Can κ– distribution Explain Observed Intensities of Si III lines in the Transition Region?

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Motivation

The analysis of the SUMER Si III spectra in EUV region from 1100 Å to 1320 Å showed that it is not possible to explain the observed spectrum under the assumption of the Maxwellian distribution of free electrons (Pinfield *et al*., 1999, ApJ **527**, 1000)

We try

- to explain observed spectrum by a non-thermal κ-distribution with an enhanced number of particles in its high energy tail
- to determine parameter of distribution, κ

We assume

- the influence of radiation field on Si III line intensities (it has not been included in any previous calculations)

We would like to show

- how a strong gradient of density and T in the transition region influences observed intensities of Si III lines and diagnosed parameters of plasma?

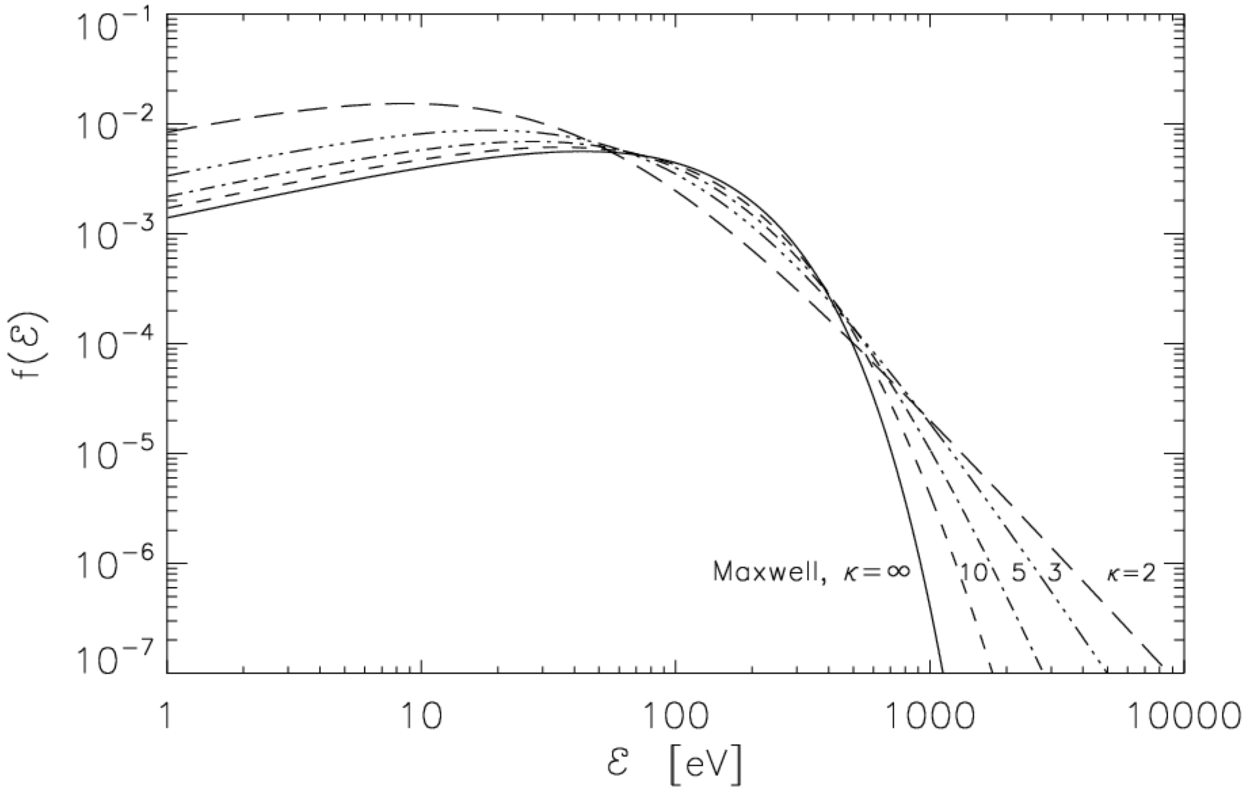
Non-thermal Electron
κ - distribution

$$f(E)dE = A_\kappa \left(\frac{m}{2\pi kT}\right)^{3/2} \left(1 + \frac{E}{(\kappa - 1.5)kT}\right)^{-(\kappa+1)} E^{1/2} dE,$$ (Shoub, 1983)

$$A_\kappa = \frac{\Gamma(\kappa+1)}{\Gamma(\kappa-0.5)(\kappa-1.5)^{3/2}}$$

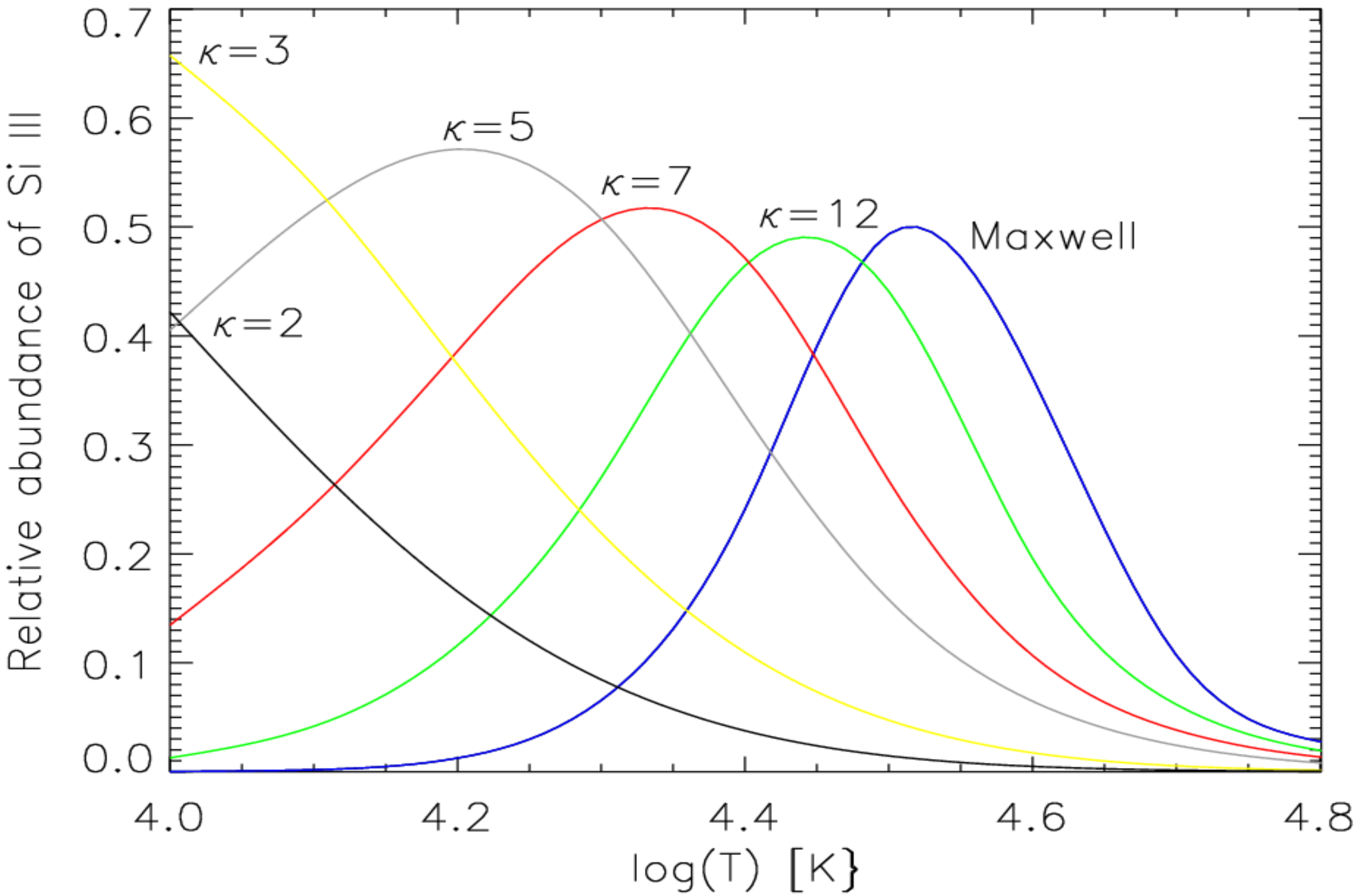
$$\langle E \rangle = 3kT/2$$

$$p = NkT$$



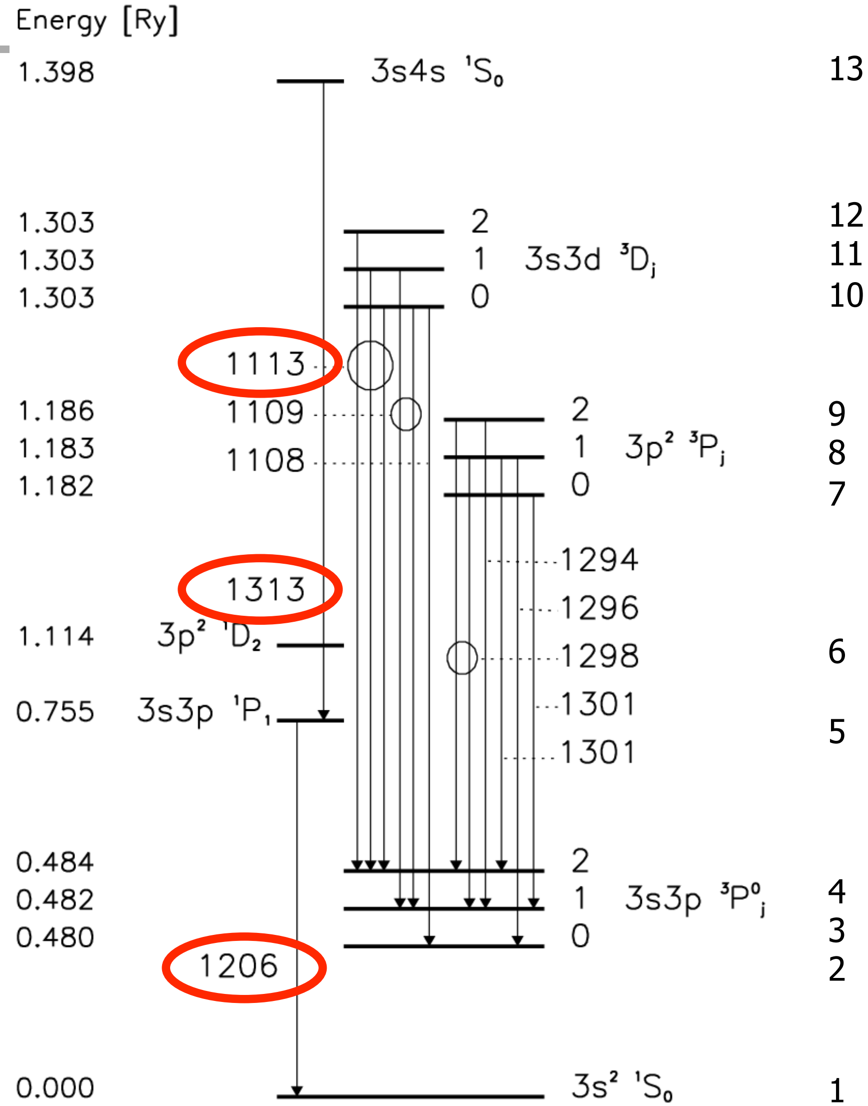
The comparison of the Maxwellian distribution with κ-distributions for κ=2, 3, 5, 10 and T=10^6 K.

Ionization equilibrium



excitation equilibrium

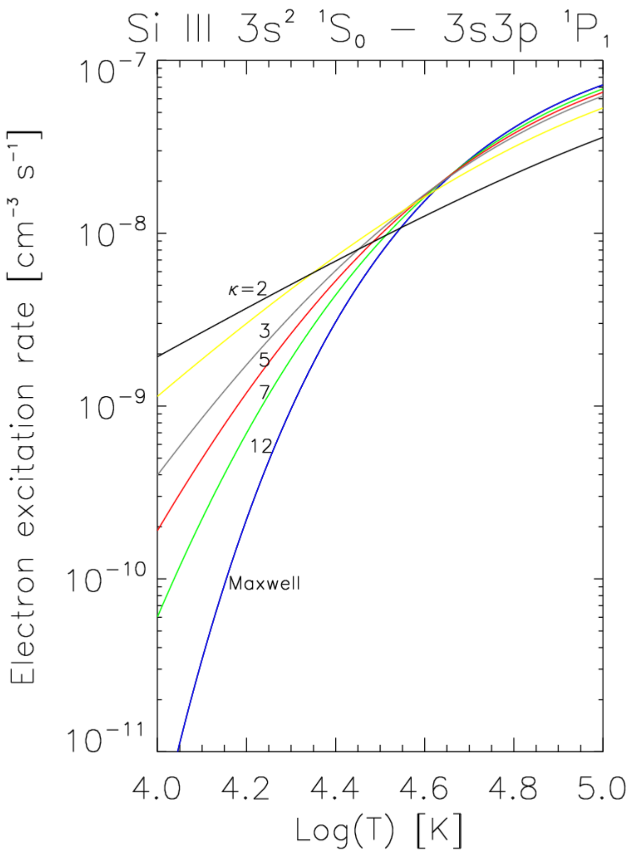
- The original modification of CHIANTI software and extended database has been used for computation of synthetic spectra under the assumption of non-thermal distributions.
- The 20 level model of Si III is included in CHIANTI.



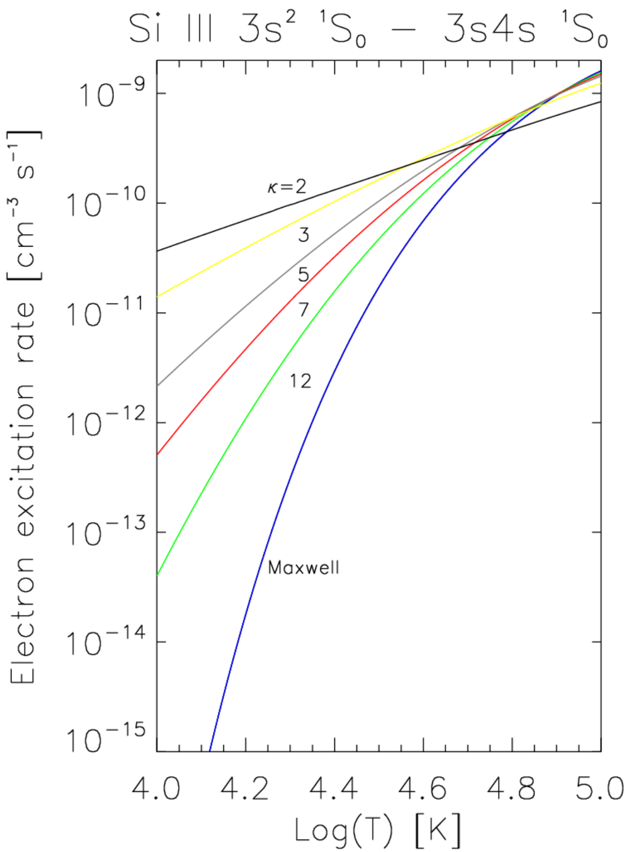
Schematic diagram of the first 12 levels with the indication of the emission lines observed by SUMER.

excitation Rates

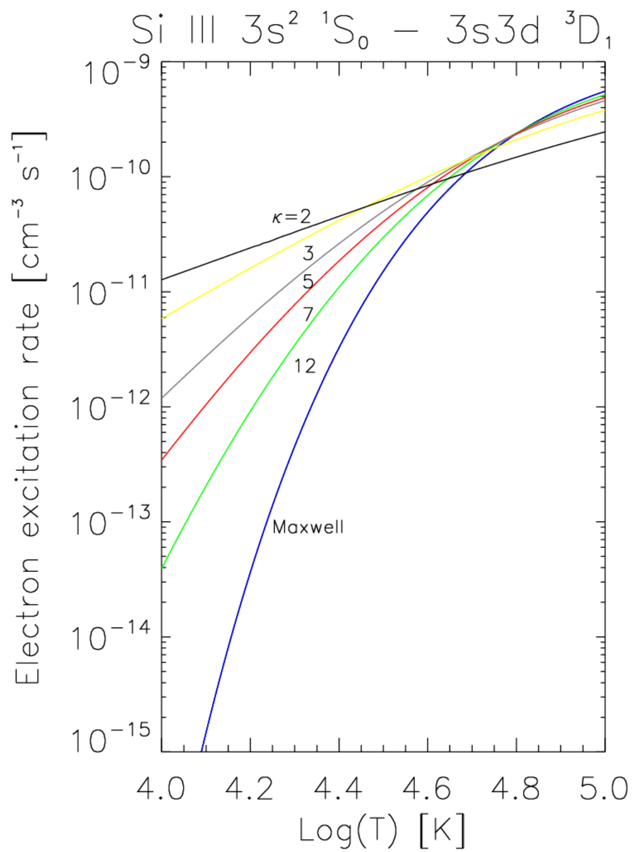
δE = 0.755 Ry



δE = 1.398 Ry



δE = 1.303 Ry



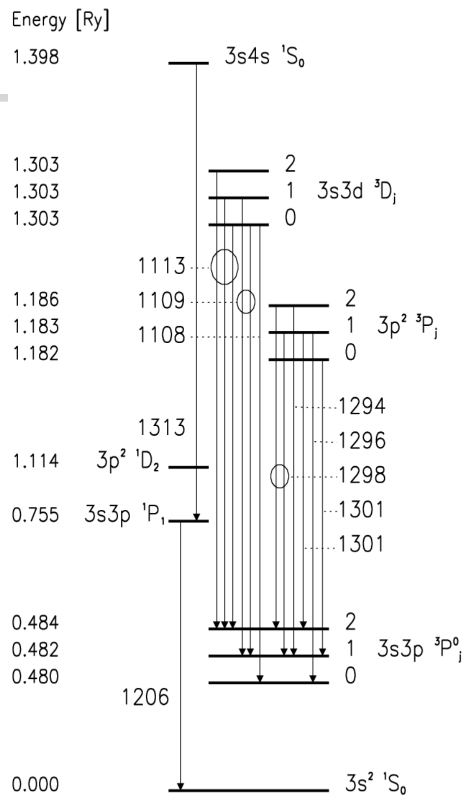
Maxwellian distribution: (blue), κ-distributions: κ=12 (green), κ=7 (red), κ=5 (grey), κ=3 (yellow), κ=2 (black) for transitions 1-5 (left), 1-13 (middle), 1-11 (right).

DiaGnostics

- the line ratios used for diagnostics (Pinfield *et al*., 1999):

R1 = 1108 /1294
R2 = 1108 /1296
R3 = 1108 /1298
R4 = 1109 /1296
R5 = 1113 /1294
R6 = 1113 /1298

R7 = 1301/1296
R8 = 1301/1298
R9 = 1313/1113
R10 = 1294/1206
R11 = 1296/1206



- first column - mainly temperature responsive
- second column - density sensitive

} Maxwellian distribution and no radiation field

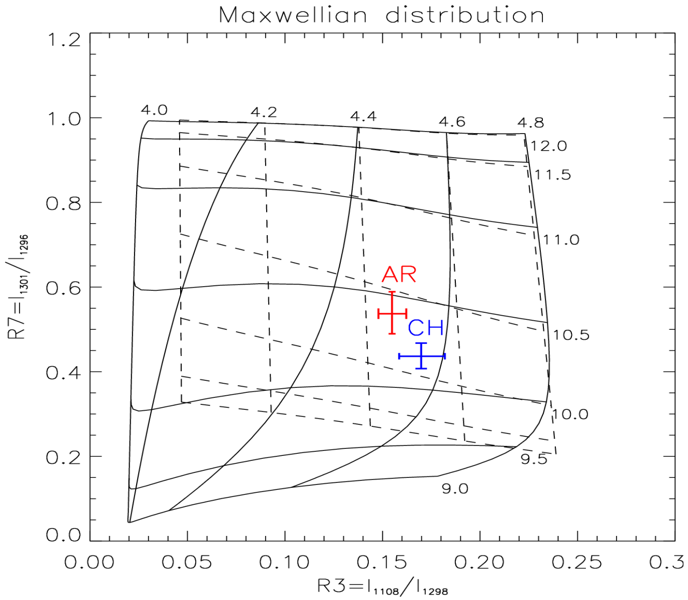
- **unfortunately, this is not valid neither for Maxwell nor for the κ-distributions when radiation field is added.**

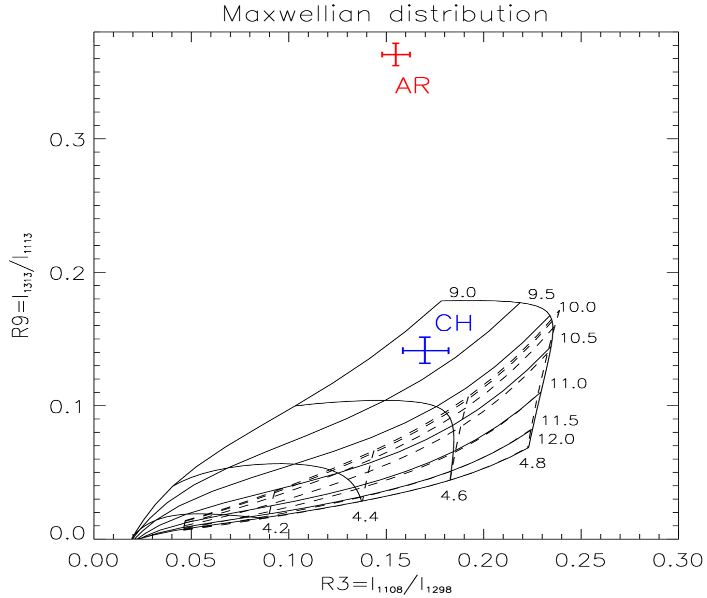
Diagnostics - Maxwellian

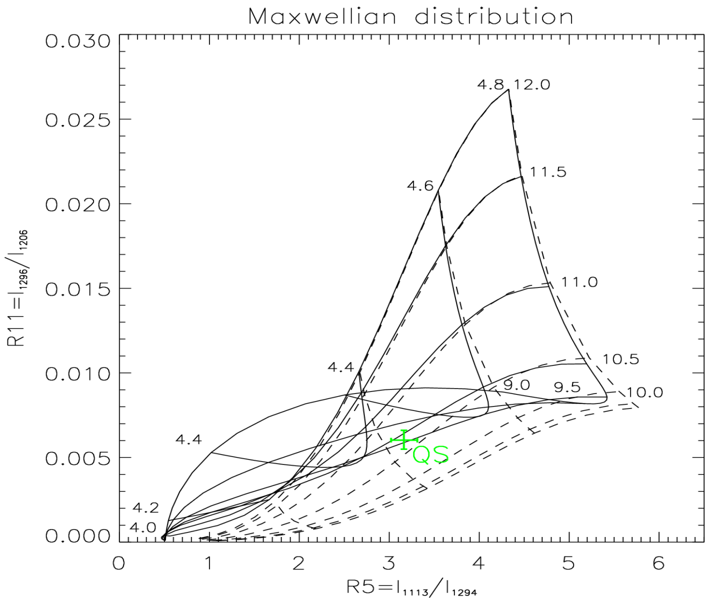
full lines:
T_{rad}= 6000 K,
r=1.003$R_{\odot}$

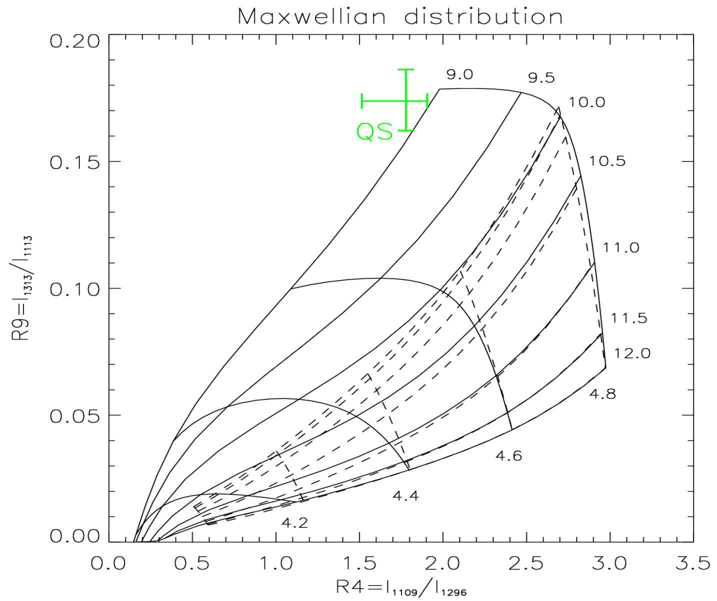
dashed lines:
no radiation field

color points with
error bars:
observed line ratios
(Pinfield *et al.* 1999)









Diagnostics - Kappa

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A grid of model spectra has been computed for:

- κ-distribution with κ= 2 - 34 and Maxwellian distribution
- T : 10^4 K - 10^5 K
- N_e: 10^8 cm^{-3} - 10^{12} cm^{-3}
- T_{rad}=6000 K, r=1.003 $R_\odot$ (25 000 km)

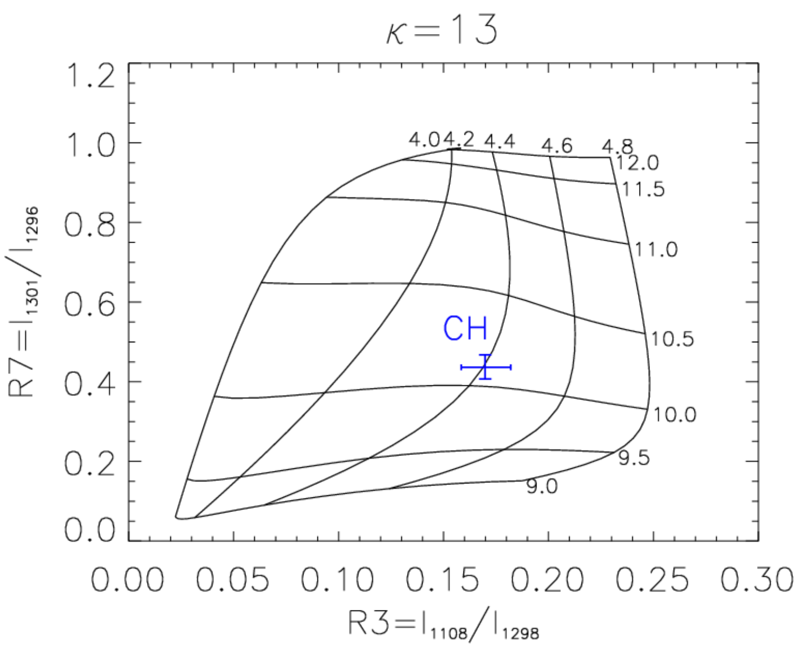
The diagnostics method uses our grid of the calculated values of R1 - R11 for different T, N_e, and κ and looks for a minimum of the differences between the observed and theoretical line ratios.

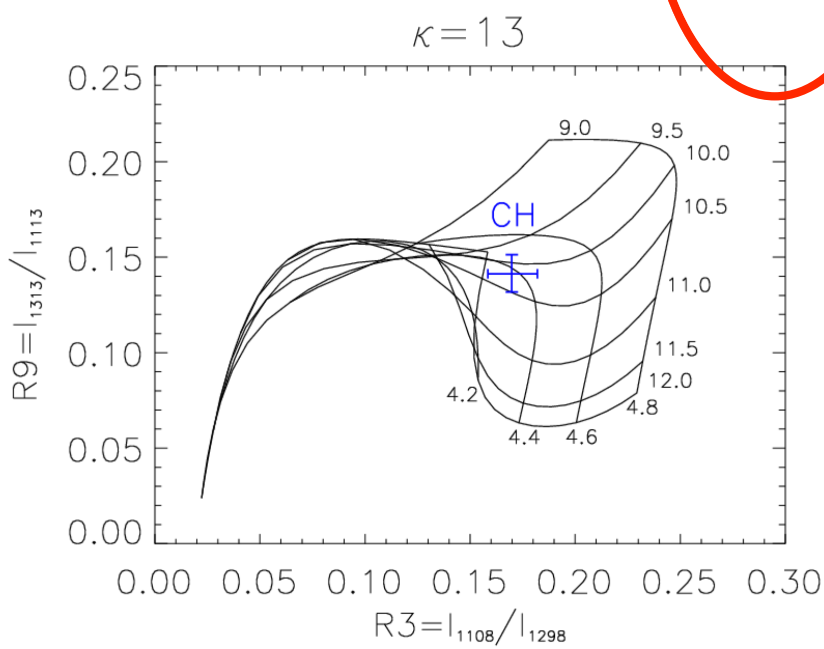
Diagnostics - Kappa

R9 = 1313/1113

CORONAL HOLE

log(T)	log(N_e)		R1	R2	R3	R7	R8	R9
4.55	10.3	Maxw.	0.60	0.75	0.17	0.48	0.11	0.08
4.40	10.15	κ = 13	0.61	0.75	0.17	0.46	0.10	0.14
4.40	10.15	κ = 14	0.60	0.73	0.17	0.45	0.11	0.14
observed ratio			0.55-0.63	0.66-0.76	0.15-0.19	0.41-0.47	0.10-0.12	0.13-0.15

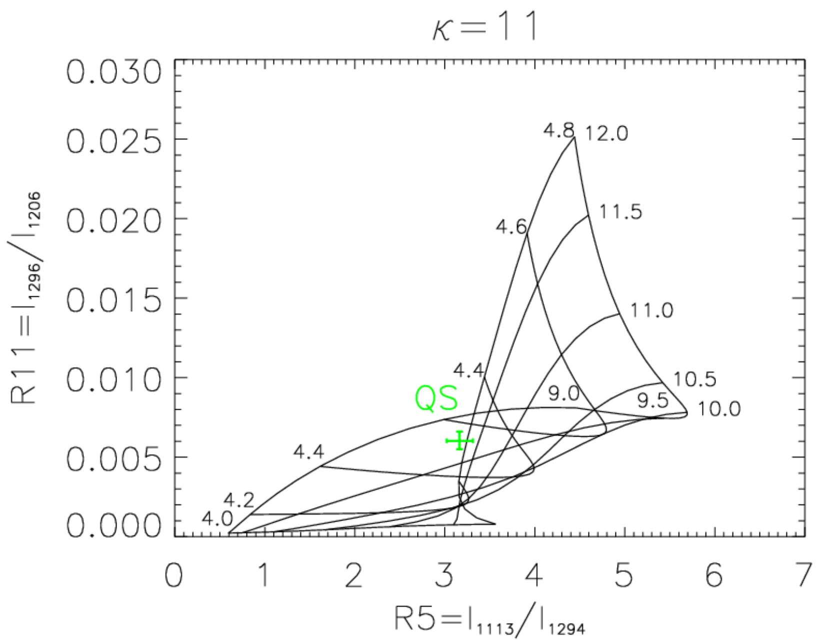


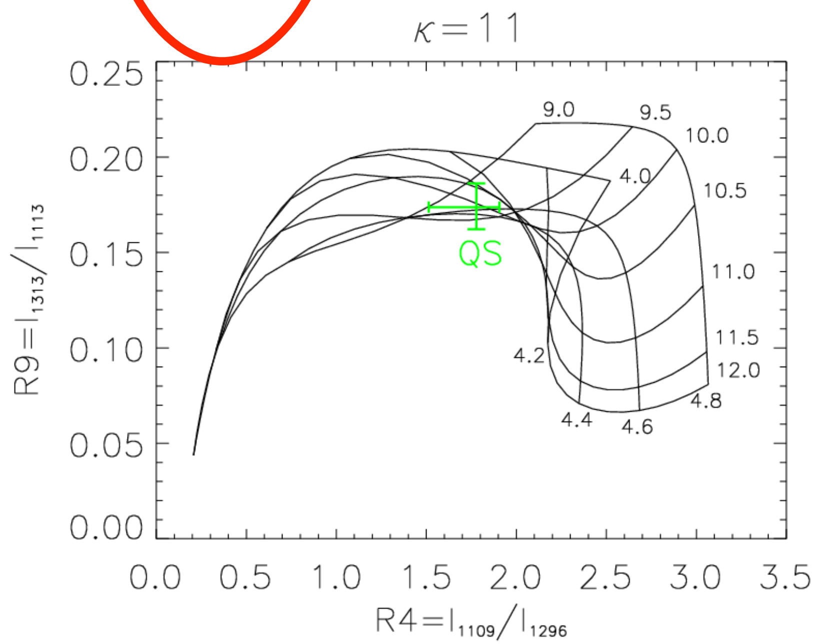


Diagnostics - Kappa

QUIET SUN **R9 = 1313/1113**

log(T)	log(N_e)		R4	R5	R6	R9	R10	R11
4.50	10.0	Maxw.	1.59	3.28	0.92	0.08	0.0076	0.0061
4.55	9.25	κ = 12	1.53	3.23	0.90	0.16	0.0078	0.0063
4.55	9.25	κ = 11	1.57	3.29	0.92	0.17	0.0077	0.0062
4.55	9.2	κ = 10	1.54	3.23	0.90	0.17	0.0077	0.0062
4.55	9.2	κ = 9	1.60	3.31	0.93	0.19	0.0075	0.0061
observed ratio			1.50-1.70	3.01-3.31	0.86-0.96	0.15-1.19	0.0074-0.0082	0.0054-0.0066



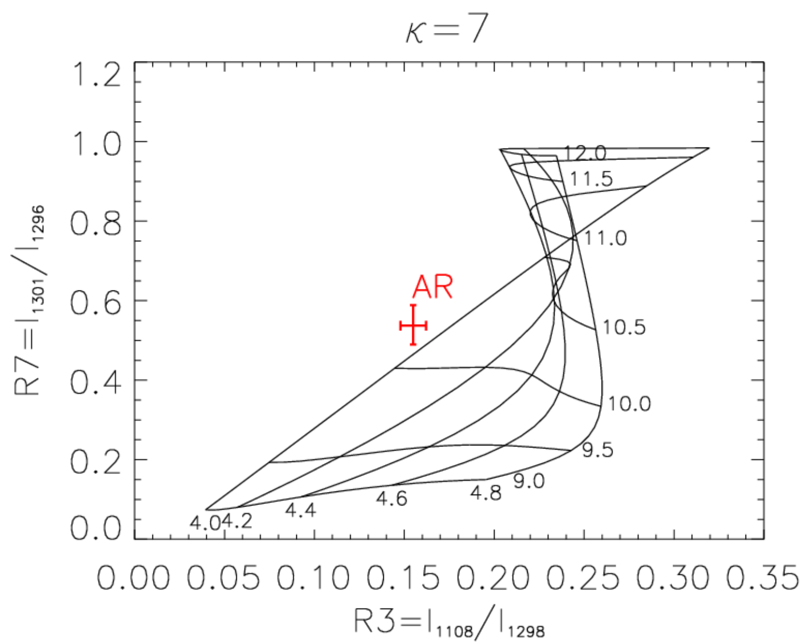


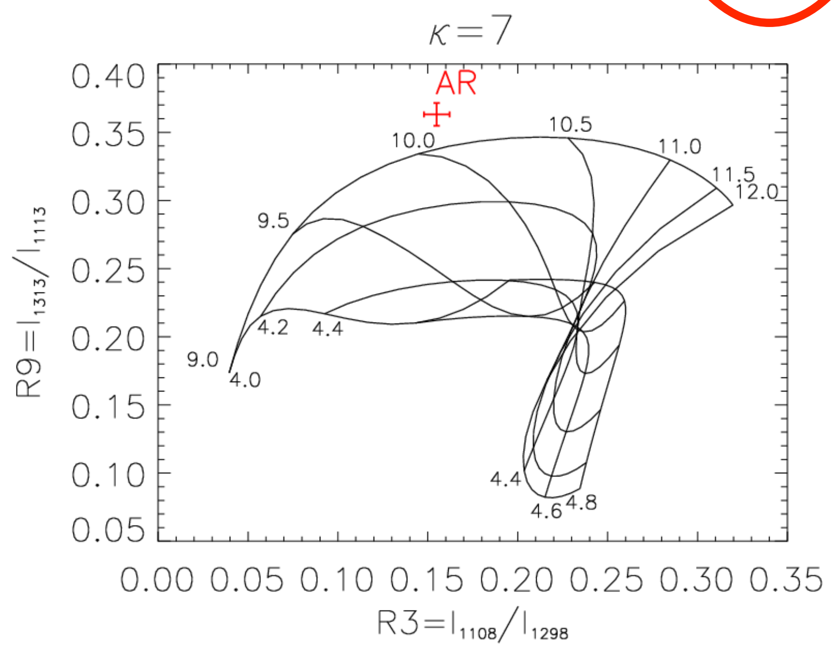
Diagnostics - Kappa

R9 = 1313/1113

ACTIVE REGION

log(T)	log(Ne)		R2	R3	R4	R7	R8	R9
4.50	10.4	Maxw.	0.67	0.16	1.81	0.53	0.12	0.07
4.00	10.1	$\kappa = 7$	0.69	0.16	1.99	0.49	0.11	0.34
observed ratio			0.63-0.69	0.15-0.17	1.58-1.74	0.49-0.59	0.11-0.14	0.35-0.37





Conclusions I.

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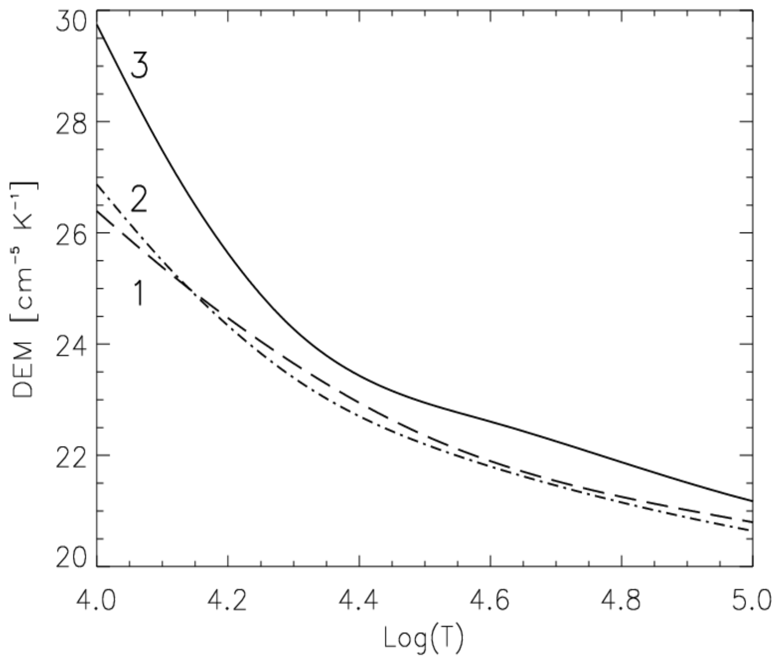
- the presence of the κ-distribution is able to explain the observed line ratios of Si III in the transition region
- N_e and T diagnosed for the κ-distribution correspond to the electron densities and temperatures derived under assumption of the Maxwellian distribution
- a degree of the non-thermality of the region on the Sun increases with their activity – probably it is related to the configuration of the magnetic field
- Scudder (1992) κ~2.2, MacNeice *et al.* (1991) - small departures from the Maxwellian distribution

Problems:

- lower N_e for QS
- low $T=10^4$ K for AR
- Is there an influence of the strong N_e and T gradient in the transition region on diagnostics?

DEM - Maxwellian

3 different DEM from CHIANTI



Assumptions:

- constant κ in the transition region
- constant pressure, $N_e x T = 10^{13}$ - 10^{16} cm^{-3} K

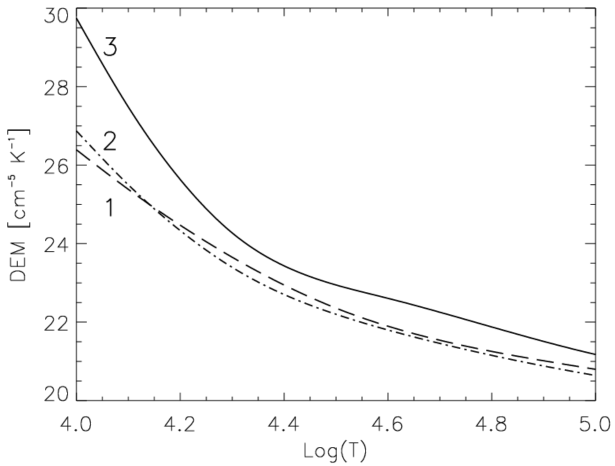
$$I_{ij} = \frac{hc}{4\pi\lambda_{ij}} A_{ij} A_{Si} \int \frac{N_i}{N_{Si}^{k+}} \frac{N_{Si}^{k+}}{N_{Si}} \frac{N_H}{N_e} N_e dl$$

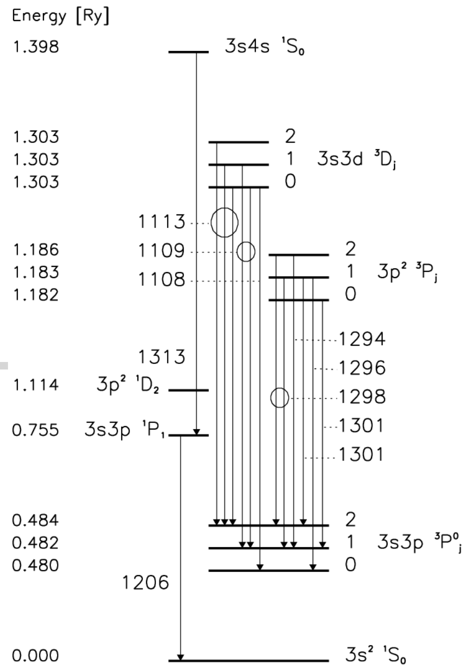
$$I_{ij} = \frac{hc}{4\pi\lambda_{ij}} A_{ij} A_{Si} \int \frac{N_i}{N_e N_{Si}^{k+}} \frac{N_{Si}^{k+}}{N_{Si}} \frac{N_H}{N_e} DEM\, dT = \int G(T) DEM\, T d\log(T)/\log(e)$$

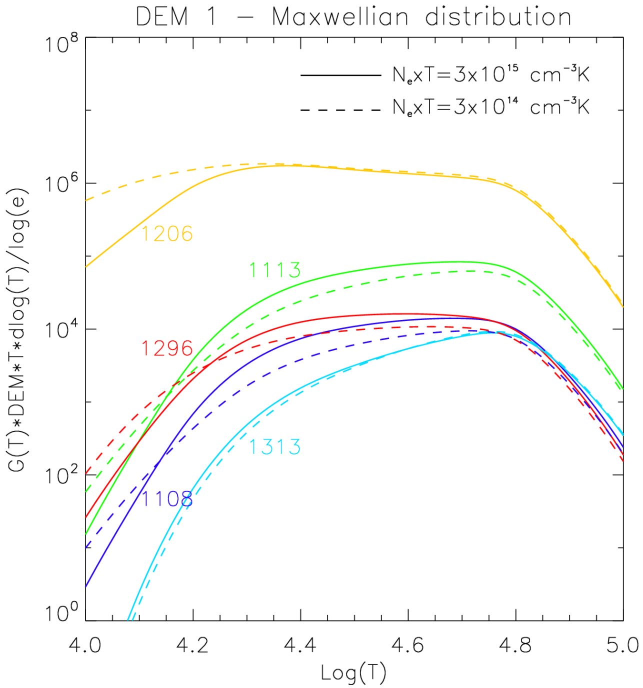
$$DEM = N_e^2 \frac{dl}{dT}$$

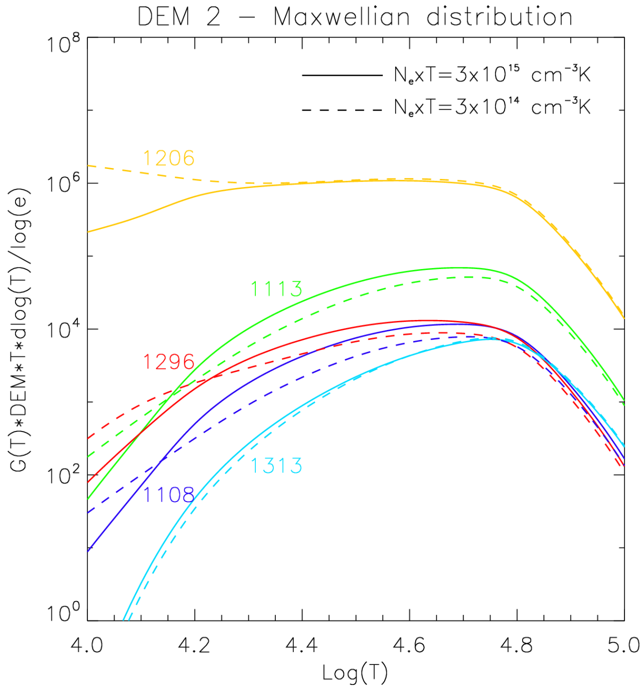
DEM - Maxwellian

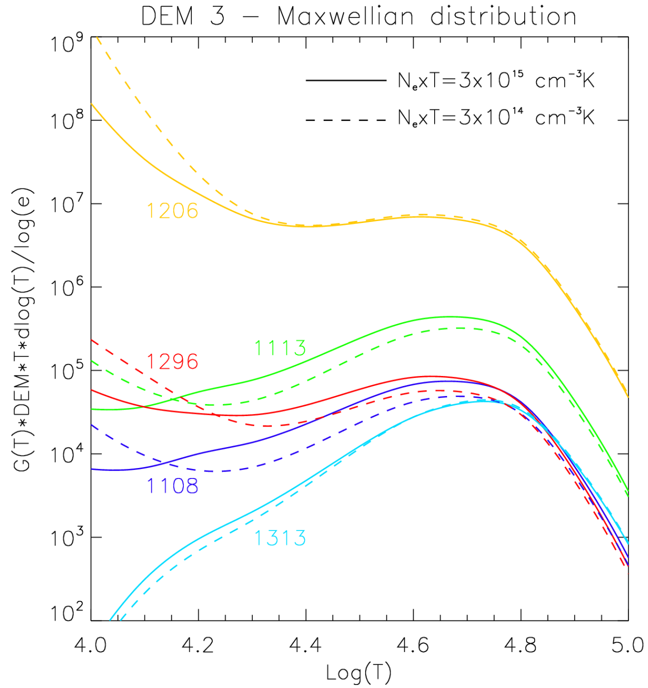
R2 = 1108 /1296
R9 = 1313/1113
R11 = 1296/1206





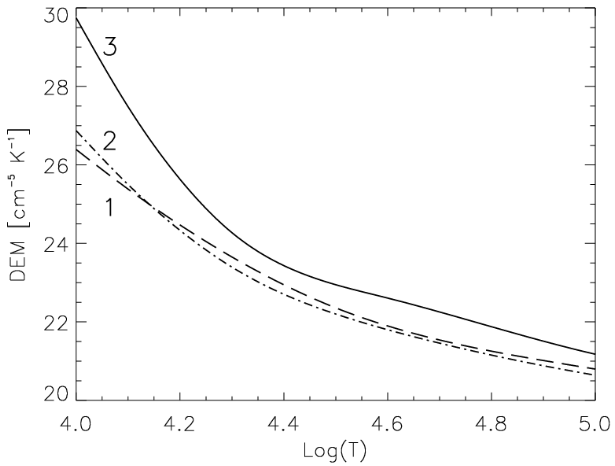


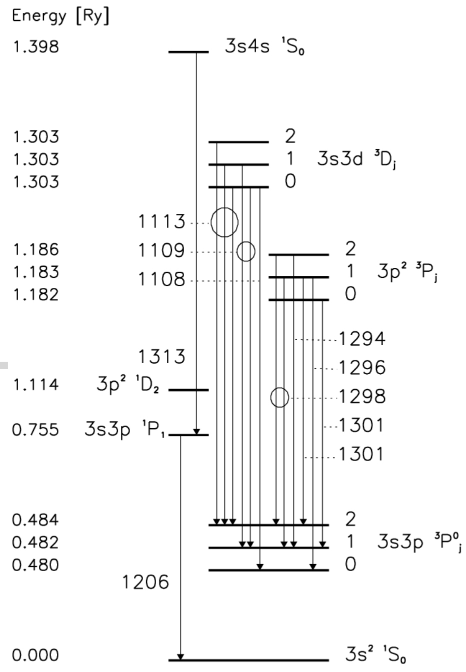


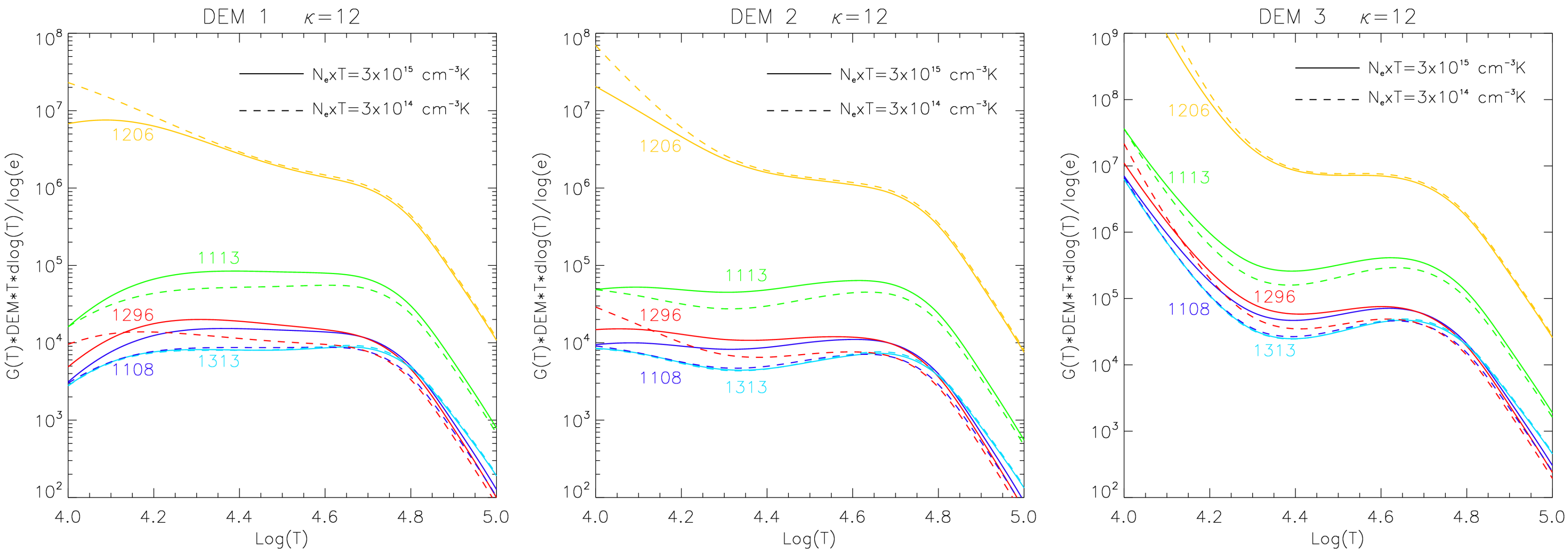


DEM – kappa =12

R2 = 1108 /1296
R9 = 1313/1113
R11 = 1296/1206





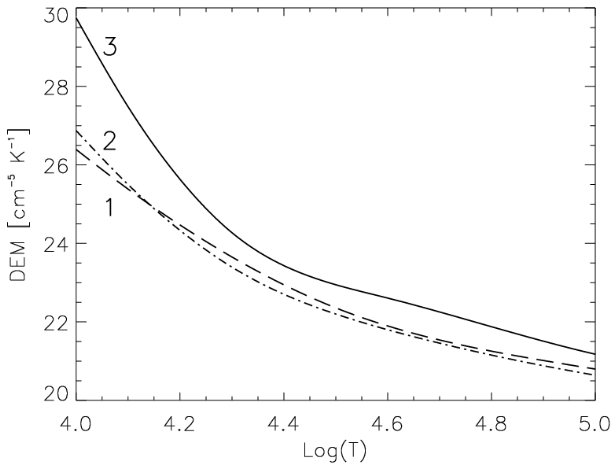


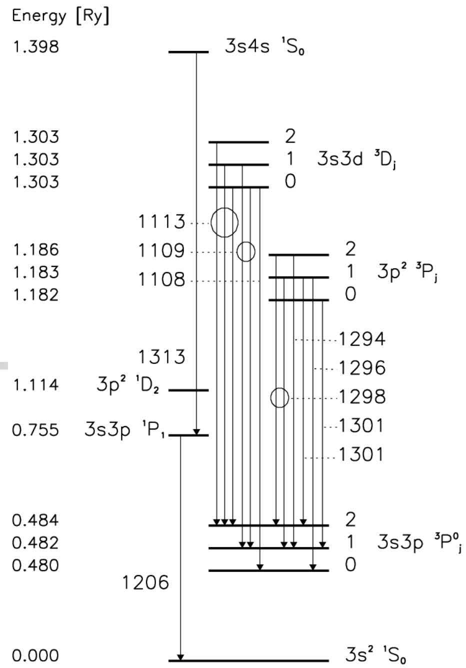
DEM – kappa =7

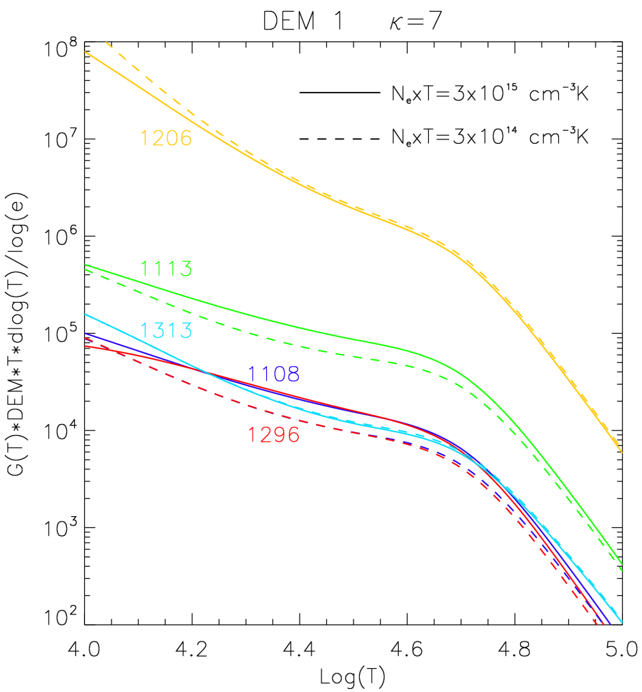
R2 = 1108 /1296

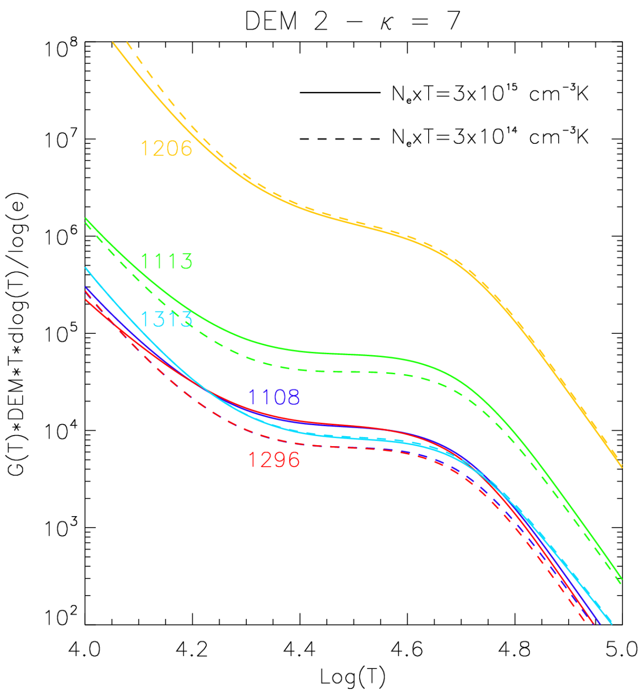
R9 = 1313/1113

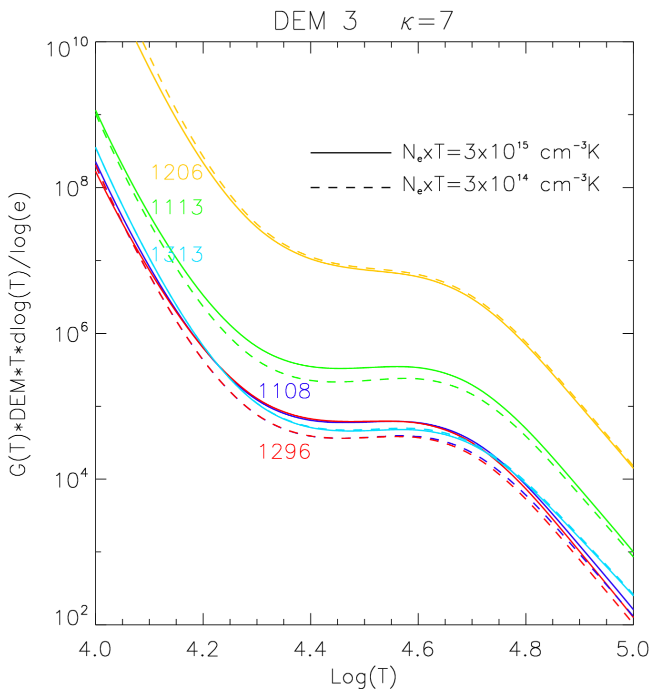
R11 = 1296/1206





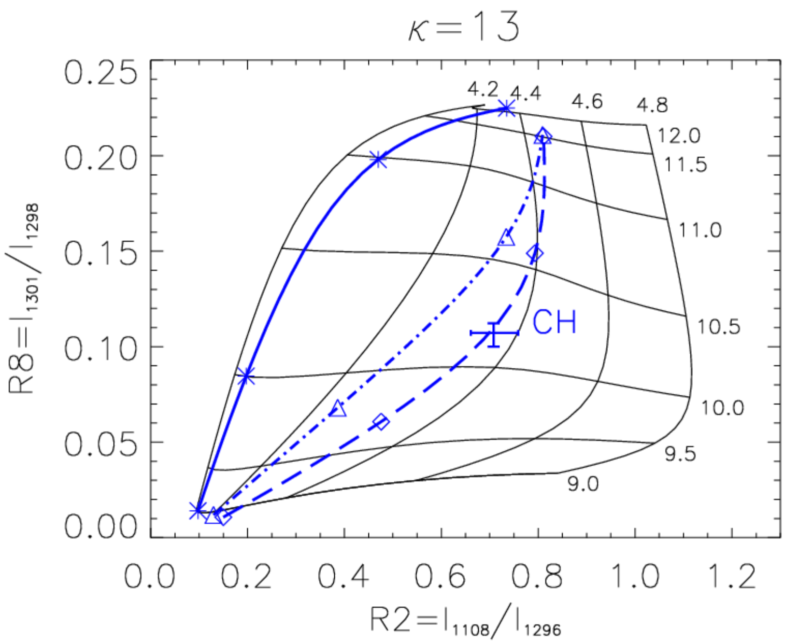


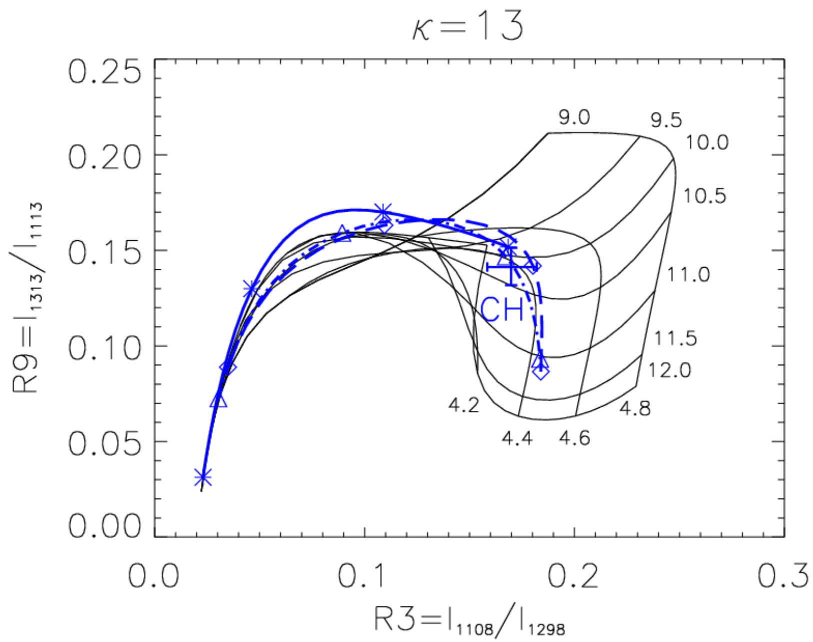




DEM – cornal hole

- corresponds to DEM 1, $\log(N_e xT)$ = 14.6 (left) and 14.8 (right) $cm^{-3}K$
- isothermal diagnostics: $\log(N_e)+\log(T)$ = 10.15+4.40=14.55 $cm^{-3}K$

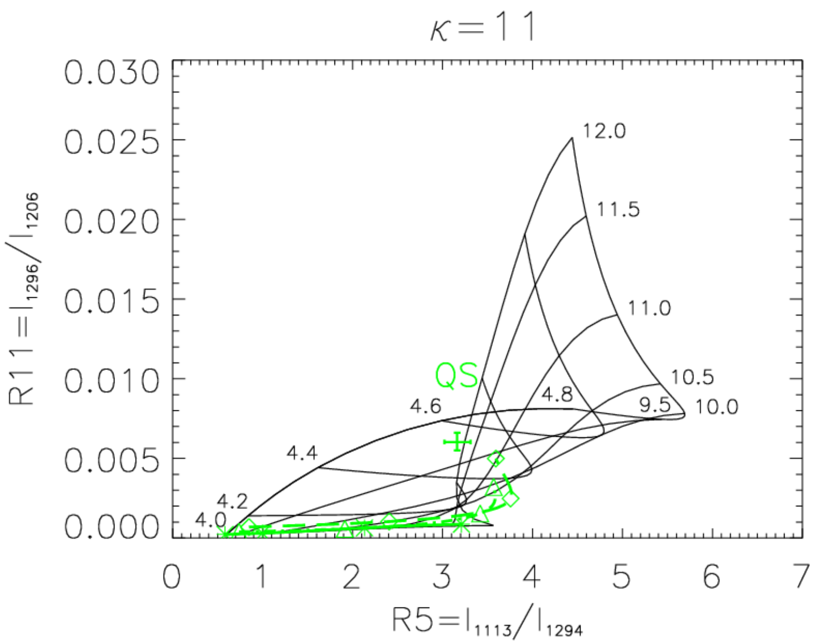


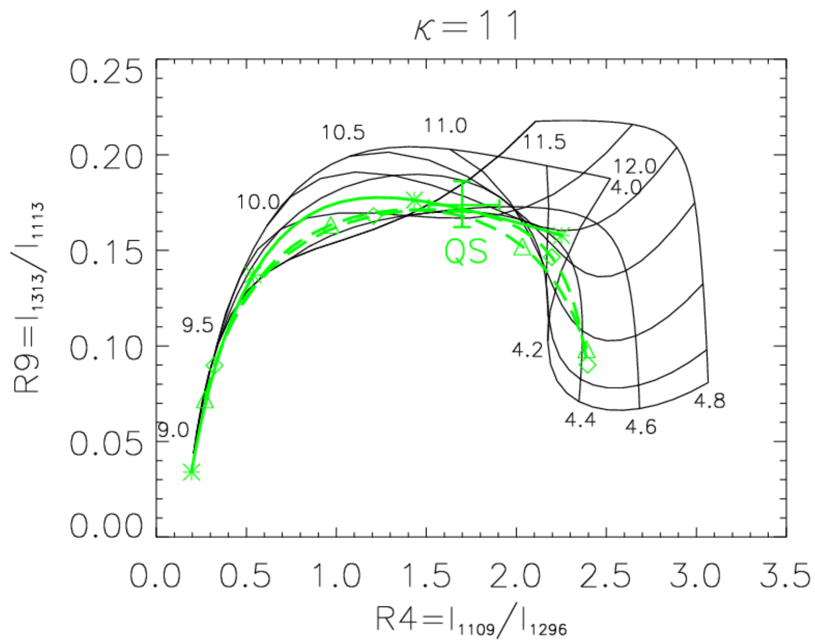


dashed line: DEM 1, dot-dashed line: DEM 2, full line: DEM 3

DEM – quiet sun

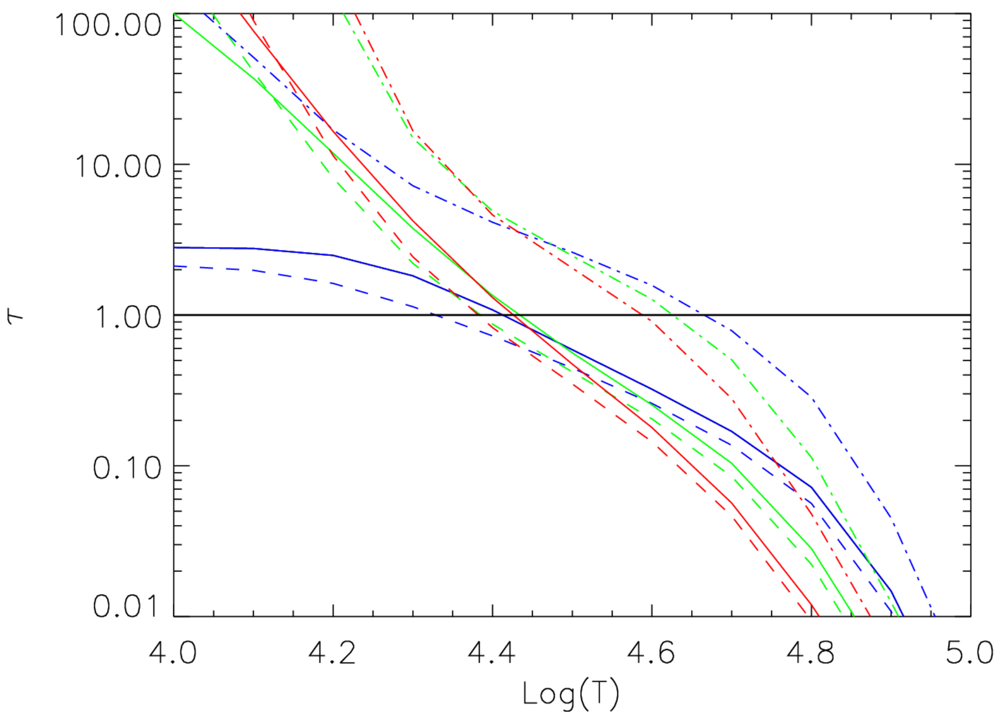
- left: the observed ratios are situated outside of calculated values - variable κ, optical thickness of 1206 Å line?
- $\log(N_e x T)$ = 14.2-15.2 $cm^{-3}K$ (right, for different DEM's)
- isothermal diagnostics: $\log(N_e)+\log(T)$ = 9.25+4.55=13.80 $cm^{-3}K$





optical thickeness of 1206 Å line

Pinfield *et al.* (1999): ***the absence of the flattening of the Gaussian profile of this line in the quiet Sun region***
Avrett & Loeser (2008): ***A line that is strong enough to have its line-center optical depth close to unity where the temperature increases with high will appear in emission if the line source function also increases with high.***

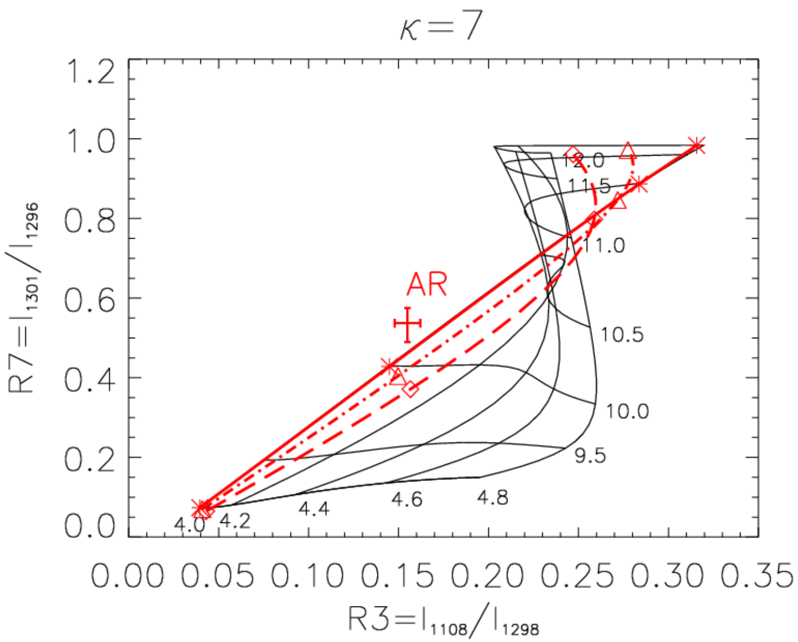


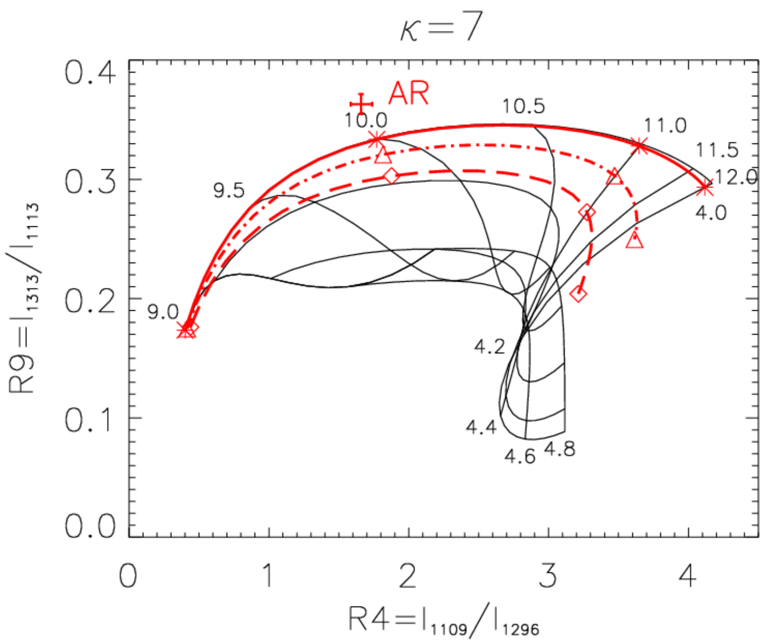
blue: Maxwellian
green: κ=12
red: κ=7

full line: DEM 1
dashed line: DEM 2
dot-dashed line:DEM 3

DEM – Active region

- log(N_exT) = 14.1 cm^{-3}K (left & right)
- isothermal diagnostics: log(N_e)+log(T) = 10.10+4.00=14.10 cm^{-3}K
- low T is a result of strong gradient T and N_e





Conclusions II.

- the presence of the κ-distribution or similar kind of the electron distribution with an enhanced number of particles in high-energy tail is able to explain the observed intensities of Si III lines in the transition region
- a gradient of N_e and T in the transition region does not influence the diagnosed value of κ; a stronger activity corresponds to the higher non-thermality of plasma
- DEM can influence diagnosed N_e and T but pressure seems to be correct
- the 1206 Å line can be optically thick – it is not suitable for diagnostics
- low T diagnosed for κ =7 in AR is a result of the strong gradient of T and N_e; the highest contribution to the total line intensities comes from the lowest parts of the transition region with the lowest T

Open problems:

- the effect of thermalization of the electron distribution at the boundary between chromosphere and transition region on diagnostics should be investigated for different DEM's
- DEM's under an assumption of κ-distribution should be calculated


Thank you
for your attention!