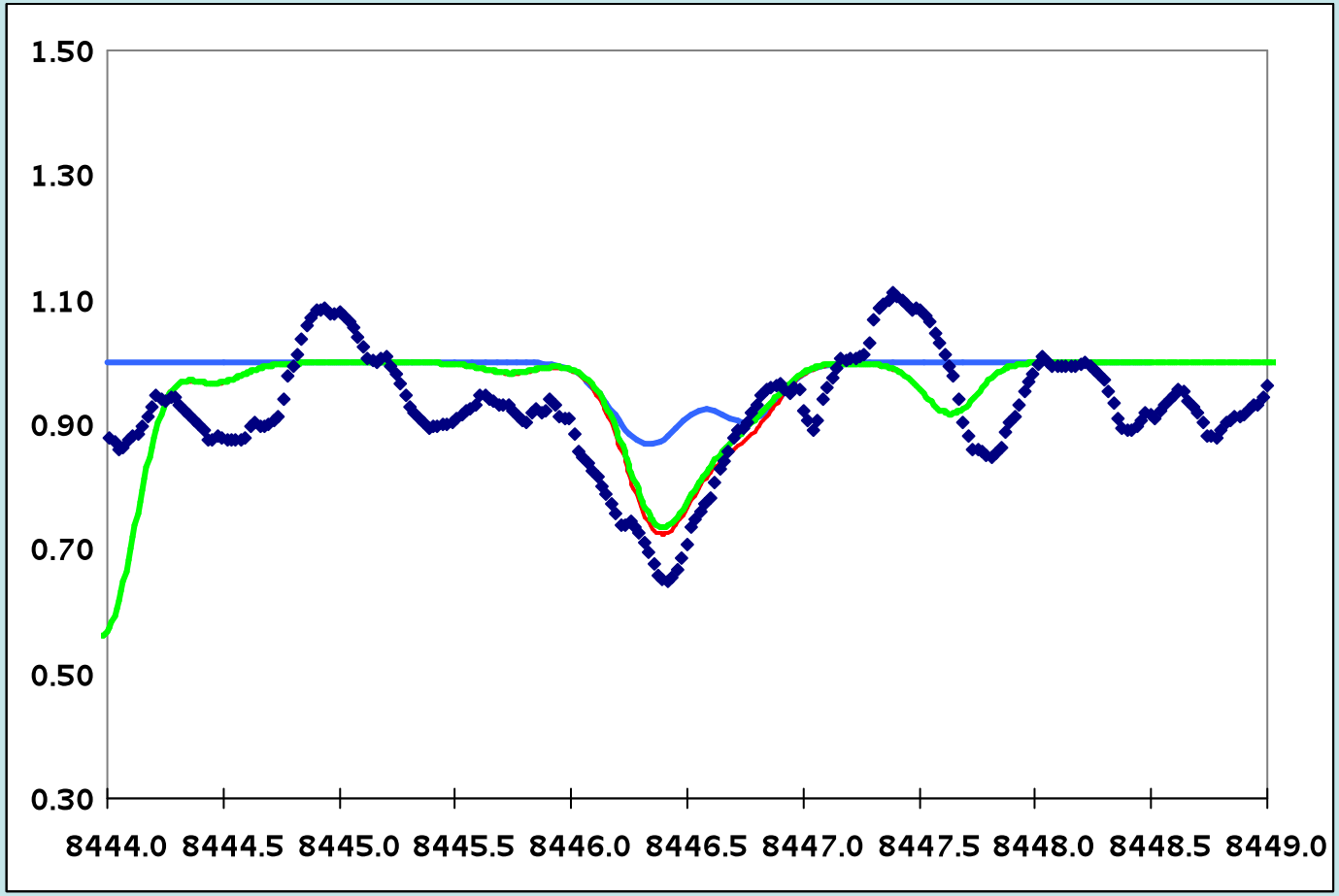
1.50
1.30
1.10
0.90
0.70
0.50
0.30
8444.0
8444.5
8445.0
8445.5
8446.0
8446.5
8447.0
8447.5
8448.0
8448.5
8449.0