Statistical modelling of prominence fine structure using the 2D multi-thread nonLTE model

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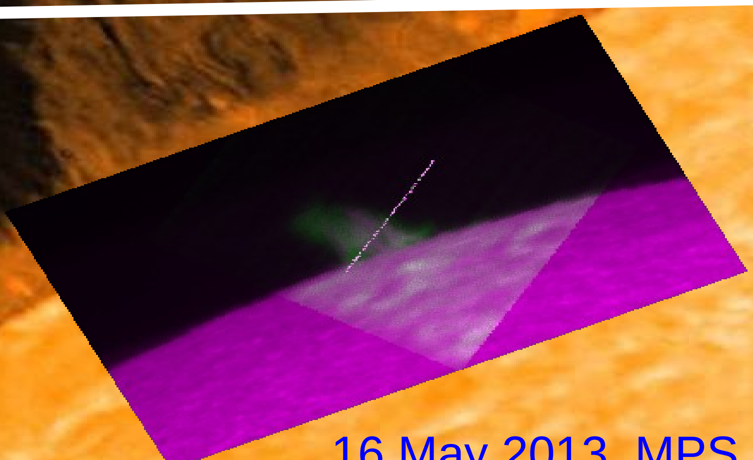
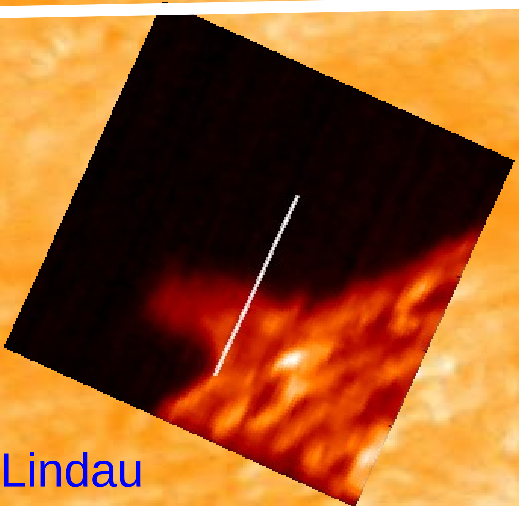
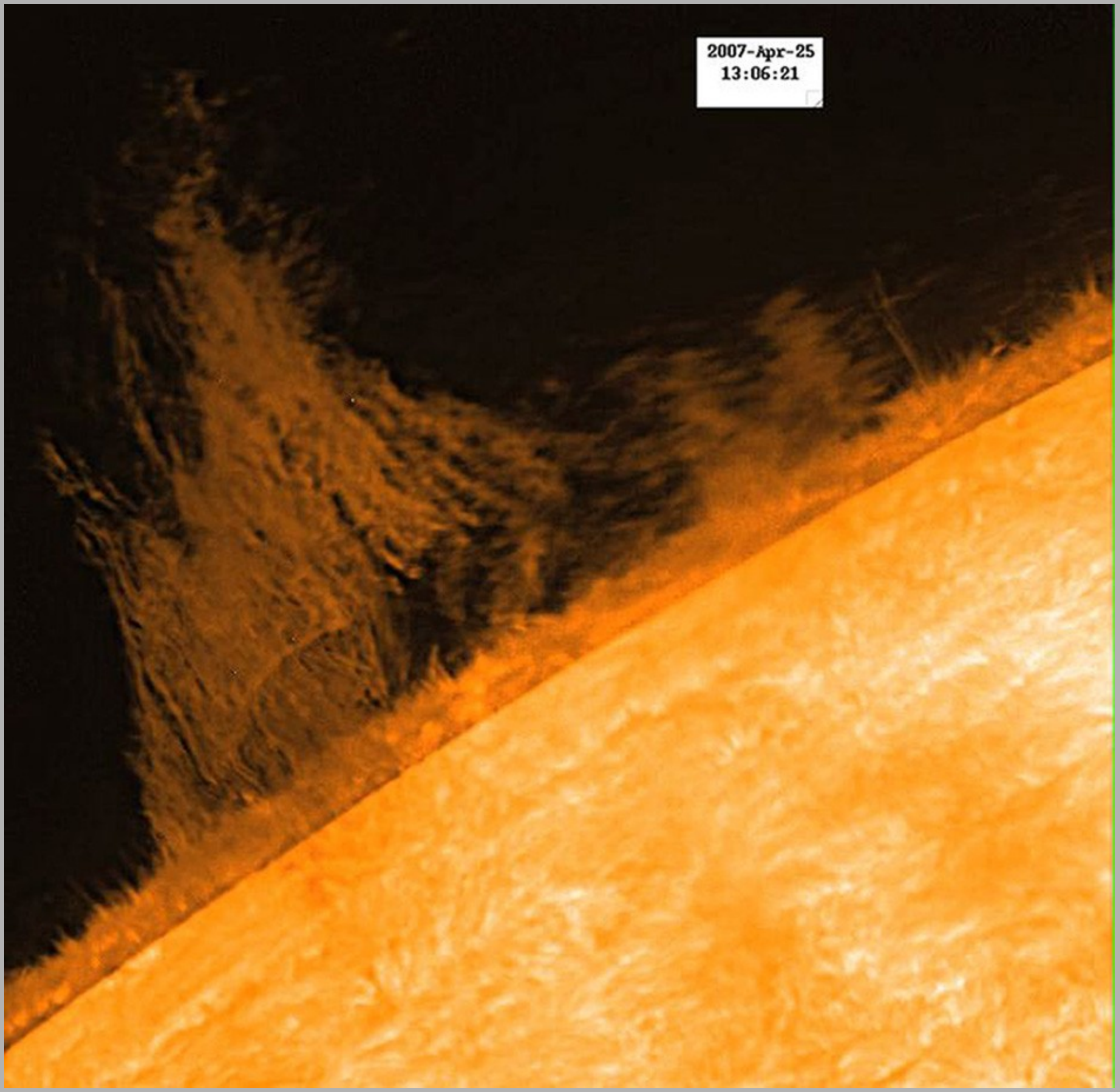
[2] **Astronomical Institute, Academy of Sciences of the Czech Republic**
[3] **Observatoire De Paris, Section Meudon, France**
[4] **Max-Planck-Institut für Astrophysik**





16 May 2013, MPS,Katlenburg-Lindau

Vertical threads in the quiescent prominence observed by SOT in Hα



2D prominence fine-structure models

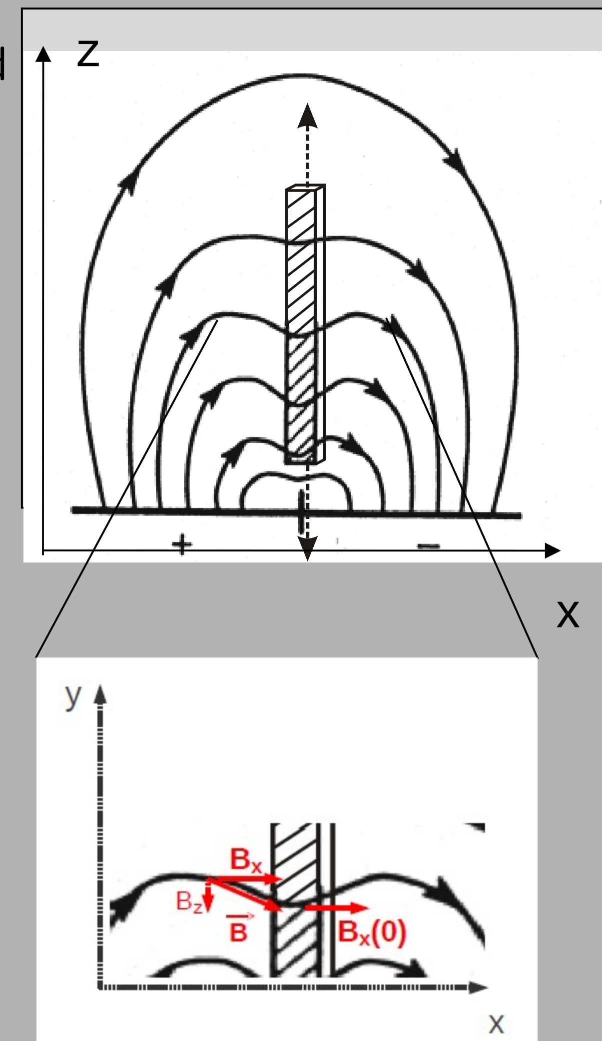
Vertically infinite fine-structure thread embedded in a dipped magnetic field

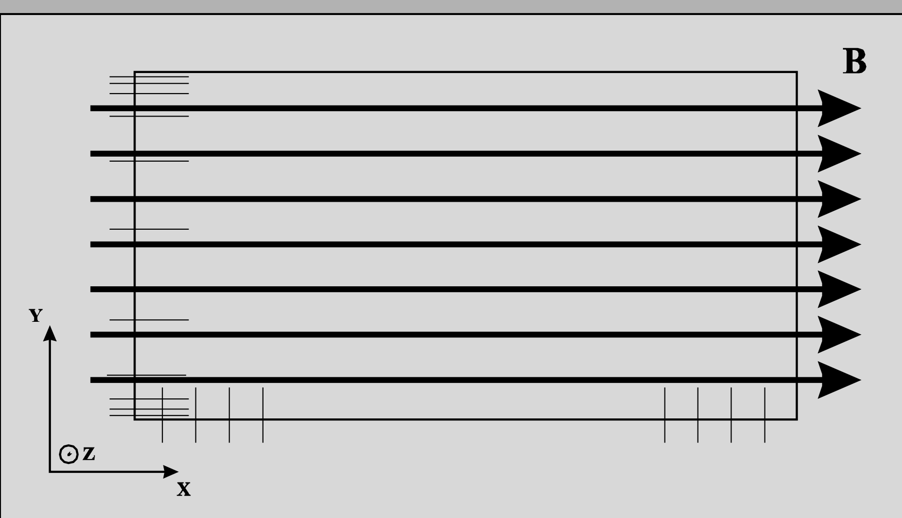
2D MHS equilibrium of Kippenhahn-Schlüter type (Heinzel & Anzer 2001).

Solution of 2D radiative transfer by MALI method (Auer & Paletou 1994) with usage of the short characteristics (Kunasz & Auer 1988)

12 level plus continuum hydrogen atom

Partial-frequency redistribution (PRD) is assumed for Lyman-α and Lyman-β lines

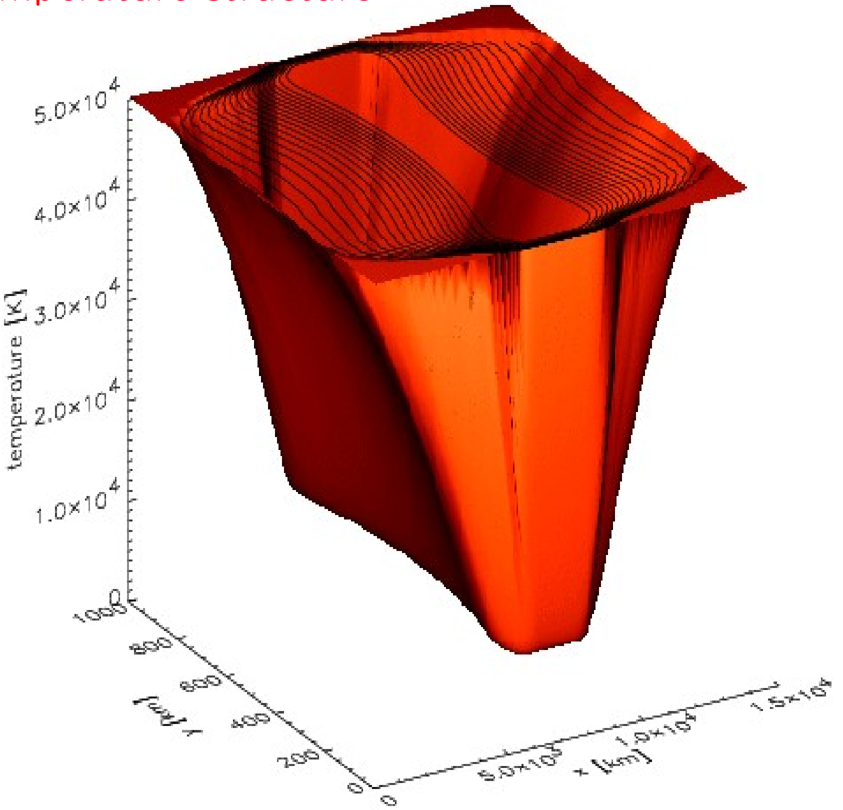




Anzer, U. a Heinzel, P.: 1999, *A&A* **349**, 974.
Auer, L.H. & Paletou, F.: 1994, *A&A* **285**, 675.
Heinzel, P. & Anzer, U.: 2001, *A&A* **375**, 1082.
Kunasz, P. & Auer, L.H.: 1988, *JQSRT* **39**, 67.

Temperature and density structure

Temperature structure



$$T(m,y) = T_{\rm cen}(y) + [T_{\rm tr} - T_{\rm cen}(y)] \left\{1 - 4\frac{m}{M(y)}\left[1 - \frac{m}{M(y)}\right]\right\}^{\gamma_1}$$

The central temperature $T_{\rm cen}(y)$

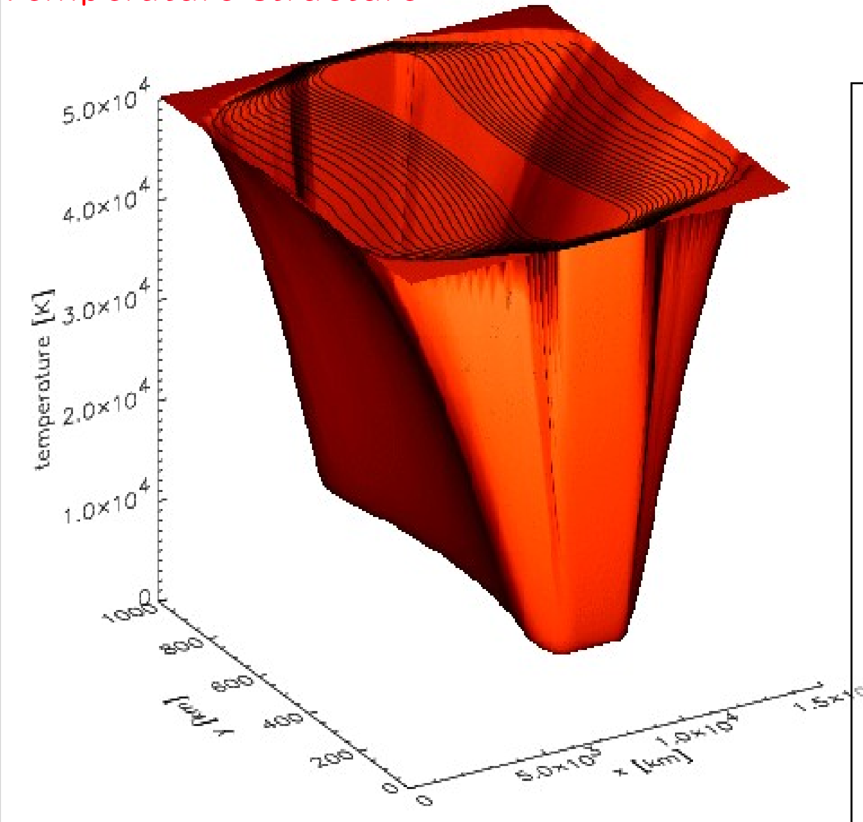
$$T_{\rm cen}(y) = T_{\rm tr} - (T_{\rm tr} - T_0)\left(1 - \left|\frac{y}{\delta}\right|^{\gamma_2}\right), \quad \text{for} \quad |y| \le \delta$$

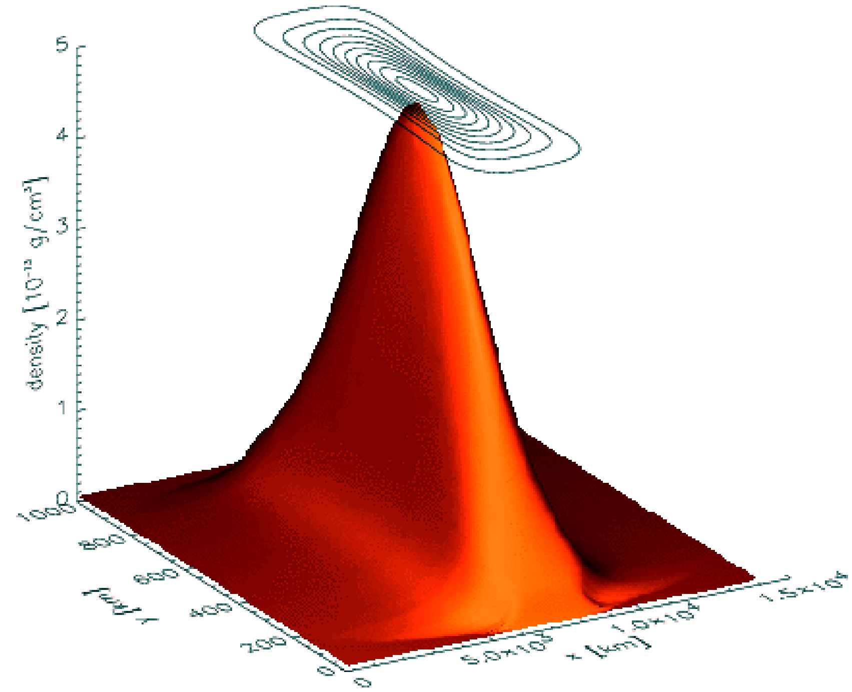
$$T_{\rm cen}(y) = T_{\rm tr}, \quad \text{for} \quad |y| > \delta$$

γ_1 and γ_2 are chosen parameters.

Heinzel, P., Anzer, U., & Gunár, S. 2005, A&A, 442, 331

Temperature and density structure





$$T(m,y) = T_{cen}(y) + [T_{tr} - T_{cen}(y)] \left\{ 1 - 4 \frac{m}{M(y)} \right.$$

$$M(y) = M_0 \left(1 - \left| \frac{y}{\delta} \right|^{\gamma_3} \right), \quad \text{for } |y| \leq \delta$$

$$M(y) = 0, \quad \text{for } |y| > \delta$$

The central temperature $T_{cen}(y)$

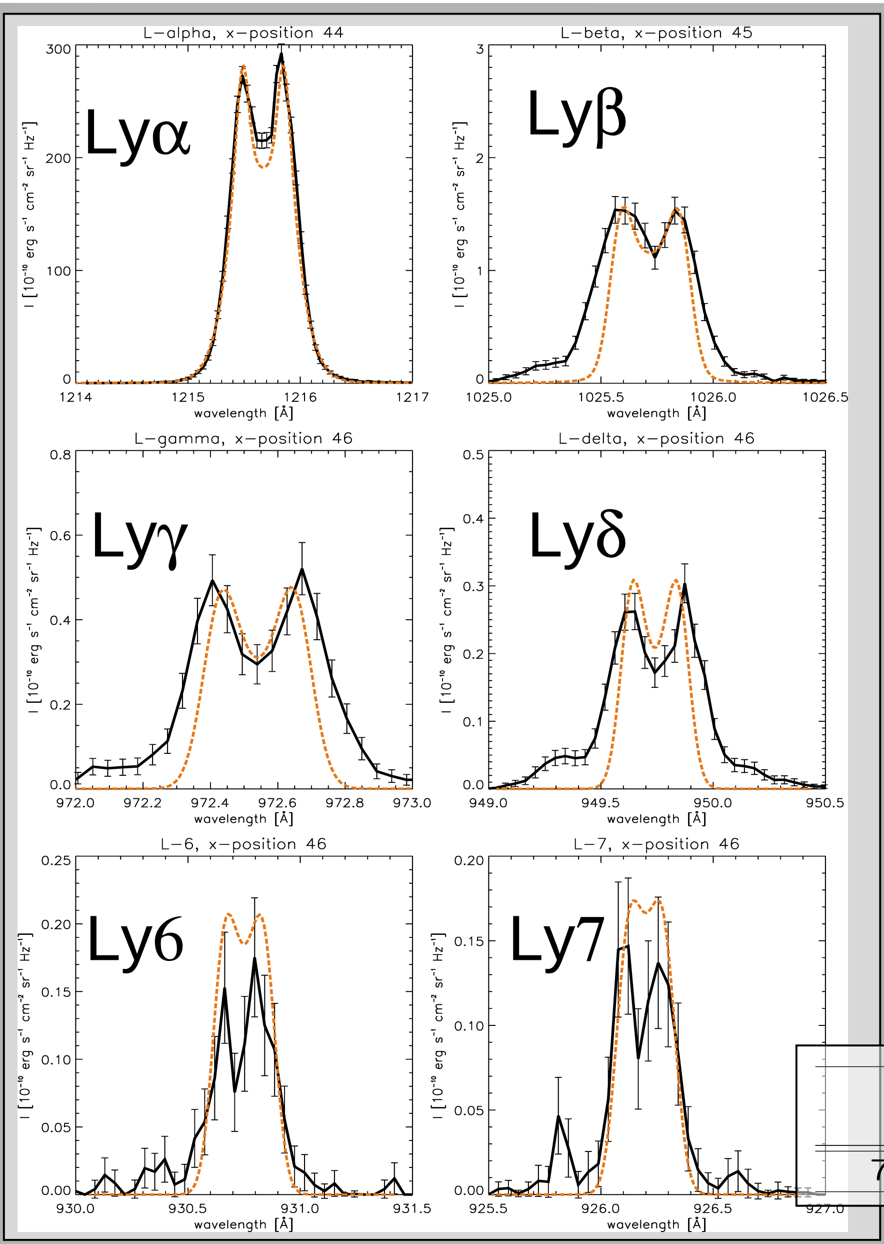
$$T_{cen}(y) = T_{tr} - (T_{tr} - T_0) \left(1 - \left| \frac{y}{\delta} \right|^{\gamma_2} \right), \quad \text{for } |y| \leq \delta$$

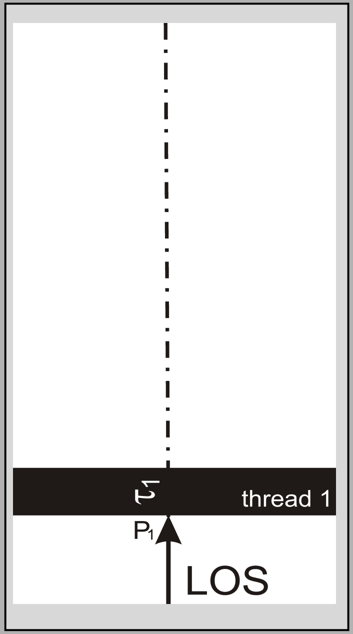
$$T_{cen}(y) = T_{tr}, \quad \text{for } |y| > \delta$$

γ_1 and γ_2 are chosen parameters.

Heinzel, P., Anzer, U., & Gunár, S. 2005, A&A, 442, 331

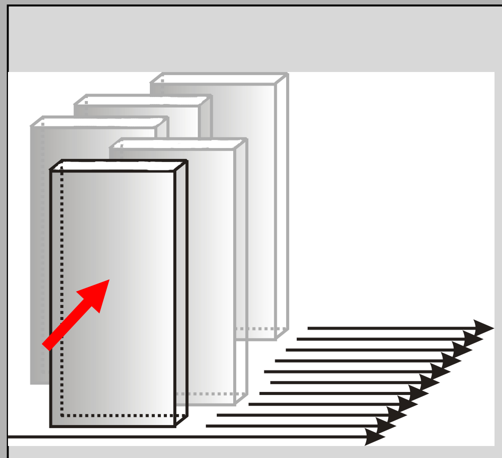
Comparison with observed spectra

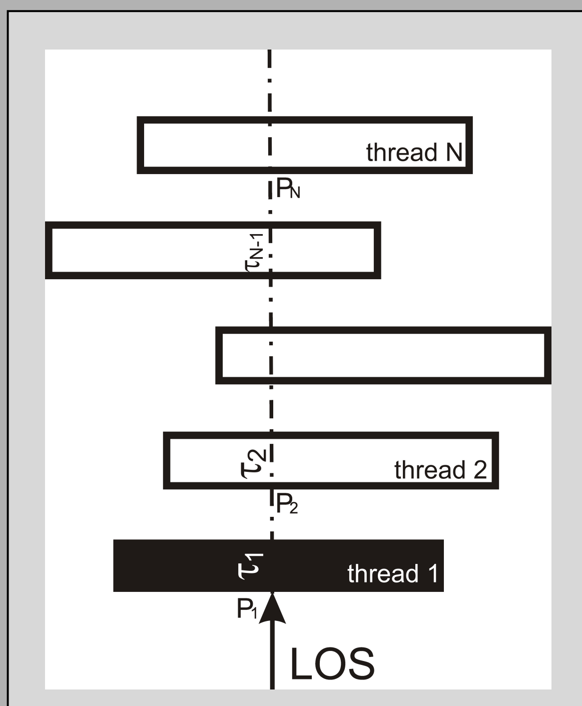


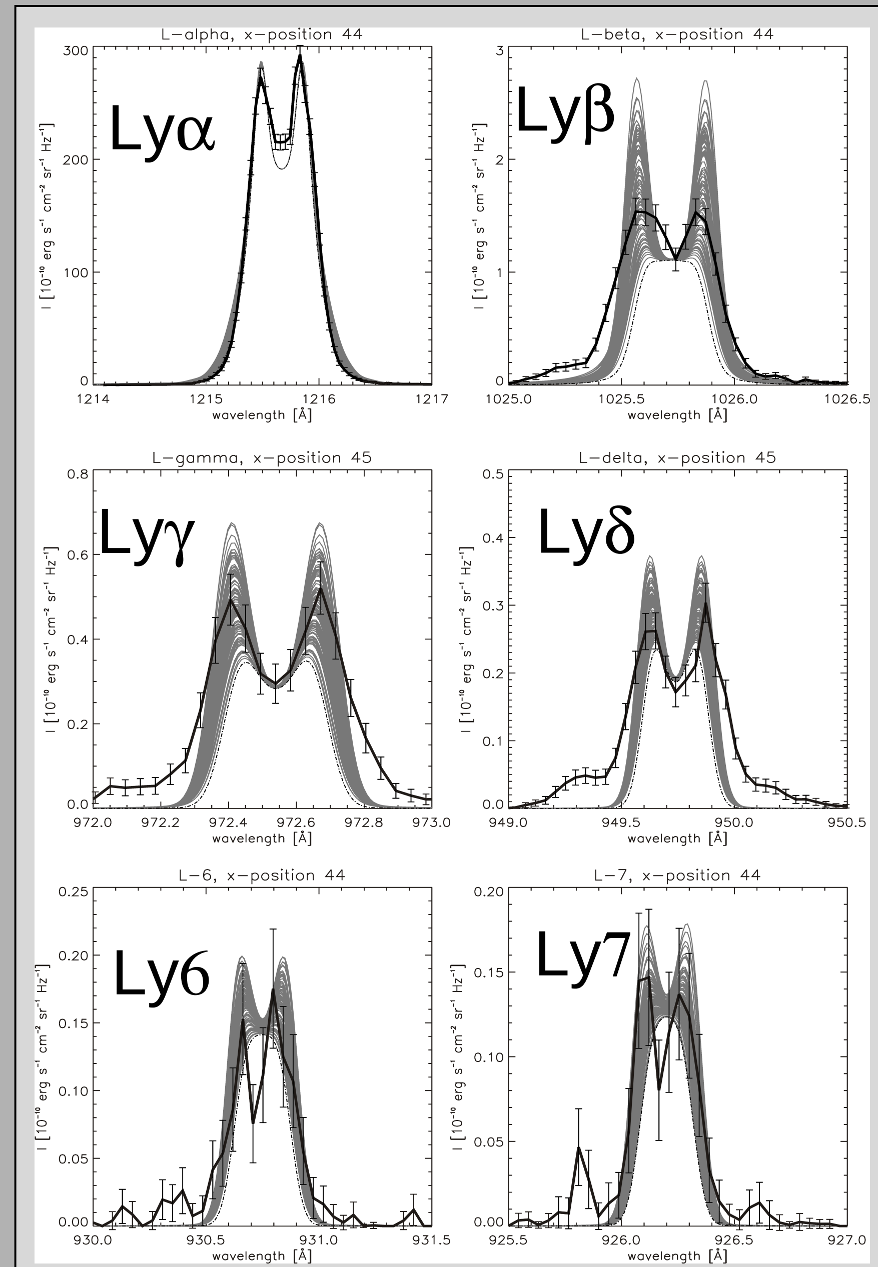


T_0 [K]	M_0 [g cm^{-2}]	$B_x(0)$ [Gauss]	p_0 [dyn cm^{-2}]	v_t [$\times\ c_s$]
7000	1.1×10^{-4}	6	0.015	0.5

Comparison with observed spectra

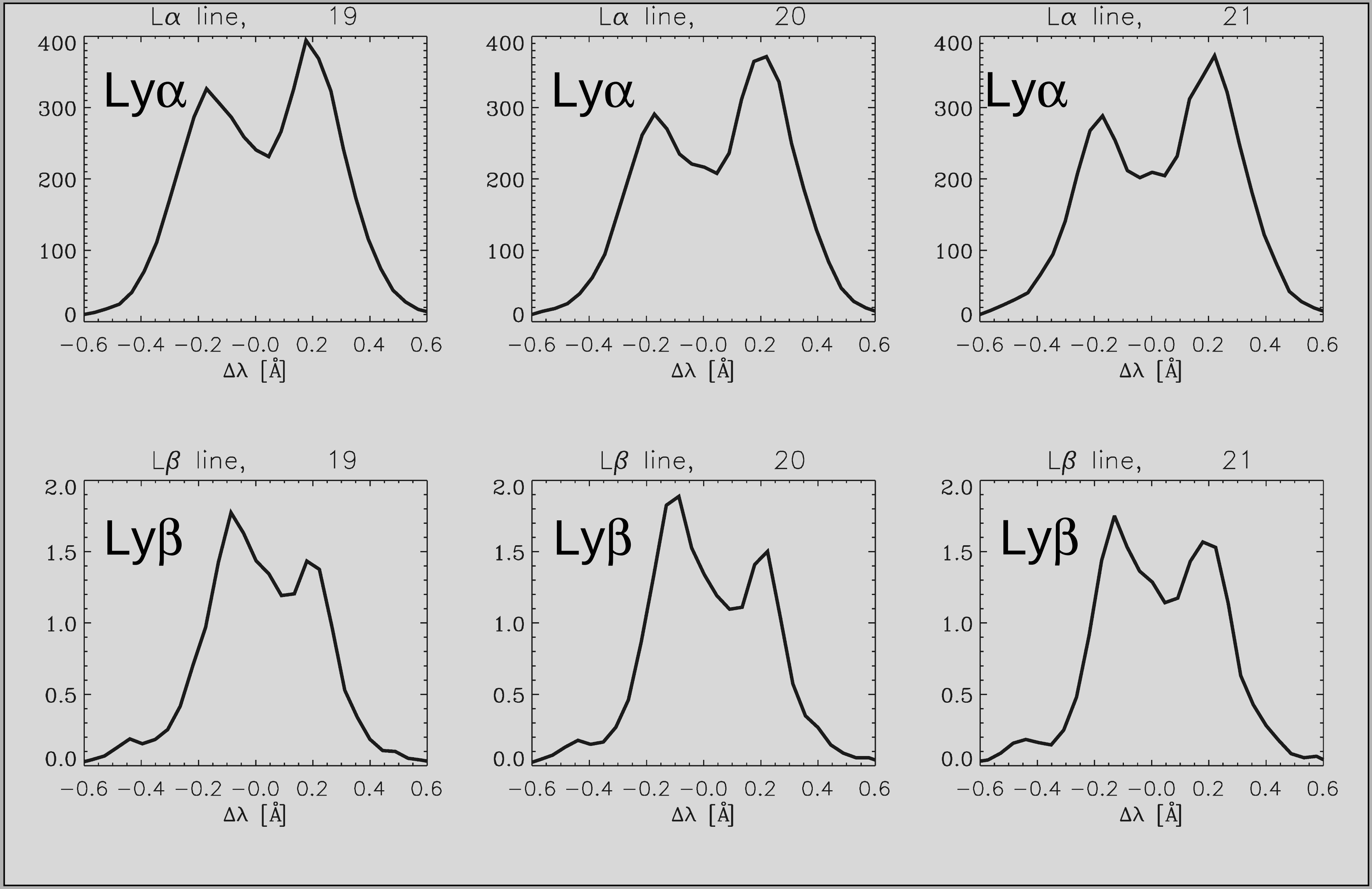






Lyman line asymmetries

Observed profiles – asymmetries of Lyβ sometimes opposite to those of Lyα



2D multi-thread models with LOS velocities

The total emerging intensity

$$I_{\text{total}}(\lambda) = \Big[... \Big[\Big[I_{\lambda(1)} \times \exp(-\tau_{\lambda(2)}) + I_{\lambda(2)} \Big] \times \exp(-\tau_{\lambda(3)}) + I_{\lambda(3)} \Big] \times \\ ... + I_{\lambda(N-1)} \Big] \times \exp(-\tau_{\lambda(N)}) + I_{\lambda(N)} \ ,$$

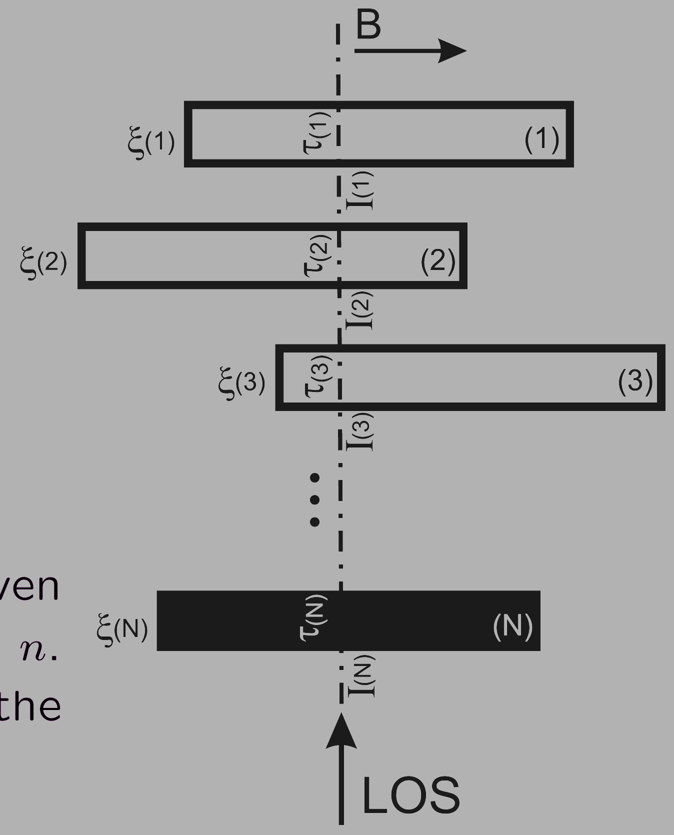
where $I_{\lambda(n)}$ and $\tau_{\lambda(n)}$ are defined as

$$I_{\lambda(n)} \equiv I(\lambda - \Delta\lambda^{(n)})$$
$$\tau_{\lambda(n)} \equiv \tau(\lambda - \Delta\lambda^{(n)}) \ .$$

$\Delta\lambda^{(n)}$ is the Doppler shift for the thread n

$$\Delta\lambda^{(n)} = \lambda_0 \frac{\xi^{(n)}}{c} \ ,$$

where λ_0 represents the line-centre wavelength of a given spectral line and $\xi^{(n)}$ is the LOS velocity of thread n. Positive values of $\xi^{(n)}$ represent velocities towards the observer.

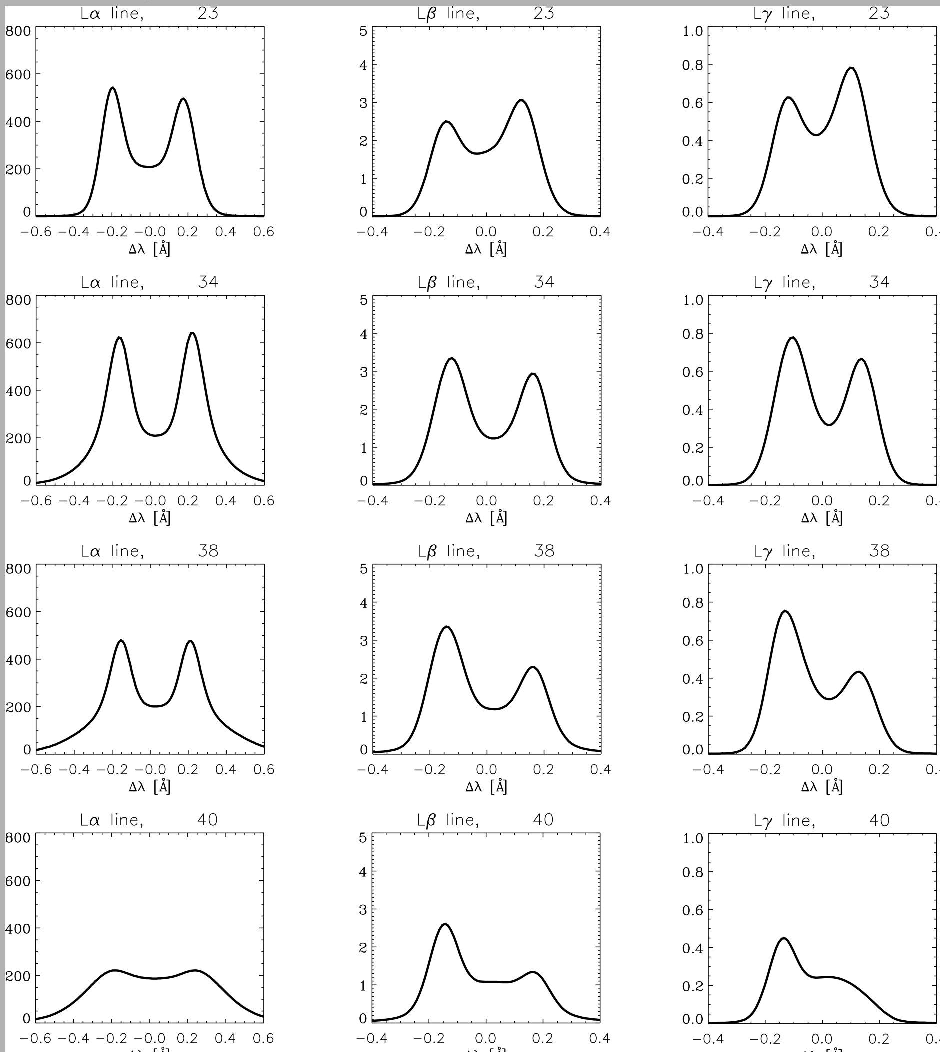


Gunár et al. 2007, A&A (472), 929

Lyman line asymmetries

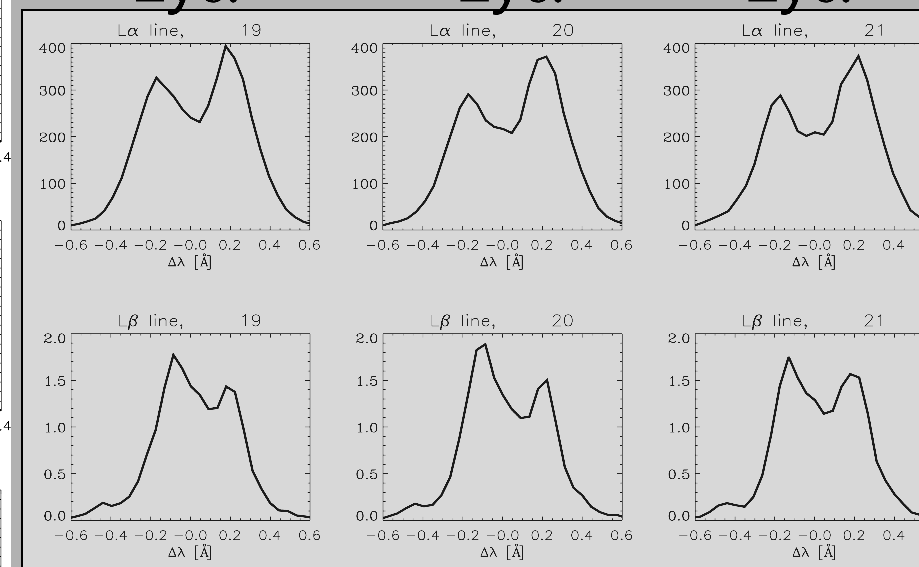
synthetic profiles

Lyα Lyβ Lyγ



profiles observed by SUMER

Lyα Lyα Lyα

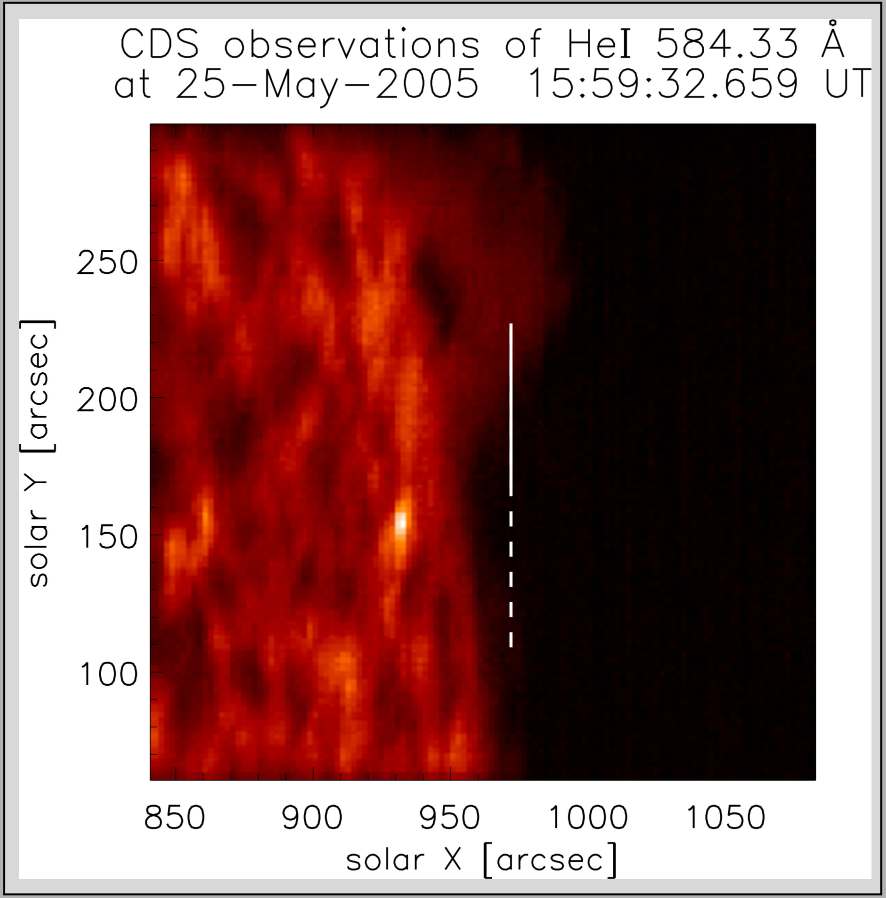


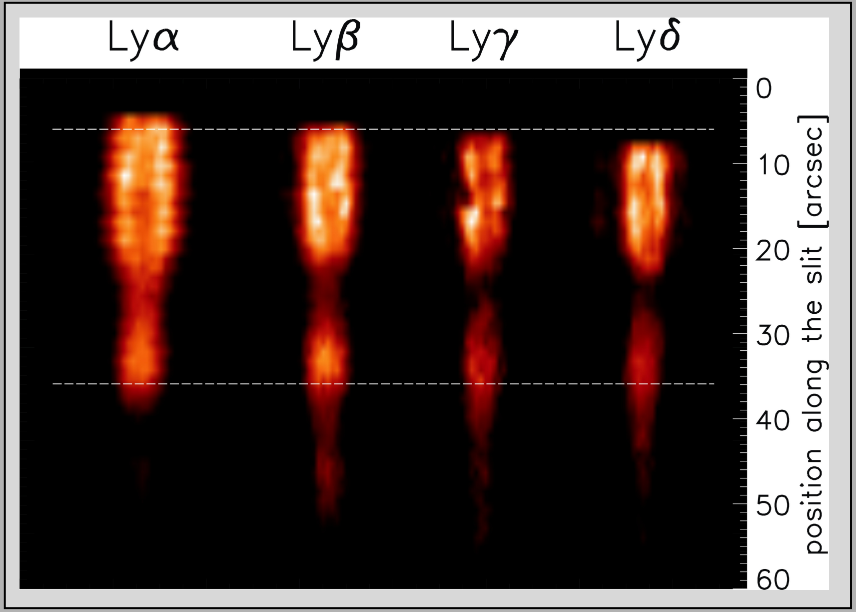
Lyβ Lyβ Lyβ

Gunár et al. 2008, A&A (490), 307

Statistical comparison

Spectral window	Number of observations within each block, May 25 to 26, 2005		
	16:03:15 UT to 20:40:59 UT	20:46:27 UT to 23:01:26 UT	23:04:54 UT to 01:21:51 UT
Lyman-α	25	12	13
Lyman-β	40	20	20
Lyman-γ and Lyman-δ	39	20	20
Lyman-5 to continuum	10	10	10





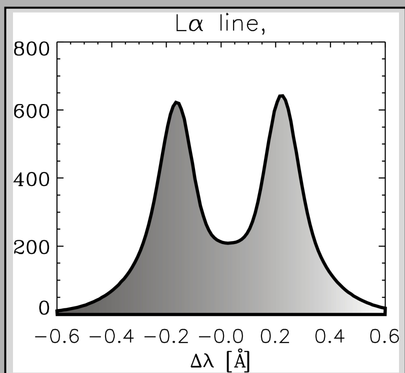
Gunár et al. 2010, A&A (514), 43

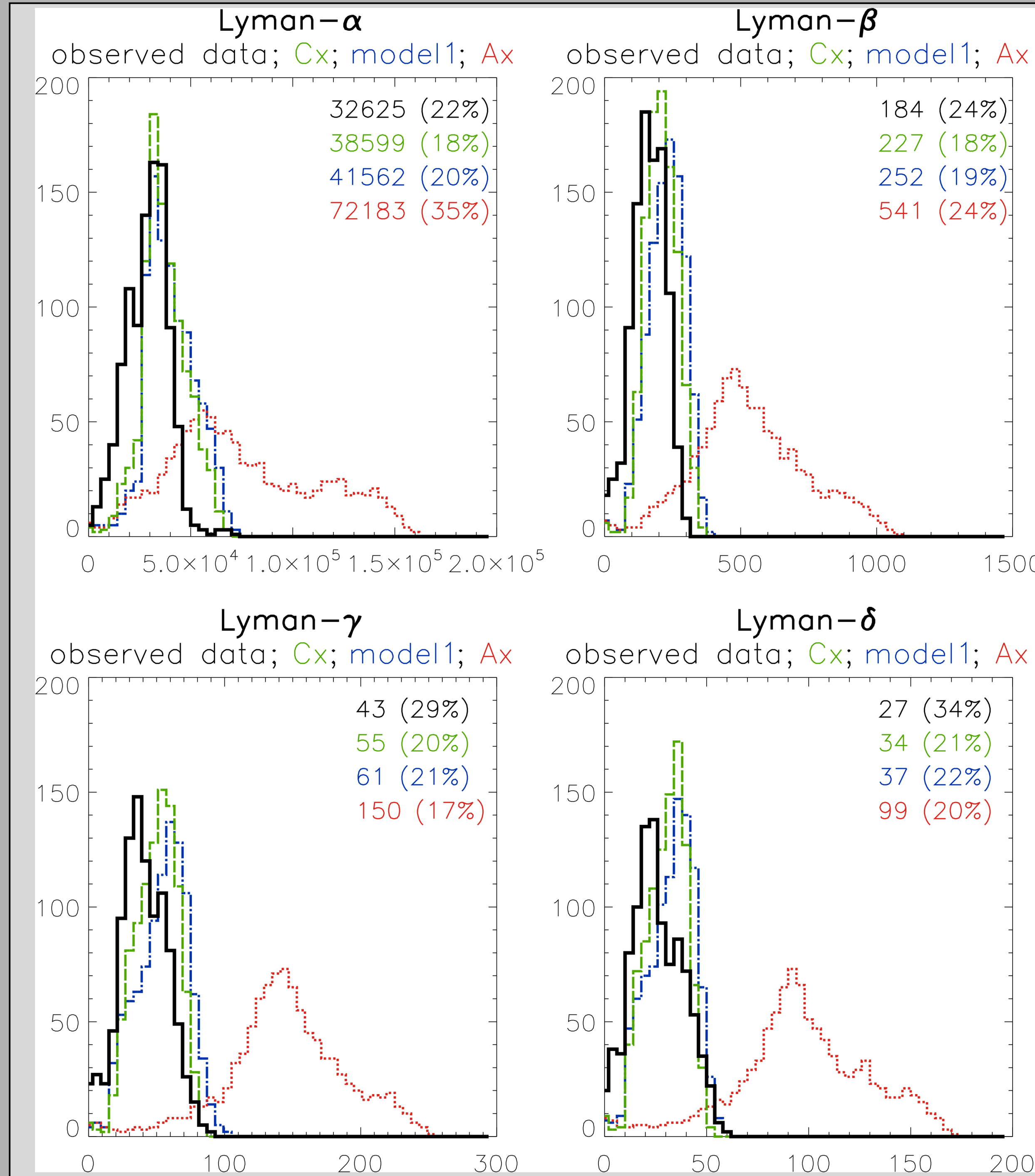
Models used for one thread of multithread model

Label	Set of input parameters
model1	T_0=7000 K; T_{tr}=100 000 K; $B_x(0)$=6 Gauss; M_0=1.1 × 10^{-4} g cm^{-2}; p_0=0.015 dyn cm^{-2}; γ_1=10; γ_2=60
Ax	T_0=7000 K; T_{tr}=100 000 K; $B_x(0)$=6 Gauss; M_0=1.1 × 10^{-4} g cm^{-2}; p_0=0.015 dyn cm^{-2}; γ_1=5; γ_2=30
Cx	T_0=7000 K; T_{tr}=100 000 K; $B_x(0)$=6 Gauss; M_0=1.1 × 10^{-4} g cm^{-2}; p_0=0.015 dyn cm^{-2}; γ_1=10; γ_2=30

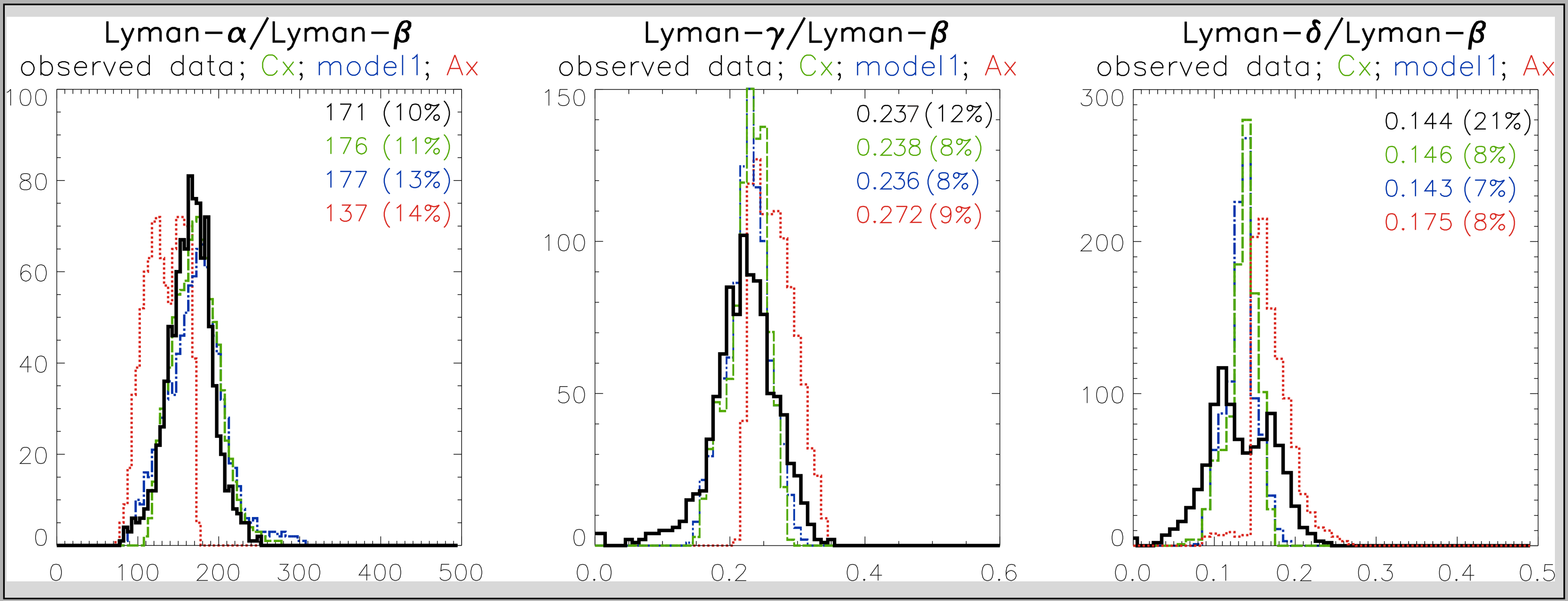
the LOS velocities from interval between -10 and 10 km/s

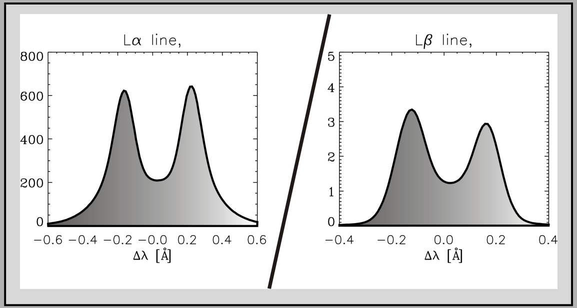
Integrated Intensities



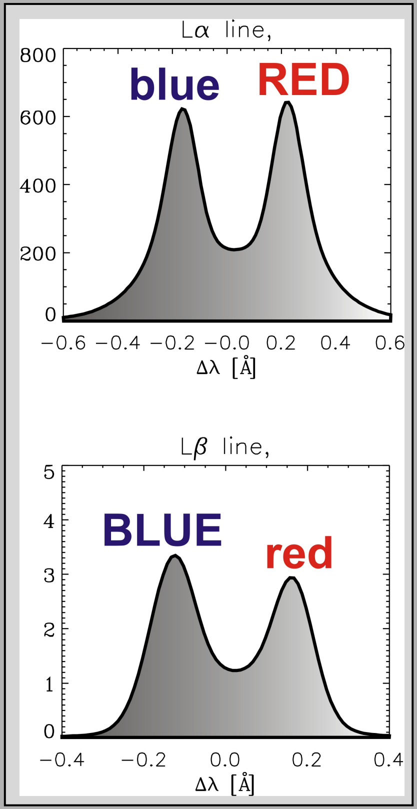


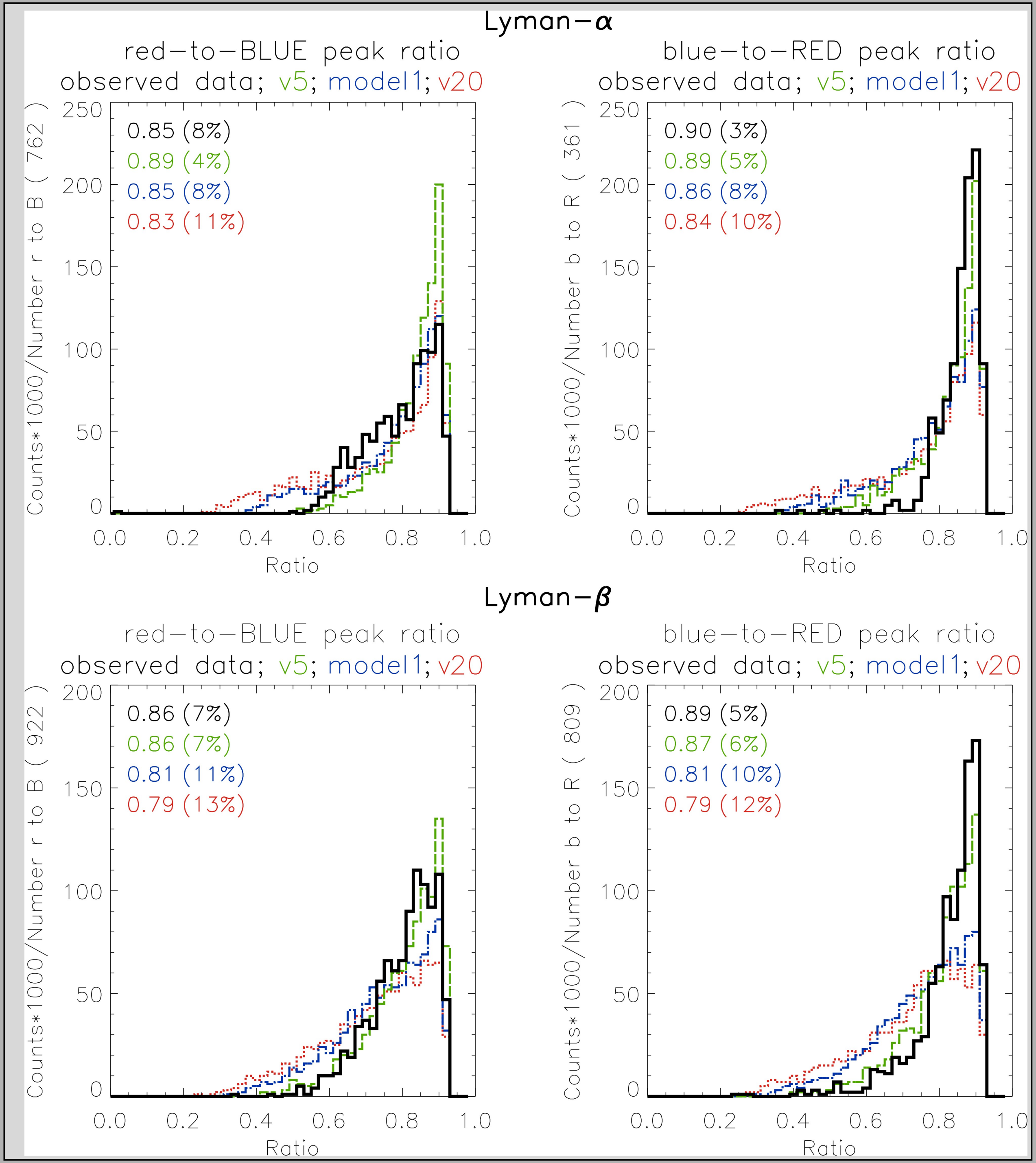
Lyman decrement ratios



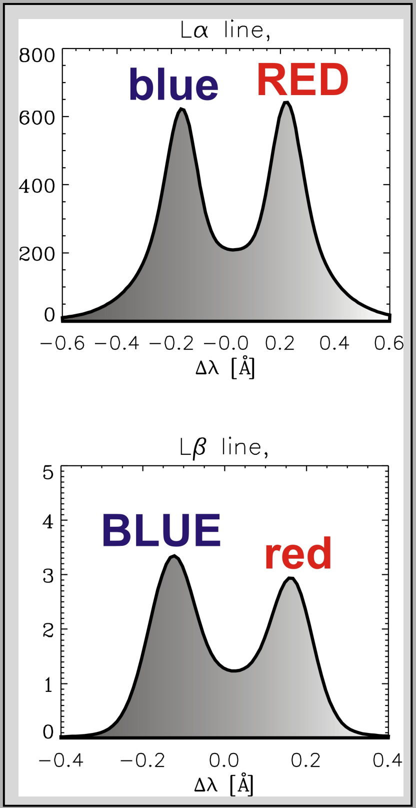


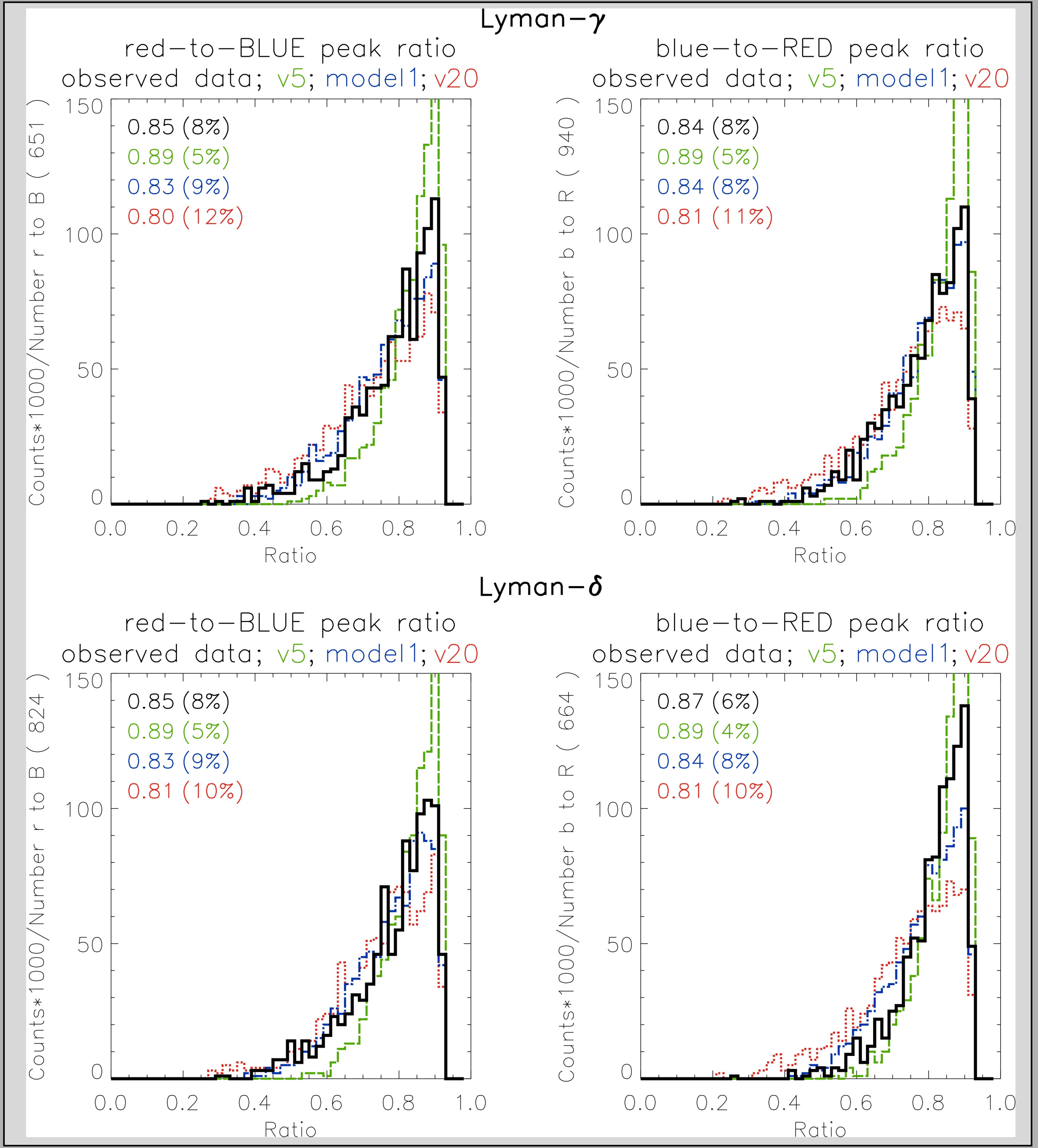
Peak asymmetries



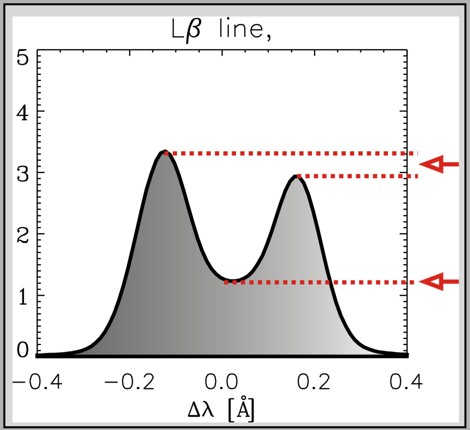


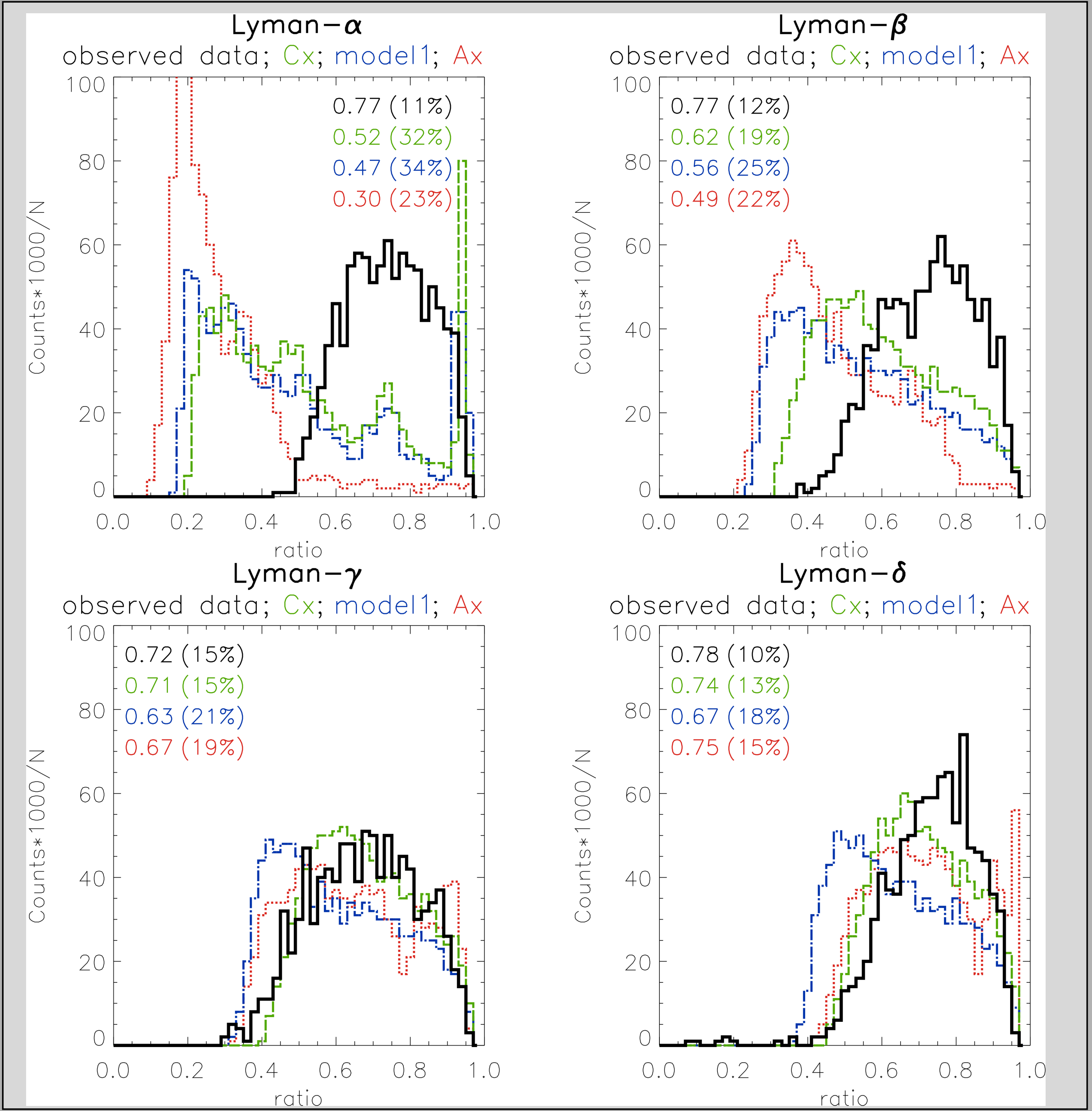
Peak asymmetries





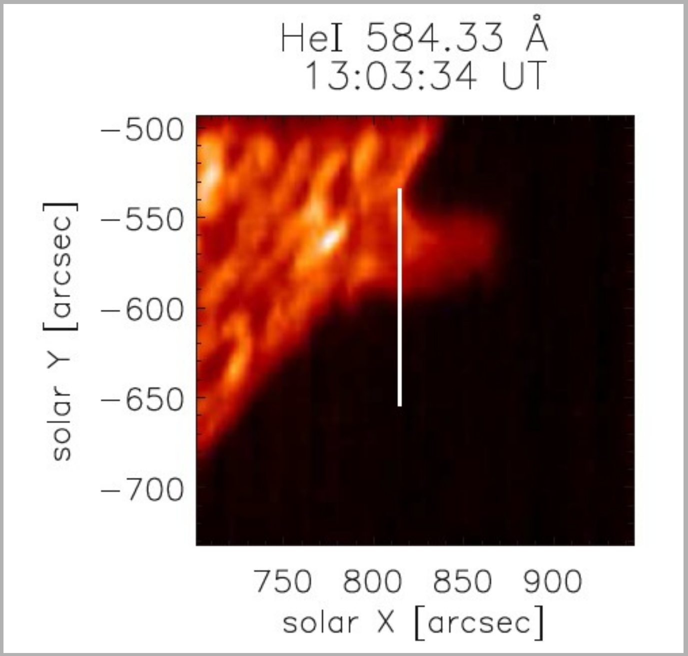
Reversal 'deepness'



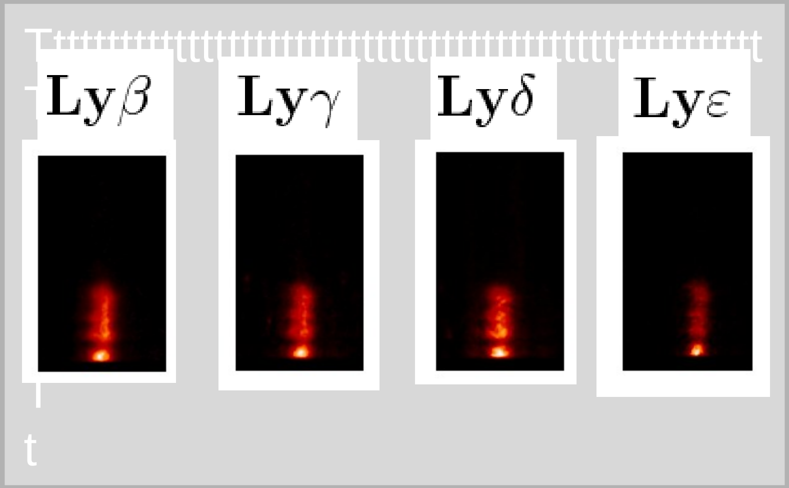


Prominence observations of April the 26, 2007

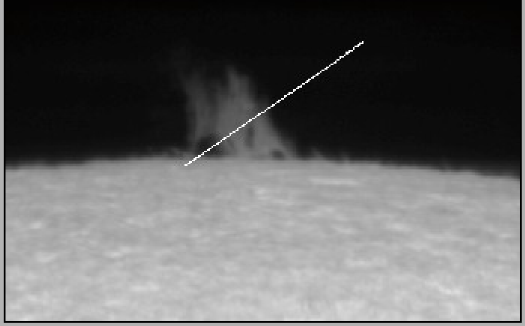
CDS observations

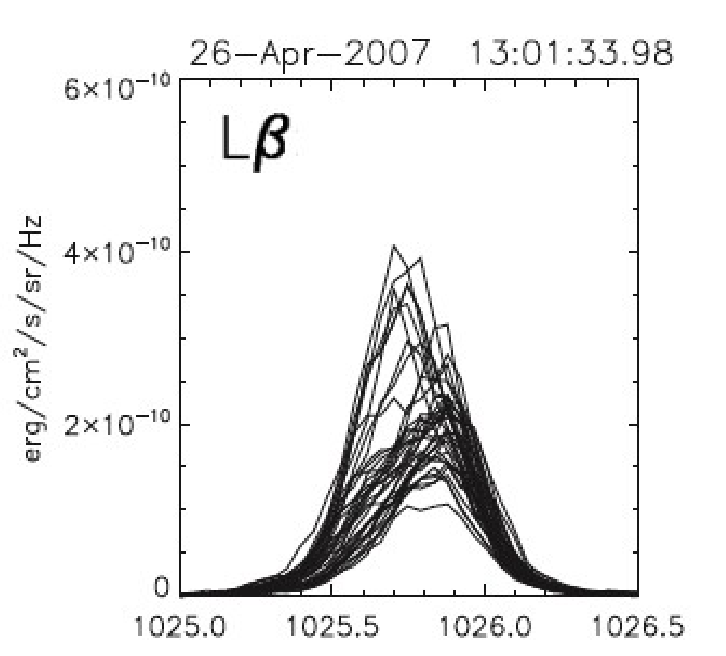


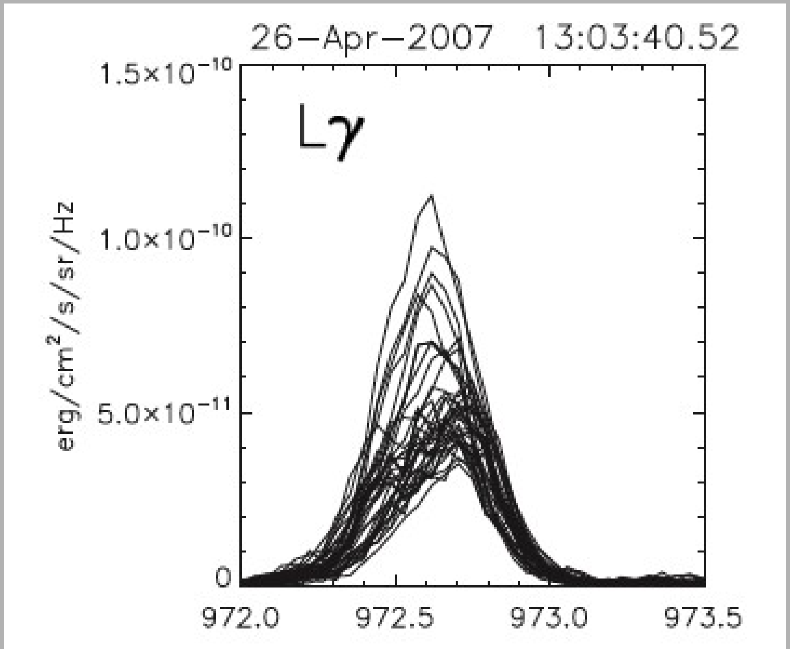
SUMER observations

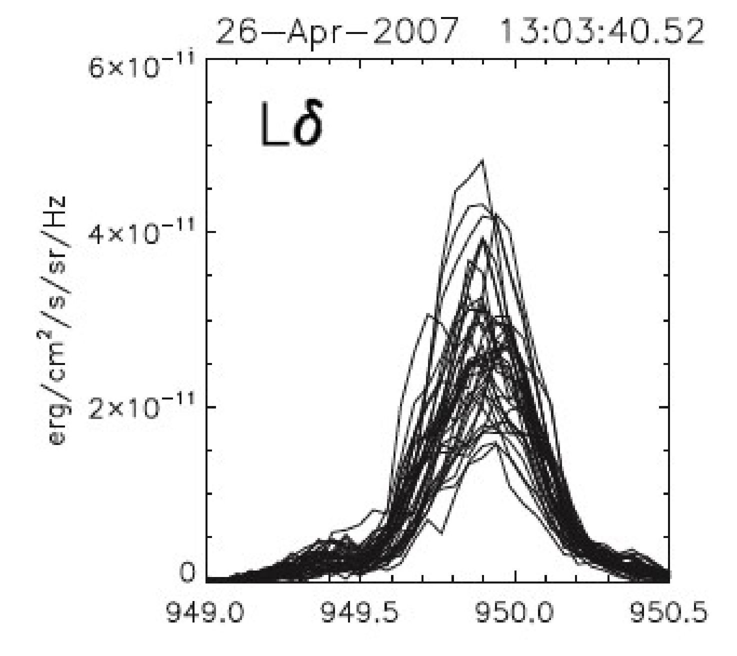


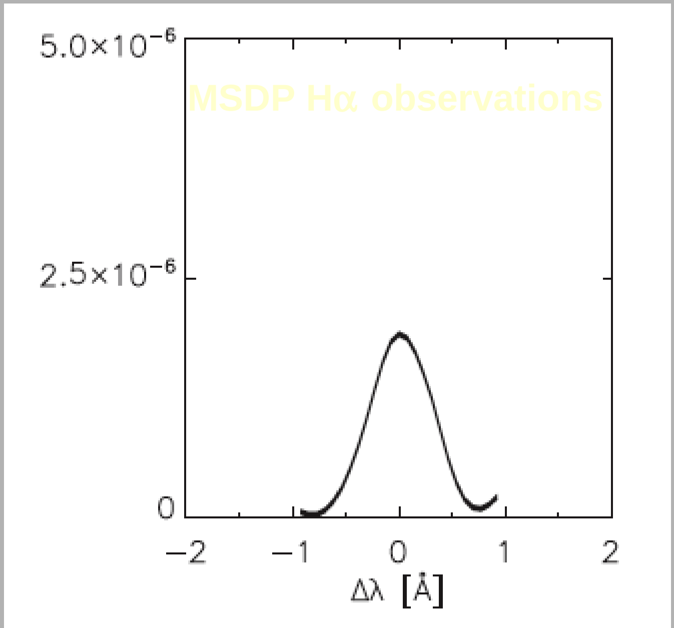
MSDP Hα observations



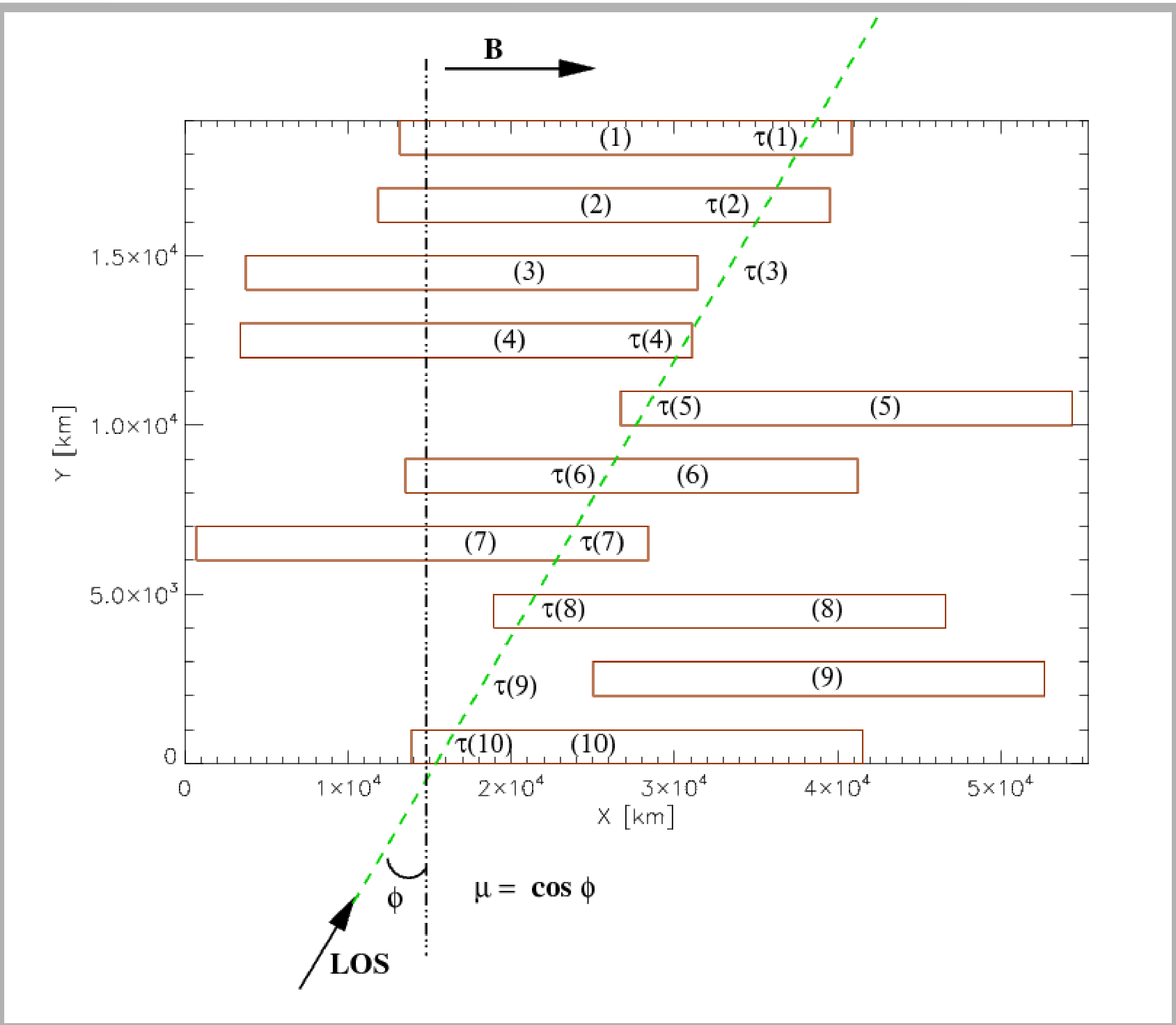

26-Apr-2007 13:01:33.98
Lβ
erg/cm²/s/sr/Hz
6×10⁻¹⁰
4×10⁻¹⁰
2×10⁻¹⁰
0
1025.0
1025.5
1026.0
1026.5


26-Apr-2007 13:03:40.52
Lγ
erg/cm²/s/sr/Hz
1.5×10⁻¹⁰
1.0×10⁻¹⁰
5.0×10⁻¹¹
0
972.0
972.5
973.0
973.5

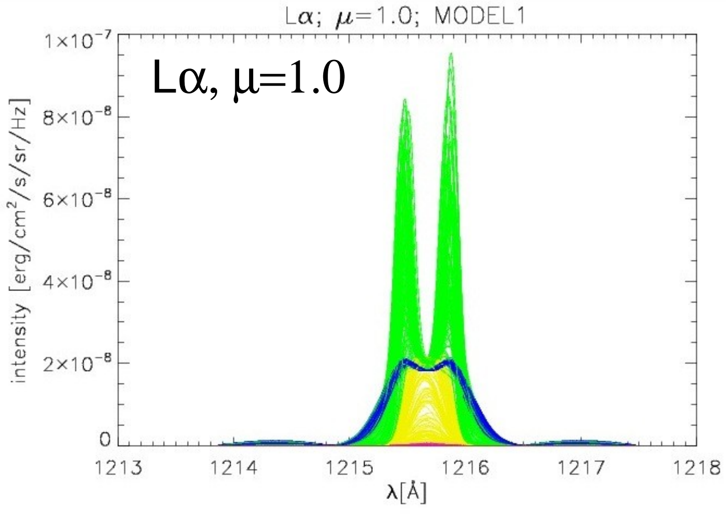

26-Apr-2007 13:03:40.52
Lδ
erg/cm²/s/sr/Hz
6×10⁻¹¹
4×10⁻¹¹
2×10⁻¹¹
0
949.0
949.5
950.0
950.5

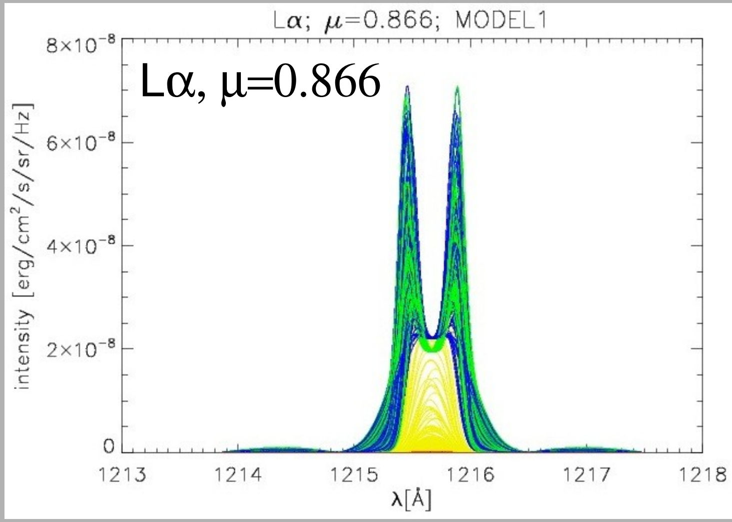

MSDP Hα observations
5.0×10⁻⁶
2.5×10⁻⁶
0
−2
−1
0
1
2
Δλ [Å]

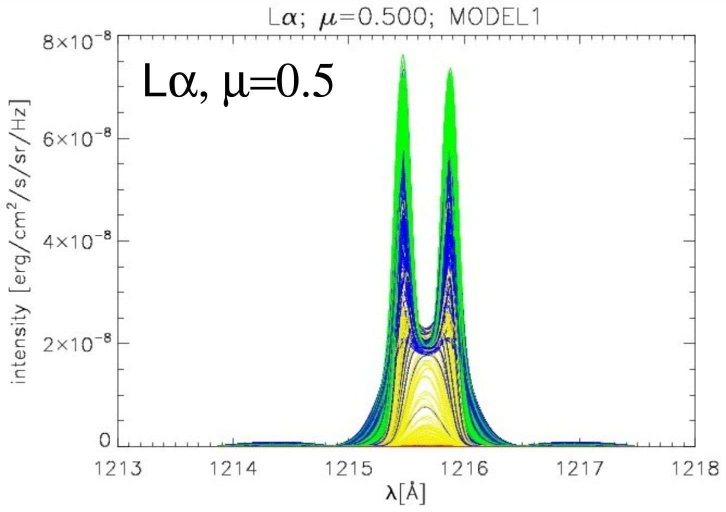
The multi-thread model at different view angles

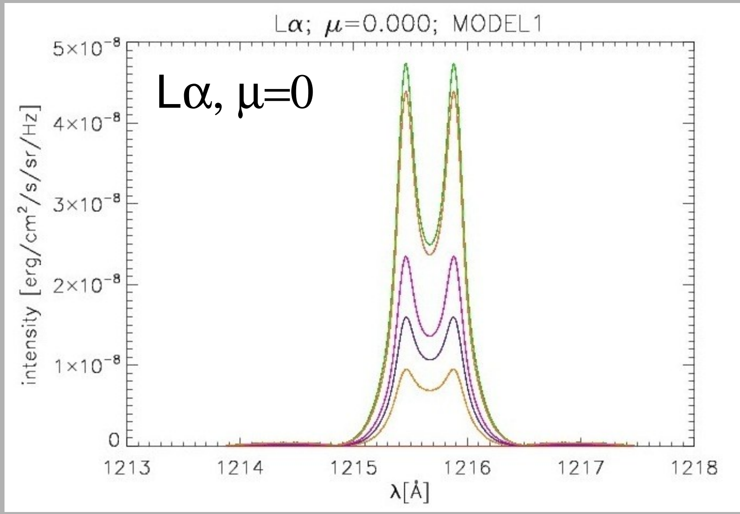


MODEL1 T_0=7000 K; $B_x(0)$=6 Gauss; γ_1=10
M_0=1.1 × 10^{-4} g cm^{-2}; p_0=0.015 dyn cm^{-2} γ_2=60



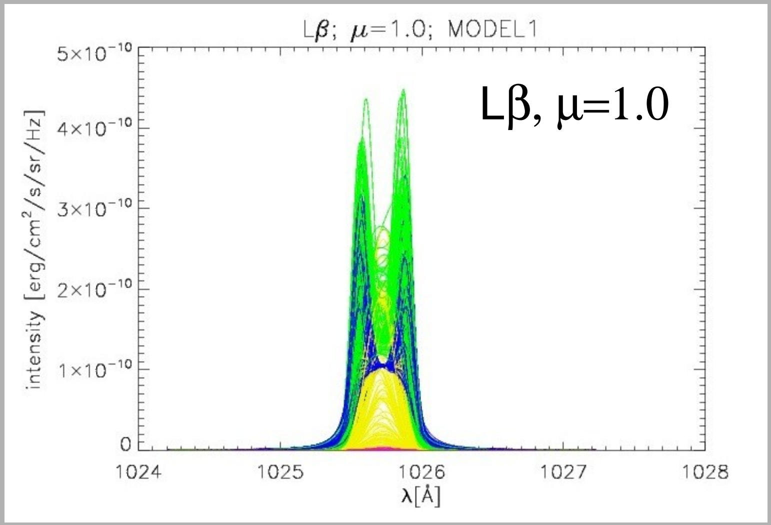


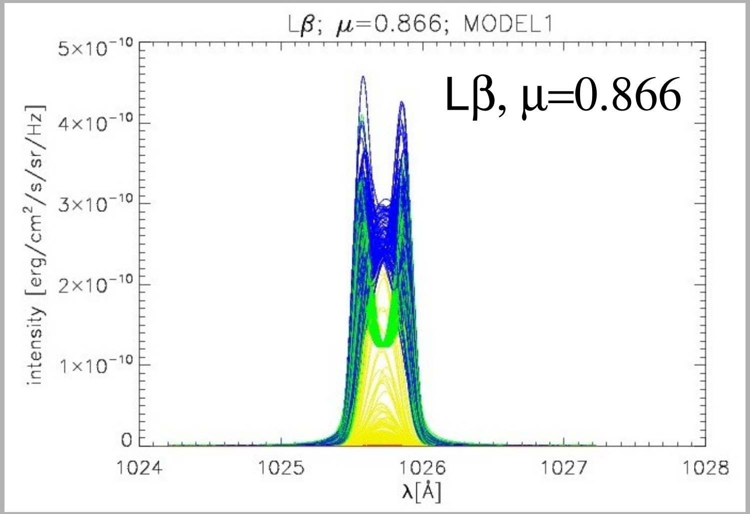


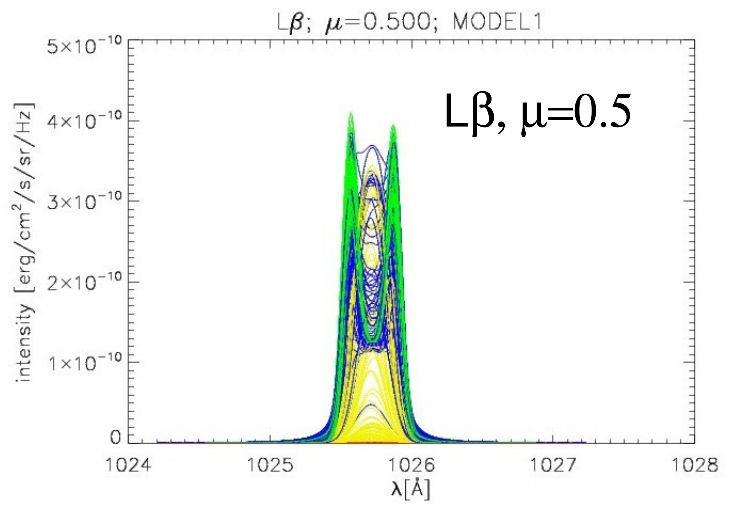


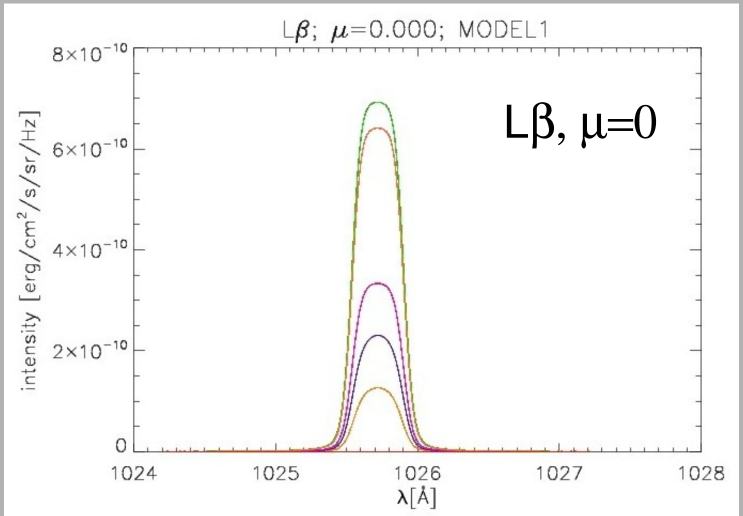
MODEL1 T_0=7000 K; $B_x(0)$=6 Gauss; γ_1=10

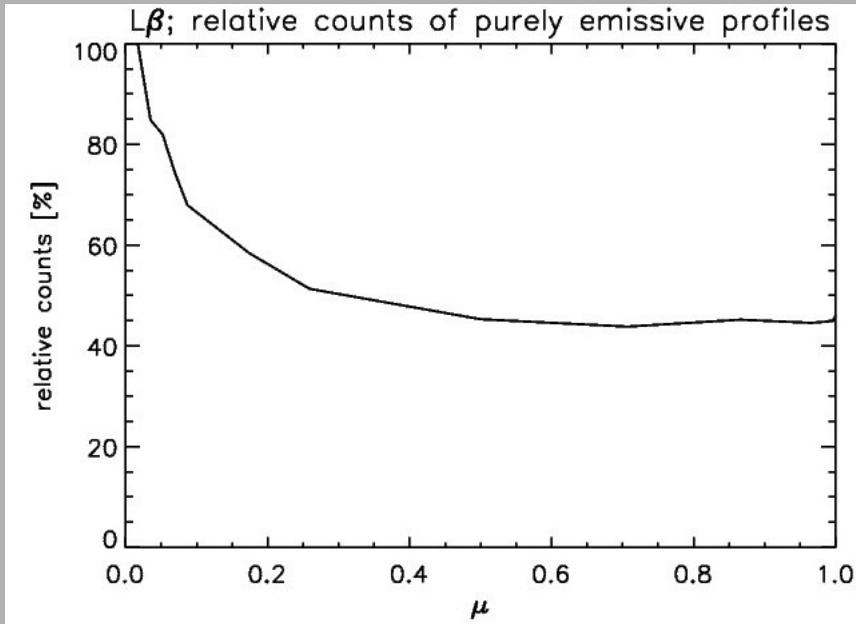
$M_0=1.1 \times 10^{-4}$ g cm^{-2}; p_0=0.015 dyn cm^{-2} γ_2=60



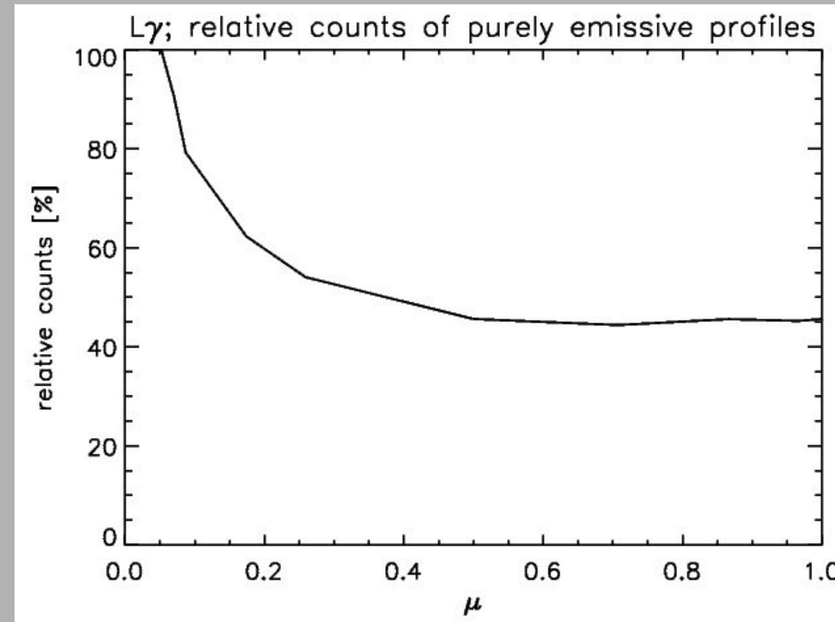




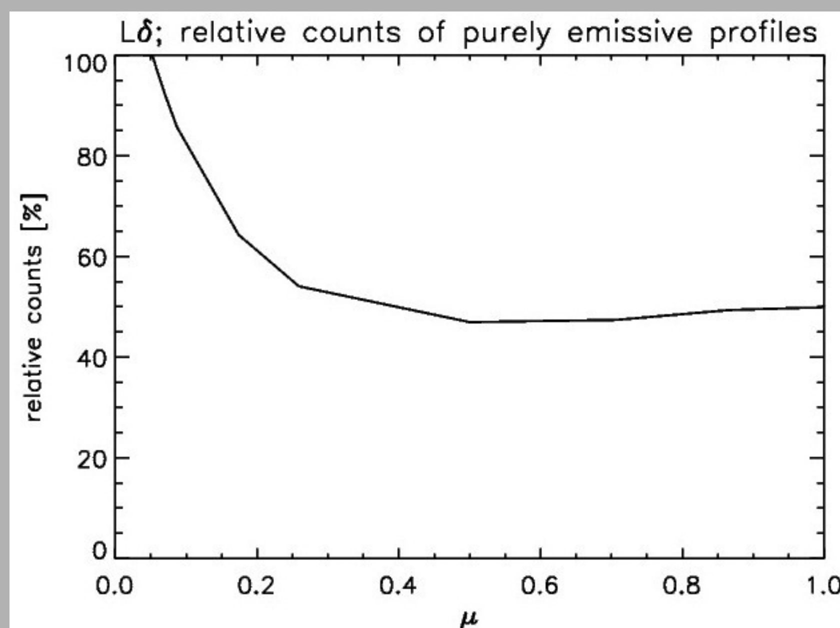




Lβ; relative counts of purely emissive profiles
relative counts [%]
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
μ

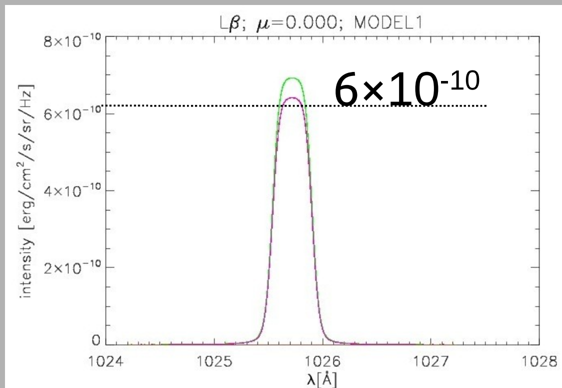


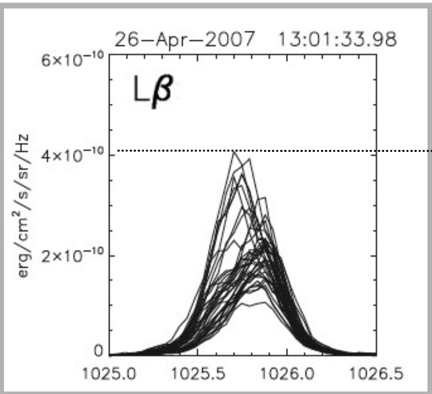
Lγ; relative counts of purely emissive profiles
relative counts [%]
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
μ



Lδ; relative counts of purely emissive profiles
relative counts [%]
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
μ

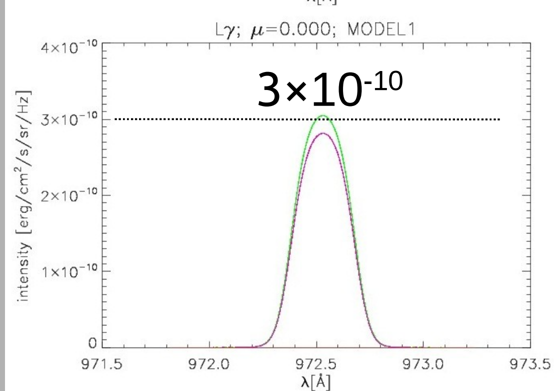
Comparison of the synthetic Lyman line profiles of MODEL1 for μ=0 with the observations

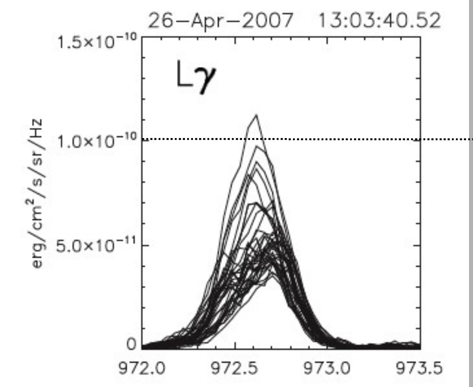




4×10^-10 erg/cm²/s/sr/Hz

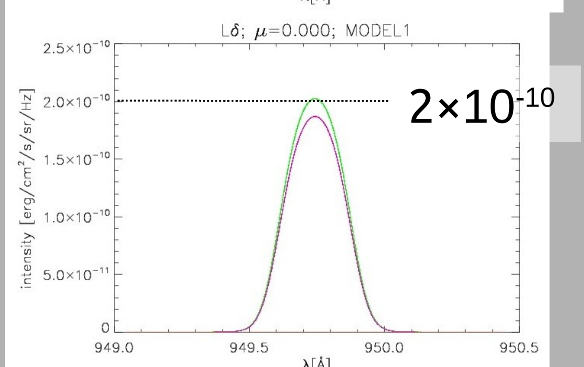
1.5-times higher synthetic intensities than observed

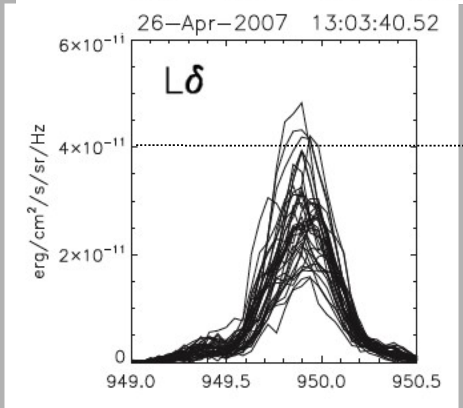




1×10^-10 erg/cm²/s/sr/Hz

3-times higher synthetic intensities than observed





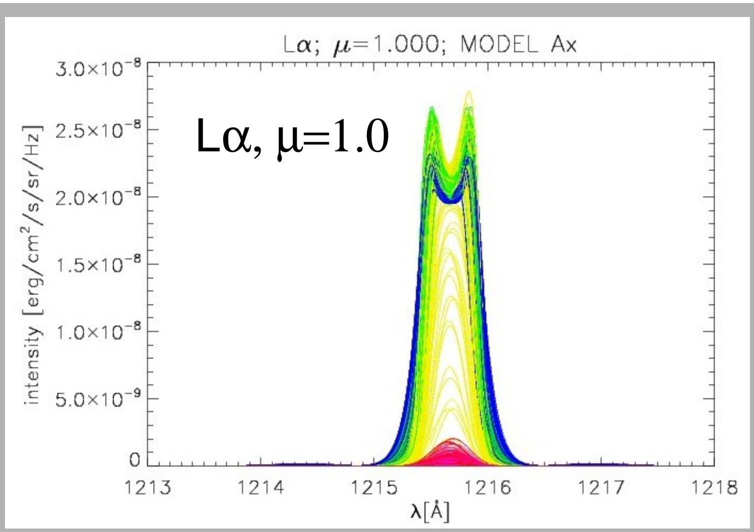
4×10^-11 erg/cm²/s/sr/Hz

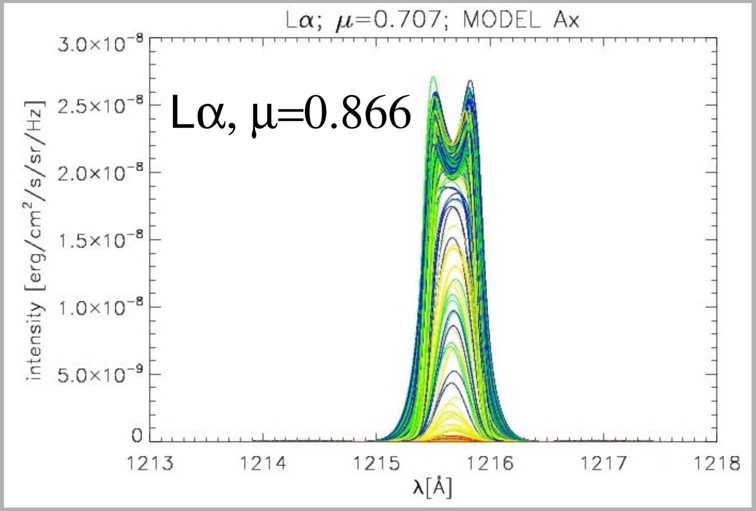
5-times higher synthetic intensities than observed

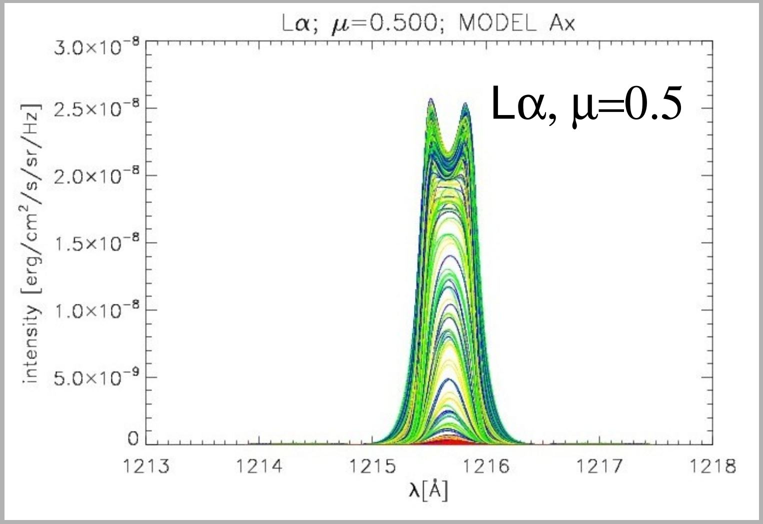
Ax1

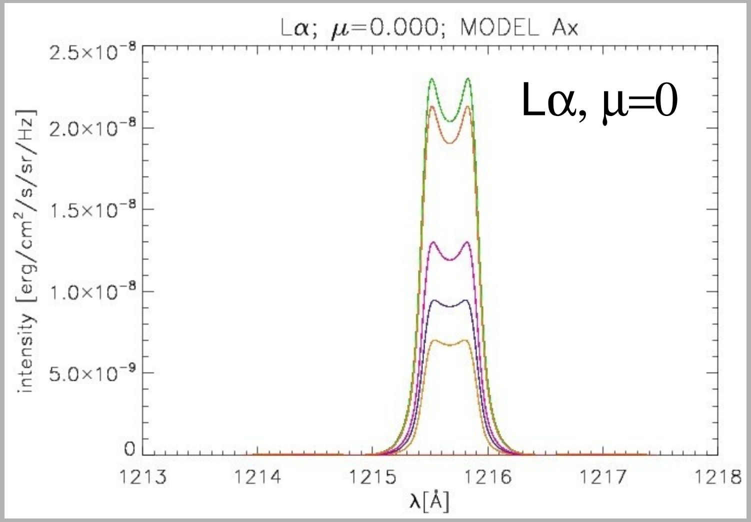
T_0=8000 K; $B_x(0)$=5 Gauss; γ_1=5

M_0=1 × 10^{-5} g cm^{-2}; p_0=0.03 dyn cm^{-2} γ_2=30



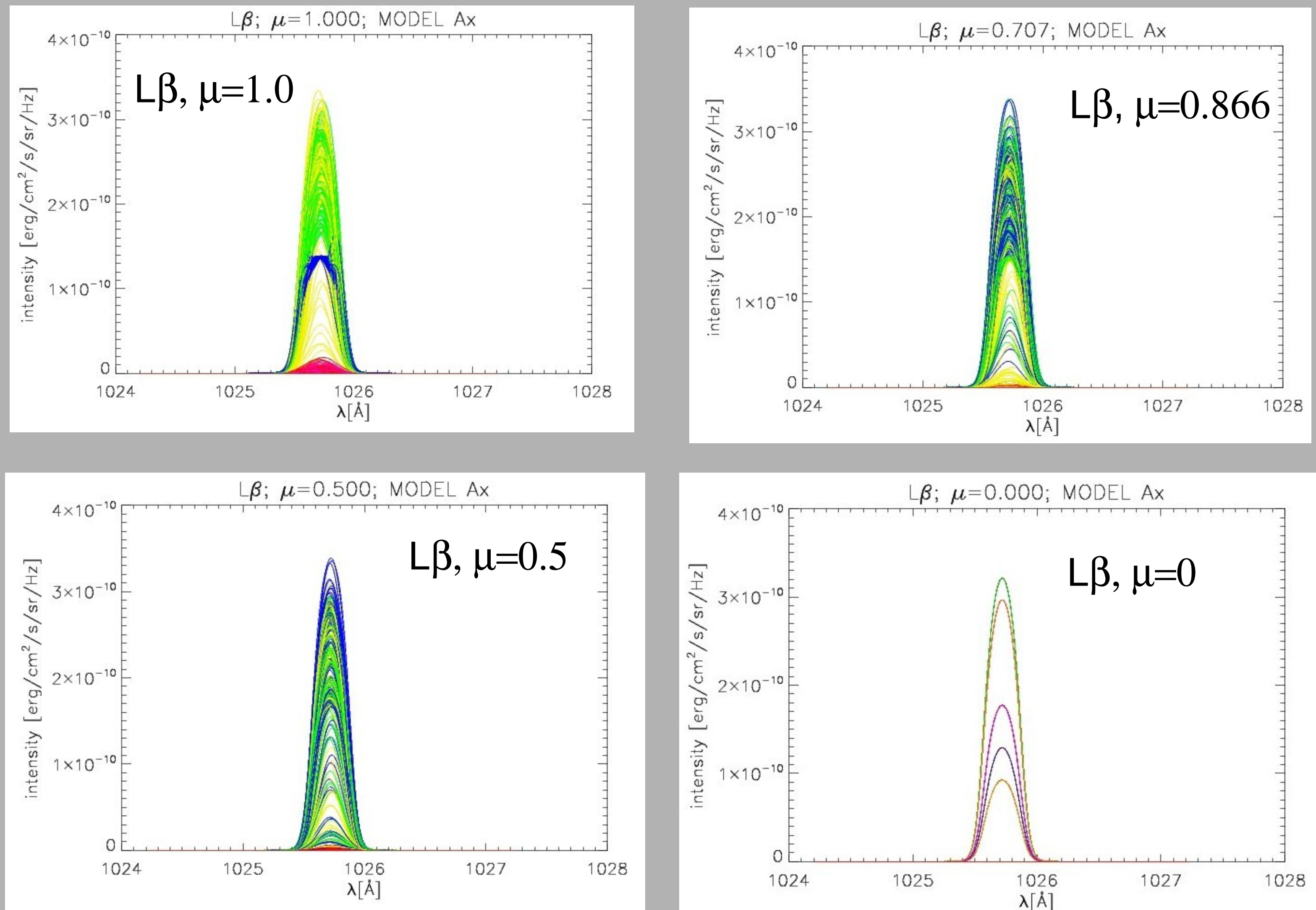






Ax1 T_0=8000 K; $B_x(0)$=5 Gauss; γ_1=5

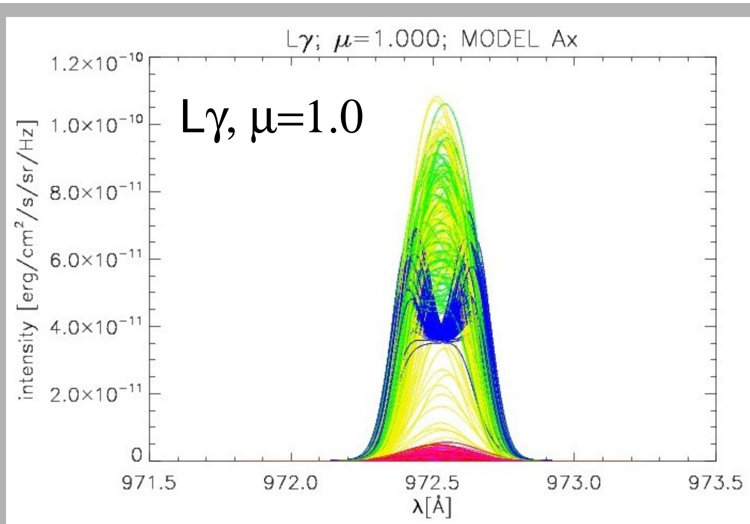
M_0=1 × 10^{-5} g cm^{-2}; p_0=0.03 dyn cm^{-2} γ_2=30

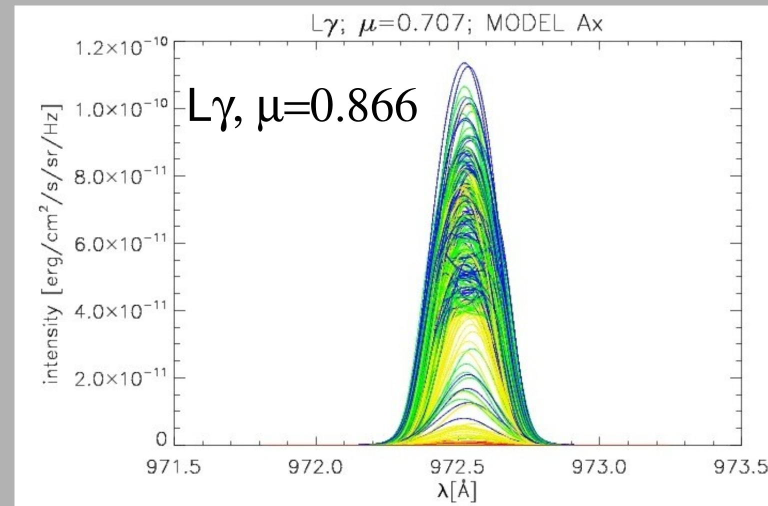


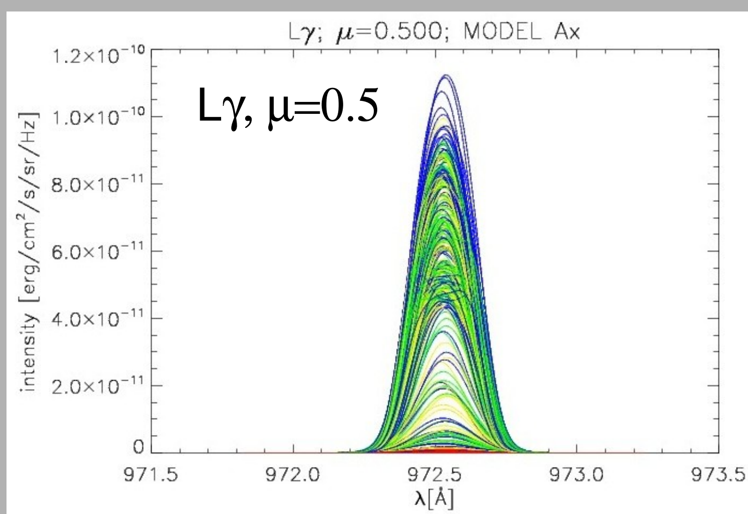
Ax1

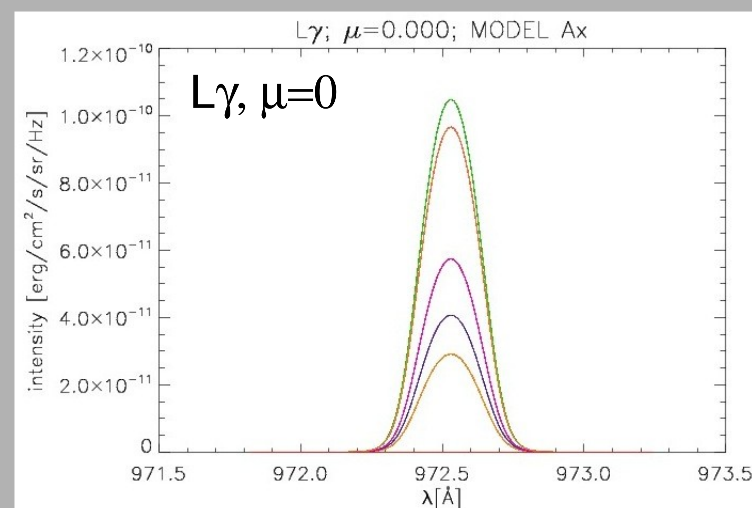
$T_0=8000$ K; $B_x(0)=5$ Gauss; $\gamma_1=5$

$M_0=1\times10^{-5}$ g cm^{-2}; $p_0=0.03$ dyn cm^{-2}; $\gamma_2=30$

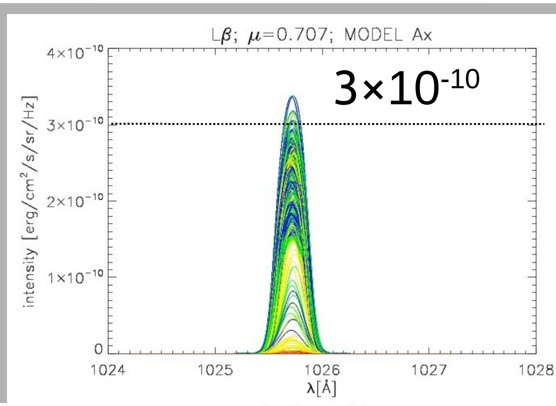


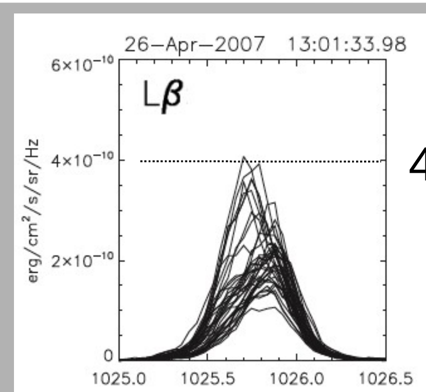




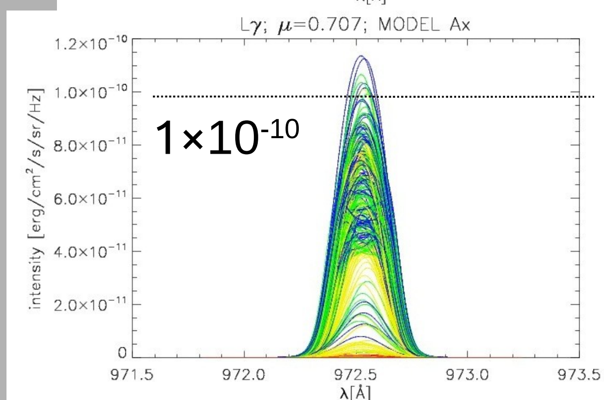


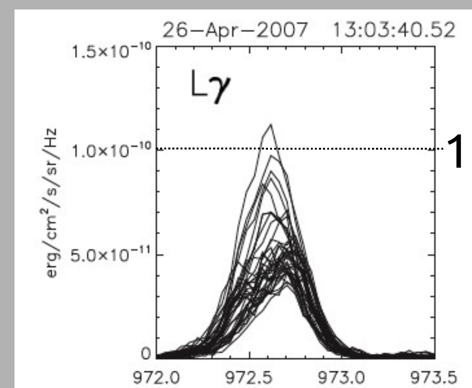
Comparison of the synthetic Lyman line profiles of MODEL Ax1 for μ=0.5 with the observations



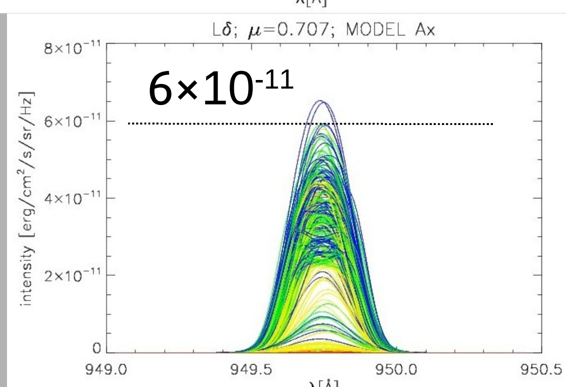


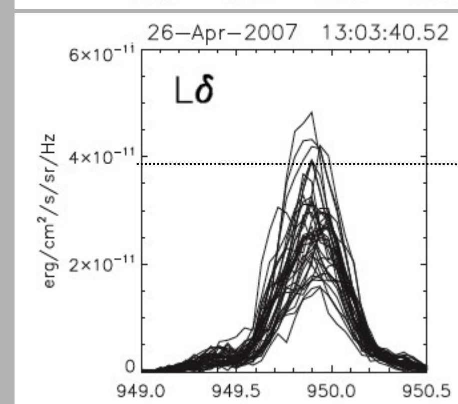
4×10^{-10} erg/cm^2/s/sr/Hz





1×10^{-10} erg/cm^2/s/sr/Hz

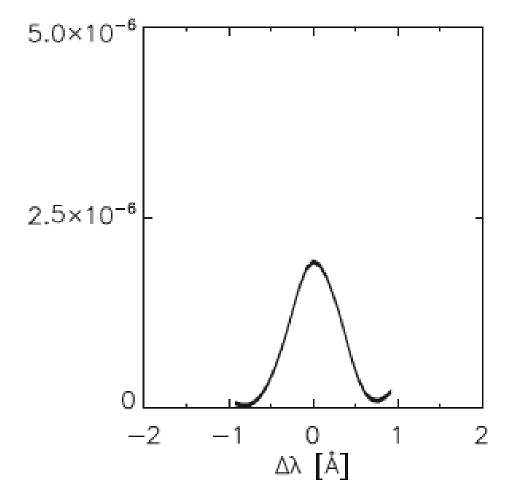




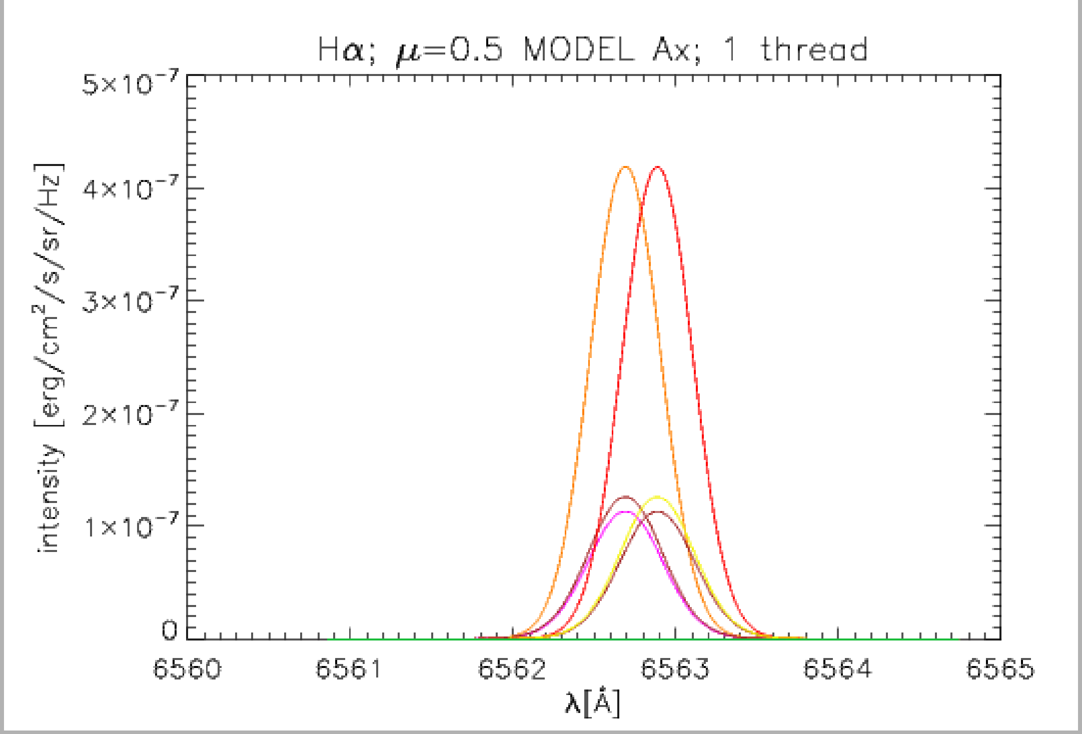
4×10^{-11} erg/cm^2/s/sr/Hz

Comparison of the synthetic Hα profiles of MODEL Ax1 for μ=0.5 with the observations

MSDP Hα observations

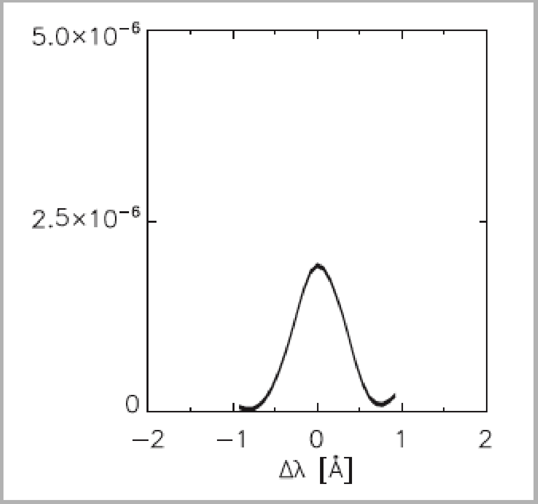


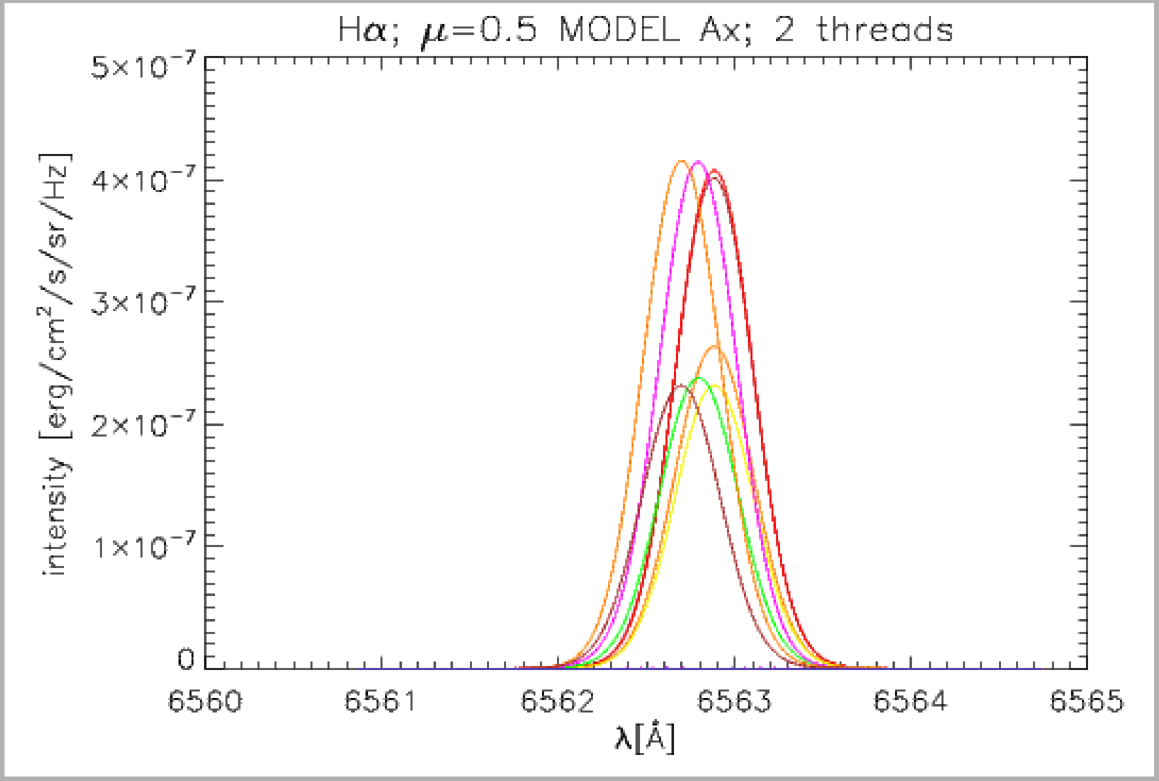
calculated profiles



Comparison of the synthetic Hα profiles of MODEL Ax1 for μ=0.5 with the observations

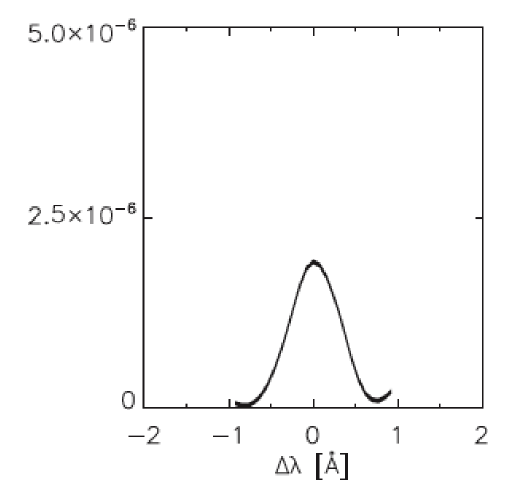
MSDP Hα observations



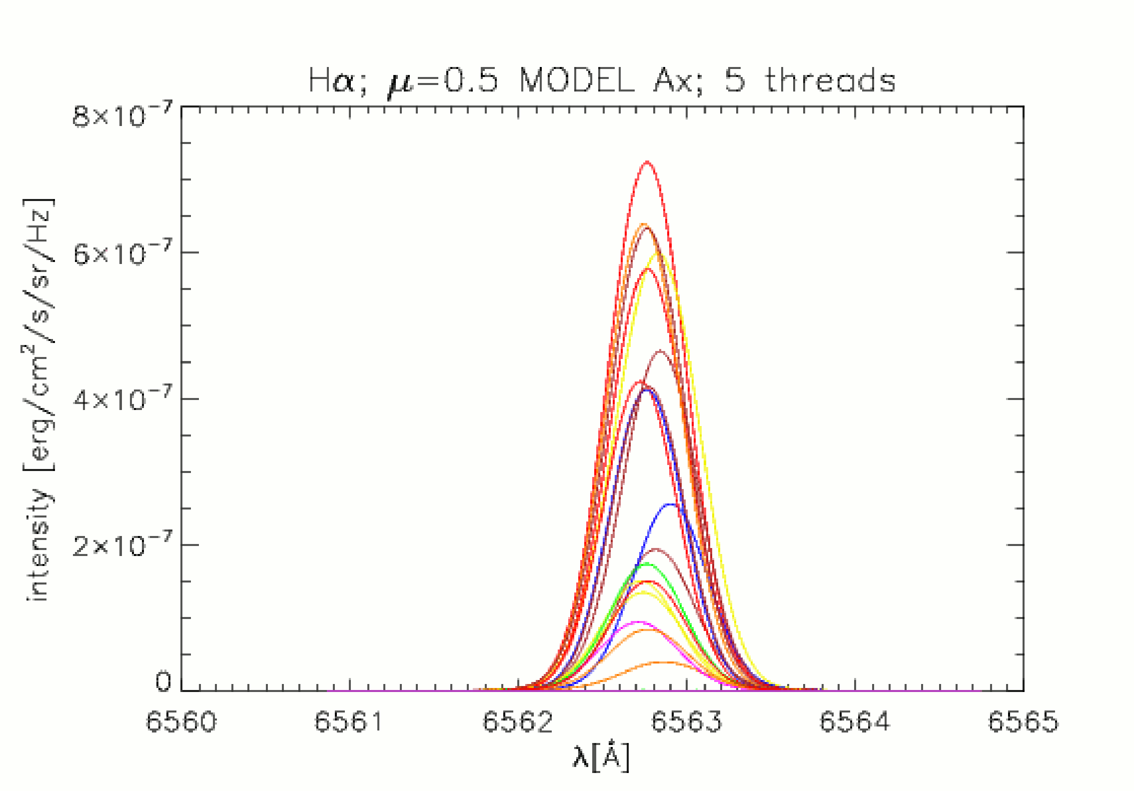


Comparison of the synthetic Hα profiles of MODEL Ax1 for μ=0.5 with the observations

MSDP Hα observations

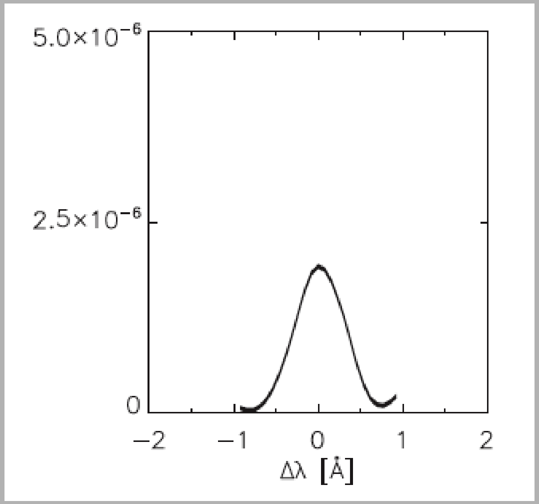


calculated profiles

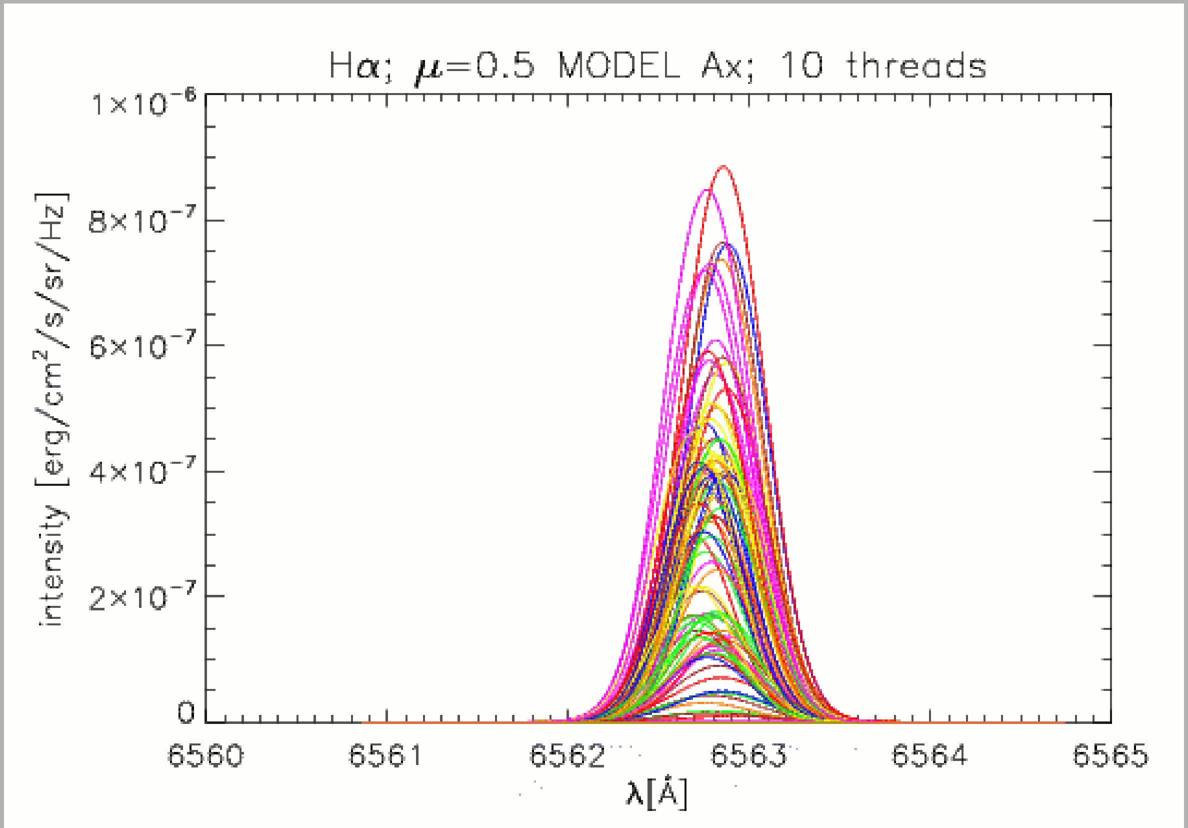


Comparison of the synthetic Hα profiles of MODEL Ax1 for μ=0.5 with the observations

MSDP Hα observations

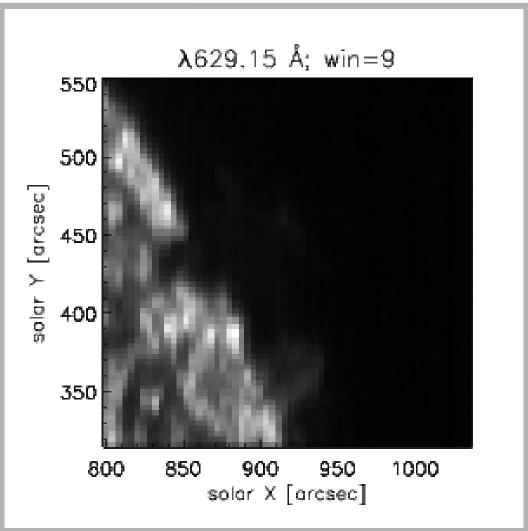


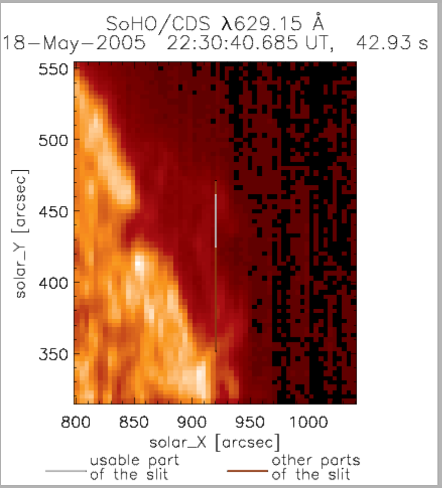
calculated profiles



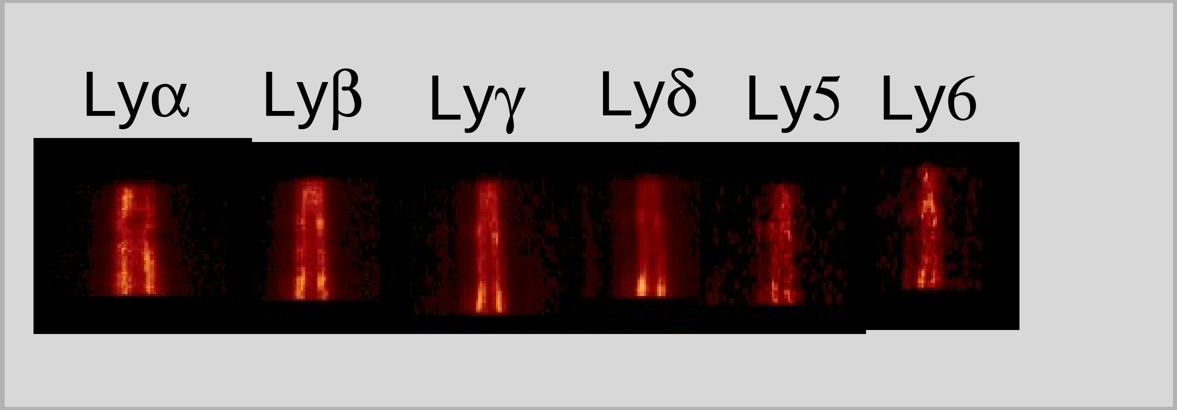
Prominence observations of May the 18, 2005

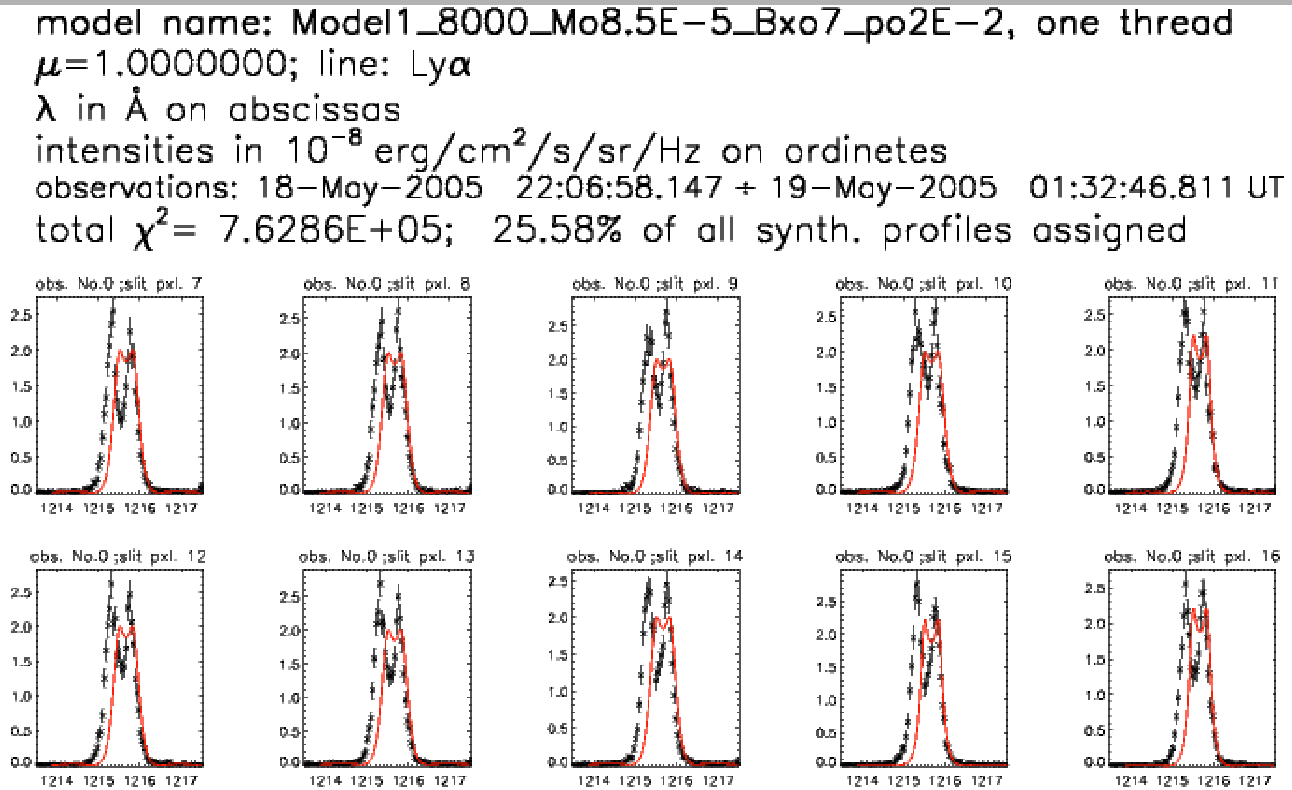
CDS observations





SUMER observations





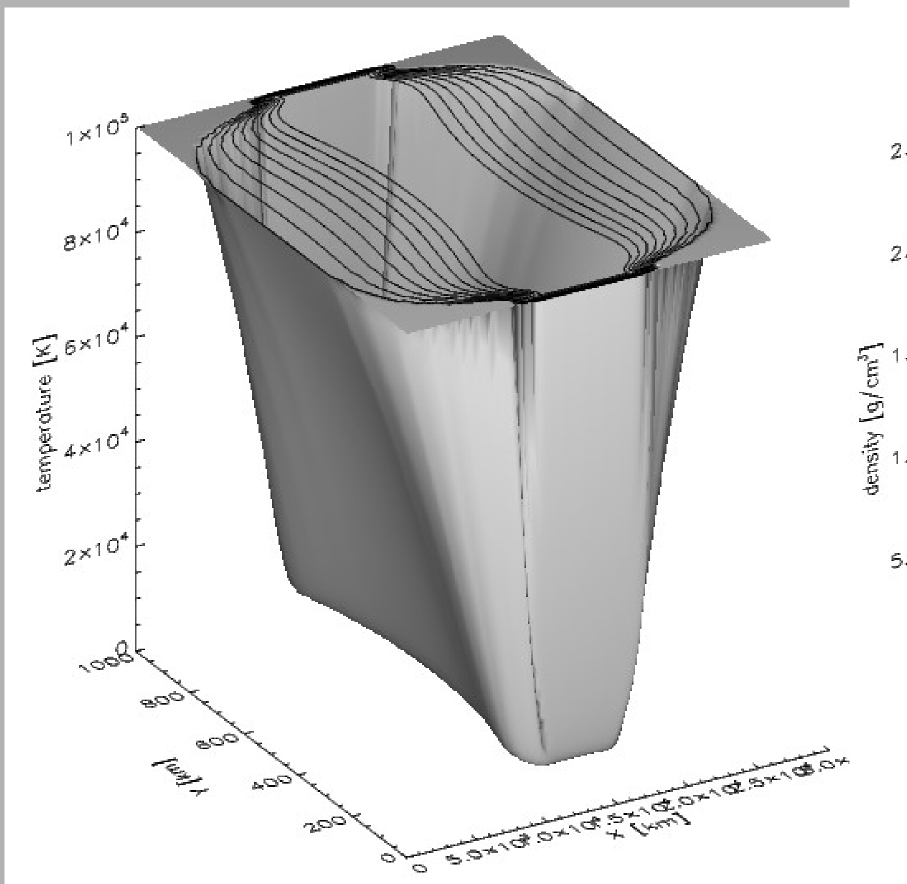
searching for model according 3 criterion:

- visual comparison
- the smallest χ^2 between observed and assigned synth. profiles
- percentage of assigned synthetic profiles from all calculated

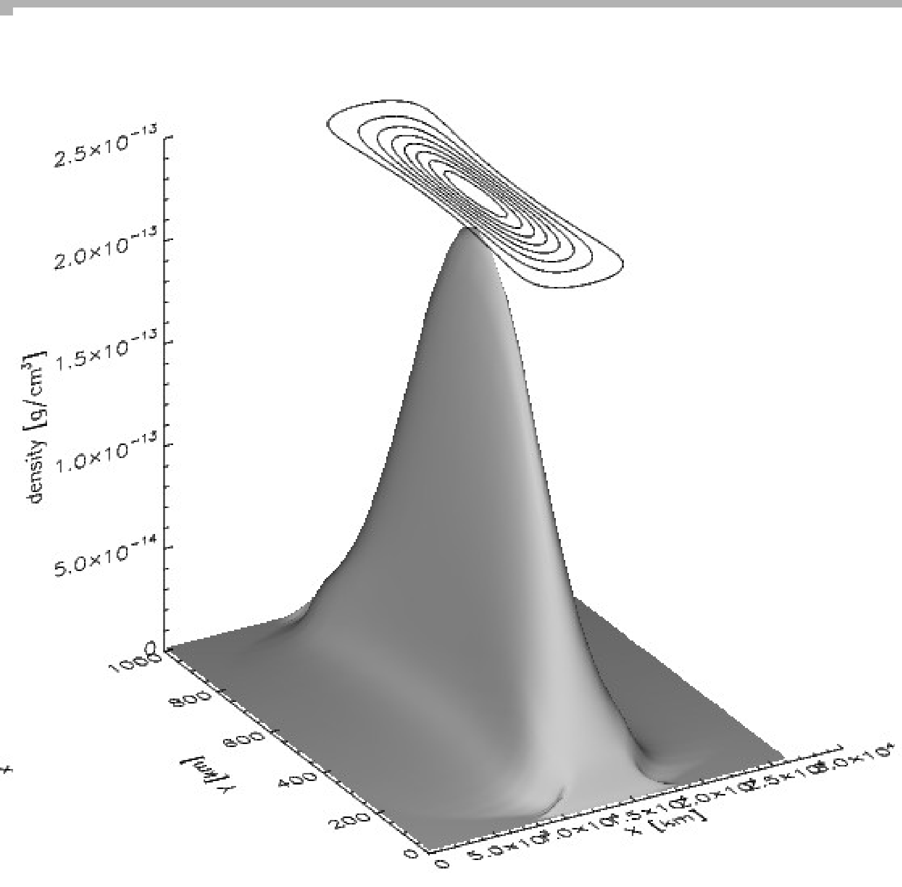
Mo9.5E-5_9000_Bxo6_po2.5E-2	T_0=9000 K; M_0=9.5 × 10^{-5} g cm^{-2};	$B_x(0)$=6 Gauss; p_0=0.025 dyn cm^{-2};	γ_1=10 γ_2=60
Model1_8000_Mo8.5E-5_Bxo7_po2E-2	T_0=8000 K; M_0=8.5 × 10^{-5} g cm^{-2};	$B_x(0)$=7 Gauss; p_0=0.02 dyn cm^{-2};	γ_1=10 γ_2=60
Model_A4_Mo4E-6_po0.03	T_0=8000 K; M_0=4.0 × 10^{-6} g cm^{-2};	$B_x(0)$=1 Gauss; p_0=0.03 dyn cm^{-2};	γ_1=5 γ_2=30

Model1_8000_Mo8.5E-5_Bxo7_po2E-2

temperature



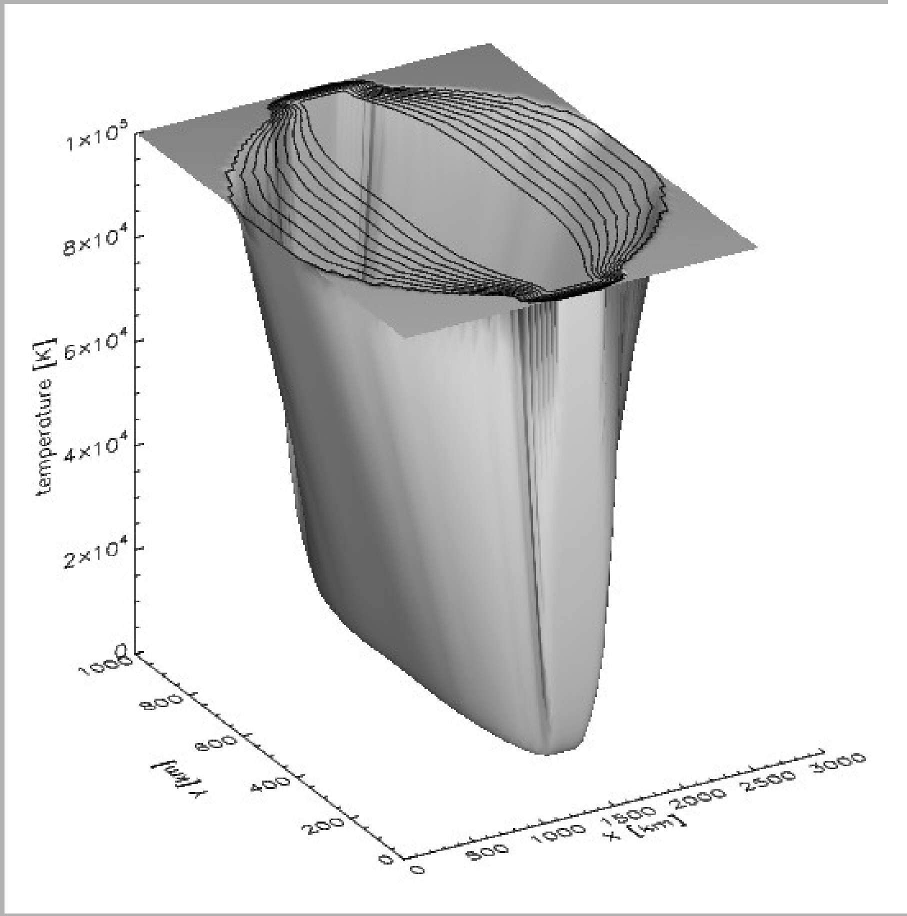
plasma density



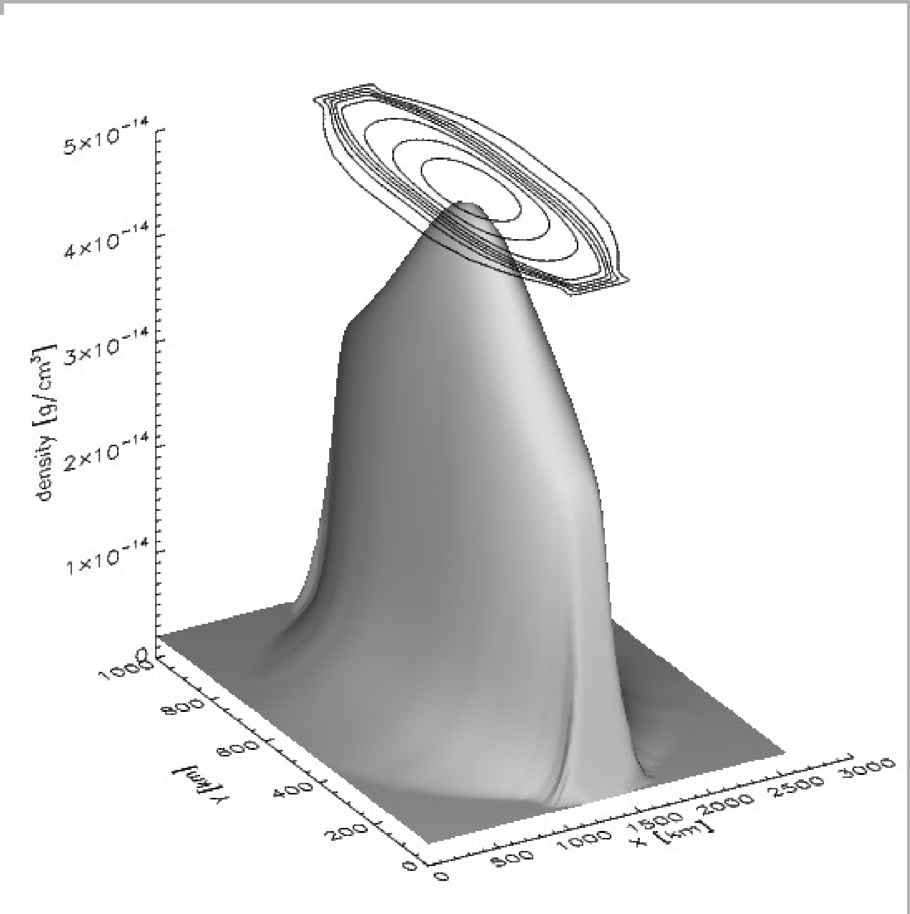
similar plasma properties also for Mo9.5E-5_9000_Bxo6_po2.5E-2

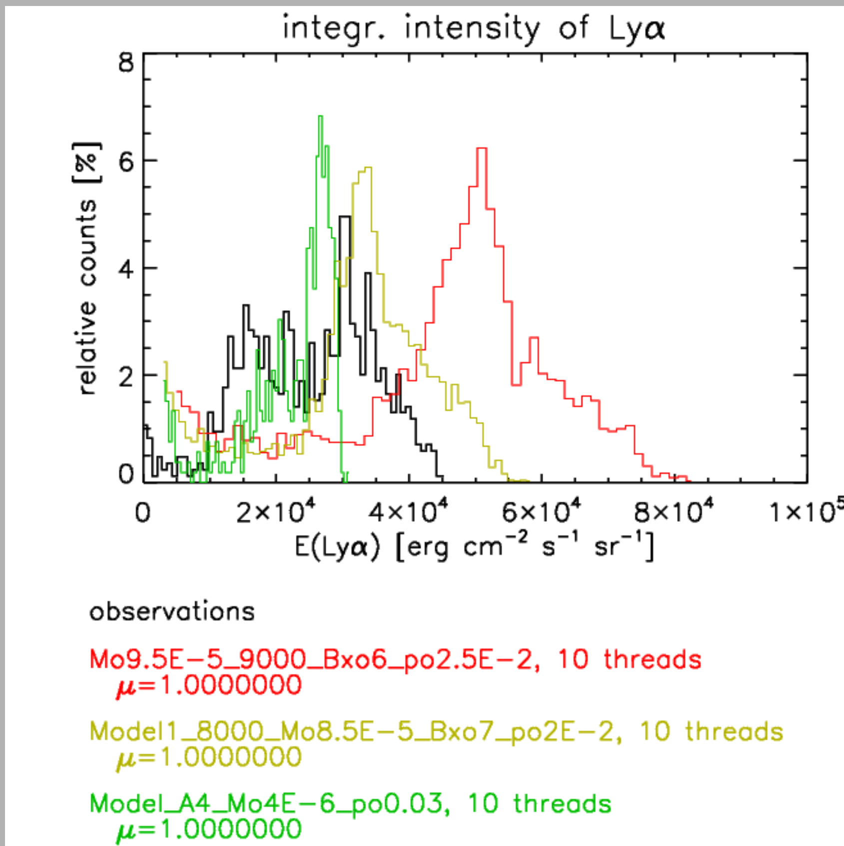
Model_A4_Mo4E-6_po0.03

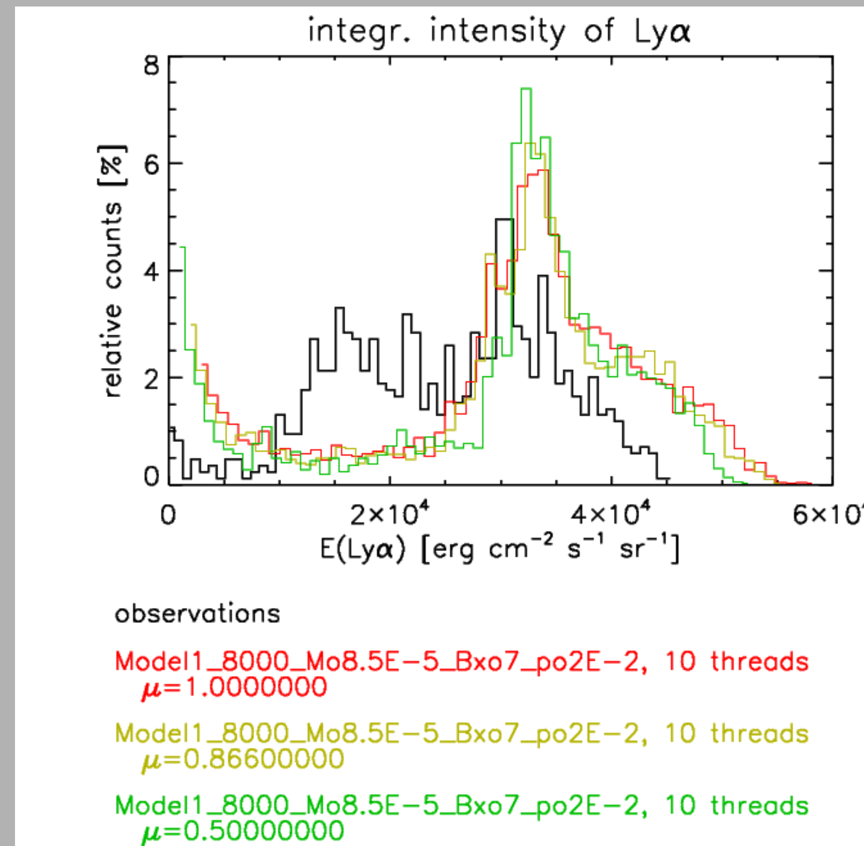
temperature

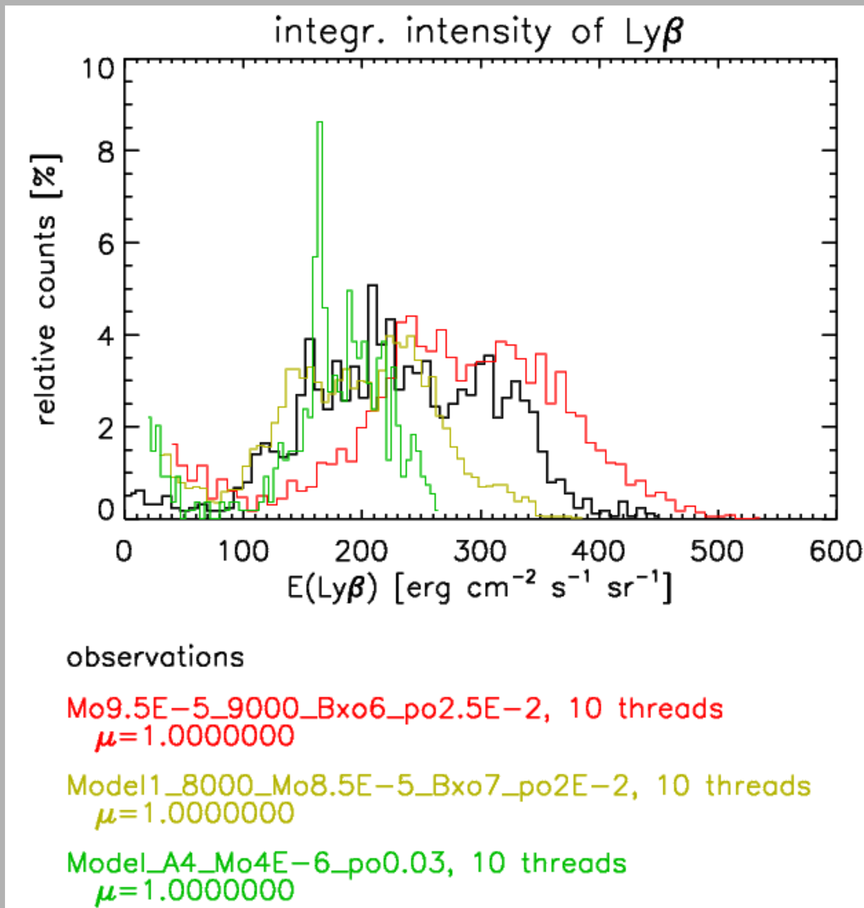


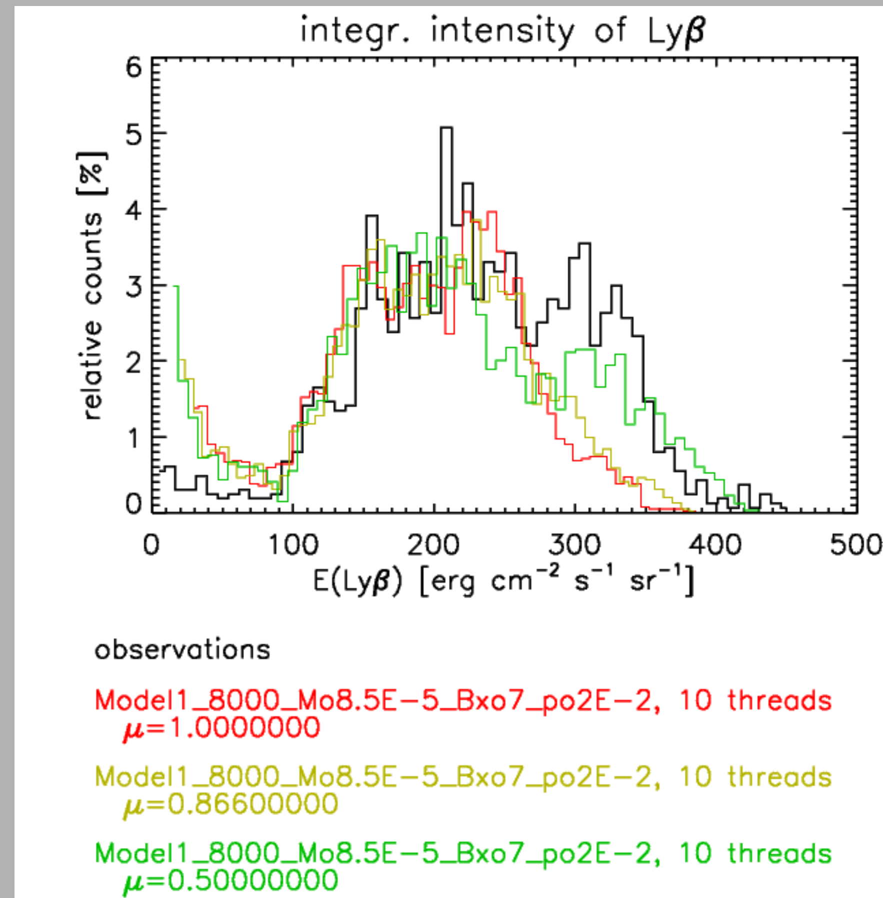
plasma density

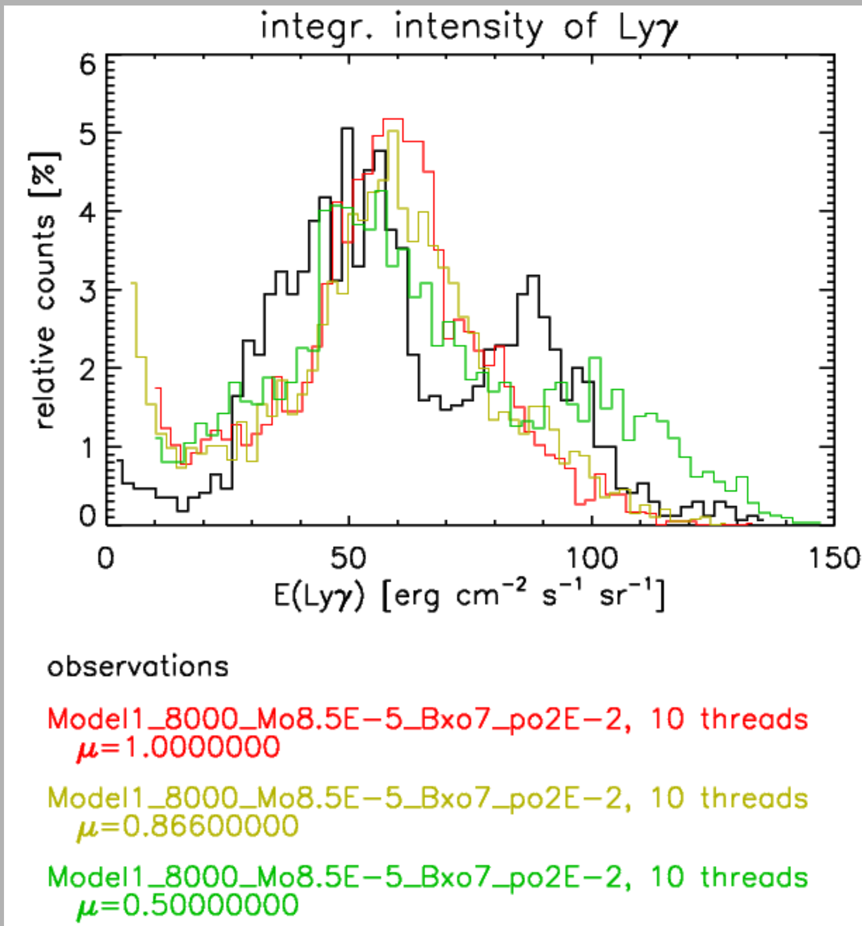


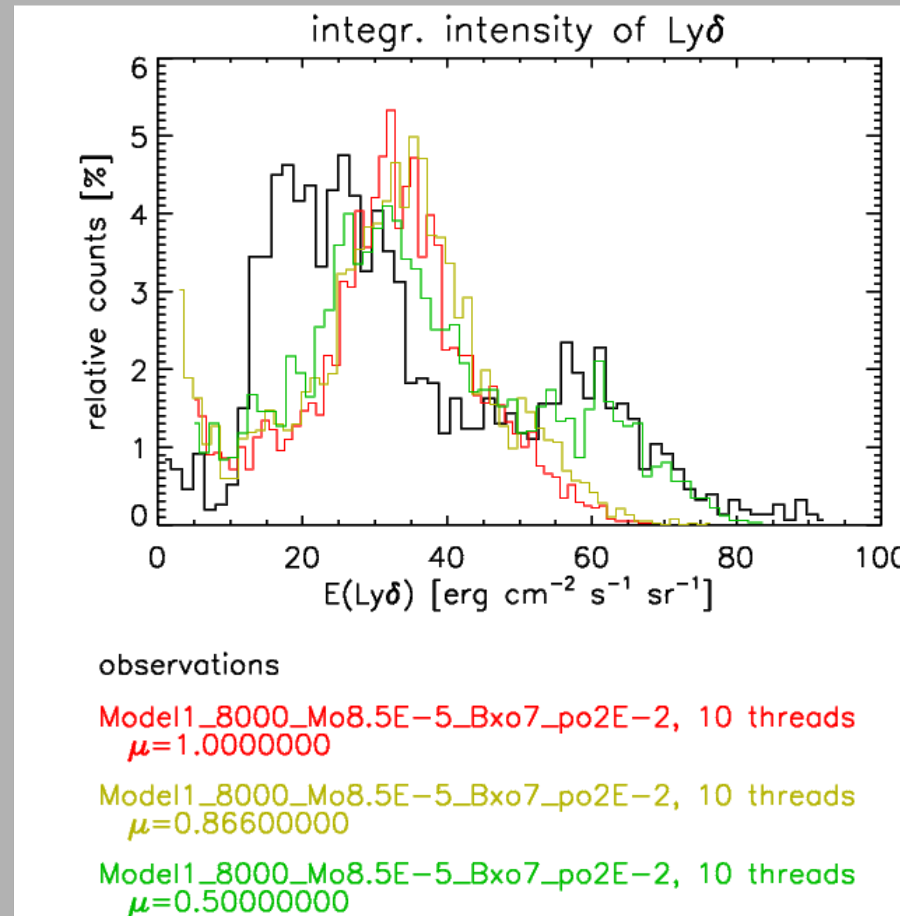

integr. intensity of Lyα
relative counts [%]
0
2
4
6
8
0
2×10⁴
4×10⁴
6×10⁴
8×10⁴
1×10⁵
E(Lyα) [erg cm⁻² s⁻¹ sr⁻¹]
observations
Mo9.5E−5_9000_Bxo6_po2.5E−2, 10 threads
μ=1.0000000
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=1.0000000
Model_A4_Mo4E−6_po0.03, 10 threads
μ=1.0000000

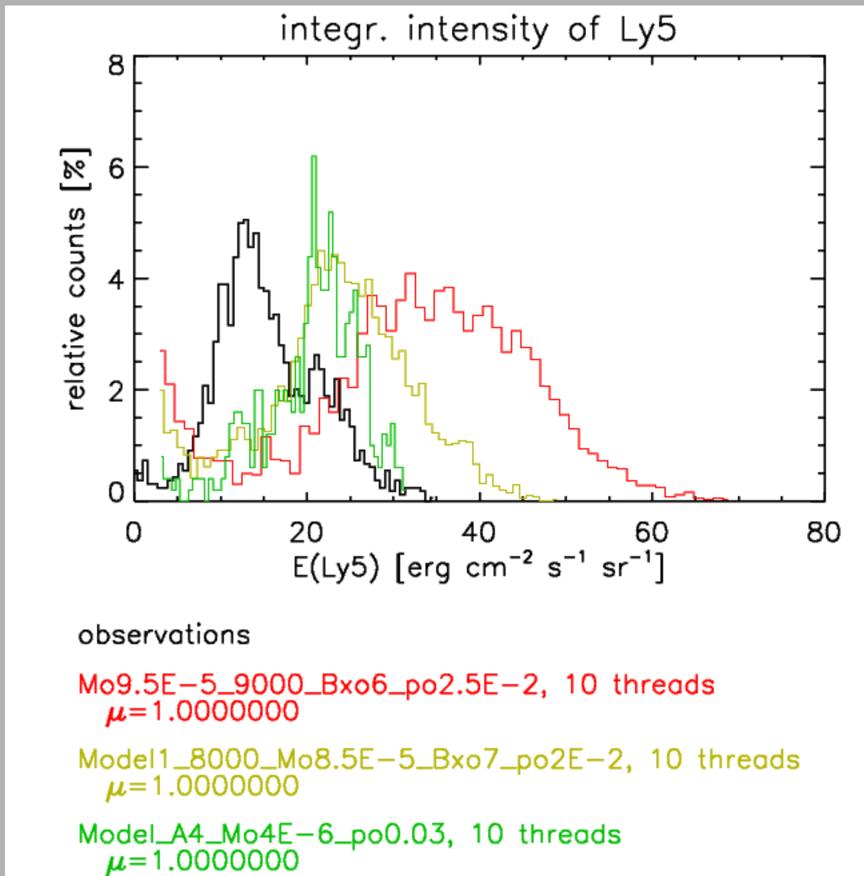

integr. intensity of Lyα
relative counts [%]
0
2
4
6
8
0
2×10⁴
4×10⁴
6×10⁴
E(Lyα) [erg cm⁻² s⁻¹ sr⁻¹]
observations
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=1.0000000
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=0.86600000
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=0.50000000

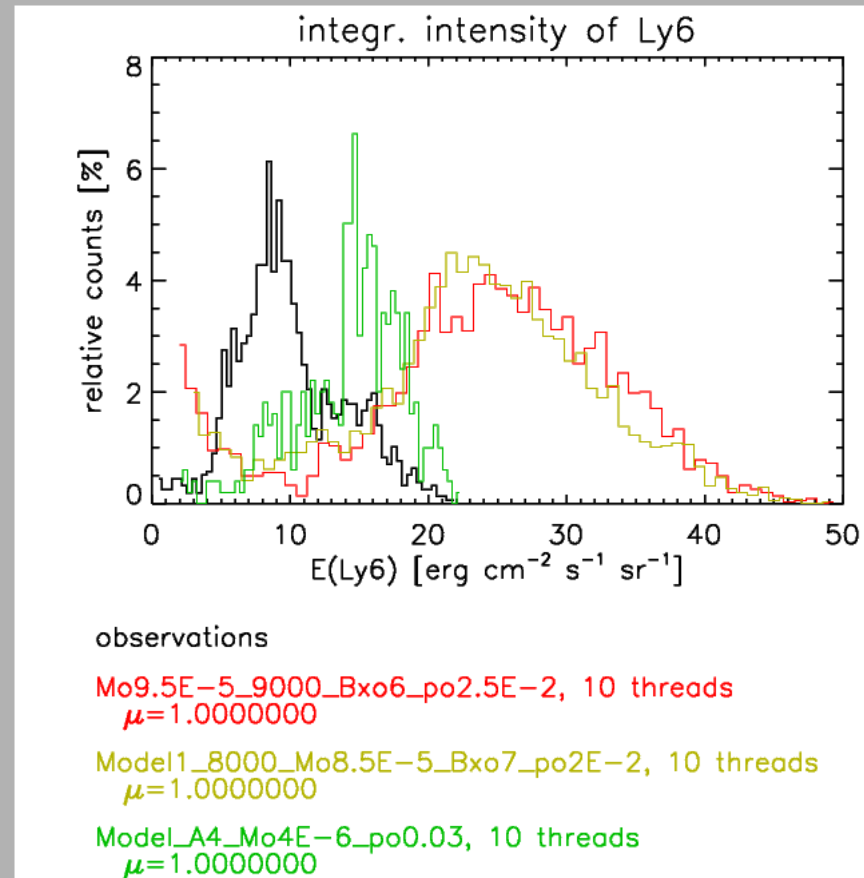

integr. intensity of Lyβ
relative counts [%]
0
2
4
6
8
10
0
100
200
300
400
500
600
E(Lyβ) [erg cm^{-2} s^{-1} sr^{-1}]
observations
Mo9.5E−5_9000_Bxo6_po2.5E−2, 10 threads
μ=1.0000000
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=1.0000000
Model_A4_Mo4E−6_po0.03, 10 threads
μ=1.0000000

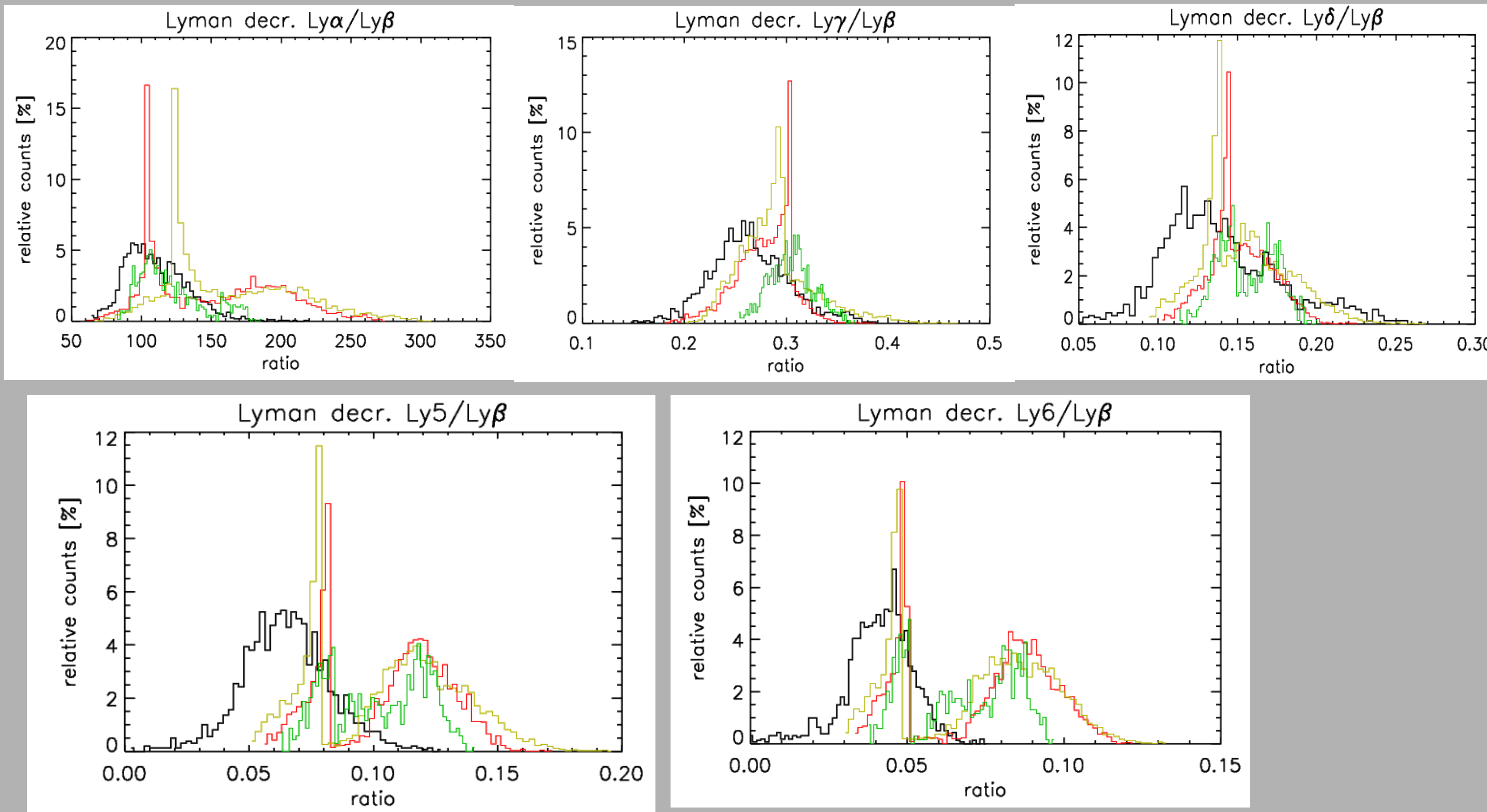

integr. intensity of Lyβ
relative counts [%]
0
1
2
3
4
5
6
0
100
200
300
400
500
E(Lyβ) [erg cm^{-2} s^{-1} sr^{-1}]
observations
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=1.0000000
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=0.86600000
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=0.50000000


integr. intensity of Lyγ
relative counts [%]
0
1
2
3
4
5
6
0
50
100
150
E(Lyγ) [erg cm^-2 s^-1 sr^-1]
observations
Model1_8000_Mo8.5E-5_Bxo7_po2E-2, 10 threads
μ=1.0000000
Model1_8000_Mo8.5E-5_Bxo7_po2E-2, 10 threads
μ=0.86600000
Model1_8000_Mo8.5E-5_Bxo7_po2E-2, 10 threads
μ=0.50000000


integr. intensity of Lyδ
relative counts [%]
0
1
2
3
4
5
6
0
20
40
60
80
100
E(Lyδ) [erg cm^-2 s^-1 sr^-1]
observations
Model1_8000_Mo8.5E-5_Bxo7_po2E-2, 10 threads
μ=1.0000000
Model1_8000_Mo8.5E-5_Bxo7_po2E-2, 10 threads
μ=0.86600000
Model1_8000_Mo8.5E-5_Bxo7_po2E-2, 10 threads
μ=0.50000000


integr. intensity of Ly5
relative counts [%]
E(Ly5) [erg cm^{-2} s^{-1} sr^{-1}]
observations
Mo9.5E−5_9000_Bxo6_po2.5E−2, 10 threads
μ=1.0000000
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=1.0000000
Model_A4_Mo4E−6_po0.03, 10 threads
μ=1.0000000


integr. intensity of Ly6
relative counts [%]
E(Ly6) [erg cm^{-2} s^{-1} sr^{-1}]
observations
Mo9.5E−5_9000_Bxo6_po2.5E−2, 10 threads
μ=1.0000000
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=1.0000000
Model_A4_Mo4E−6_po0.03, 10 threads
μ=1.0000000



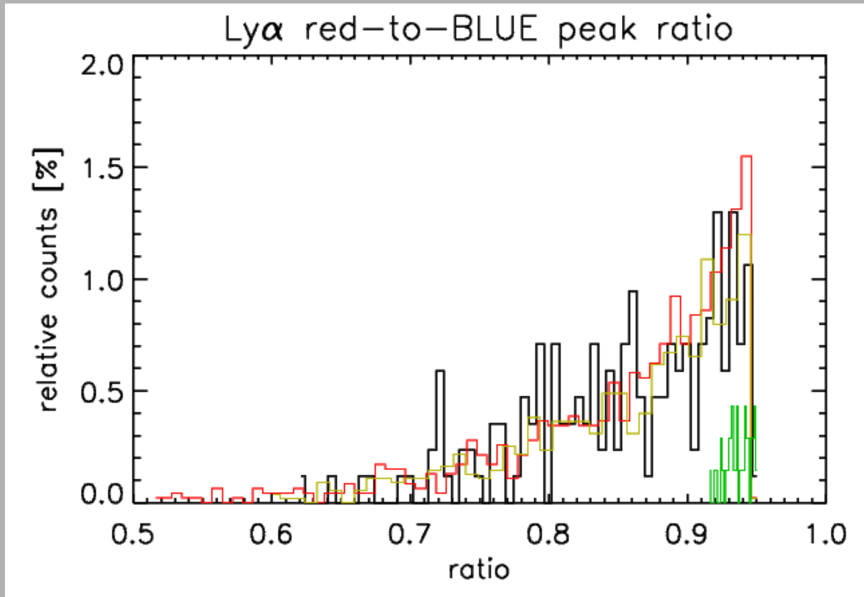
observations

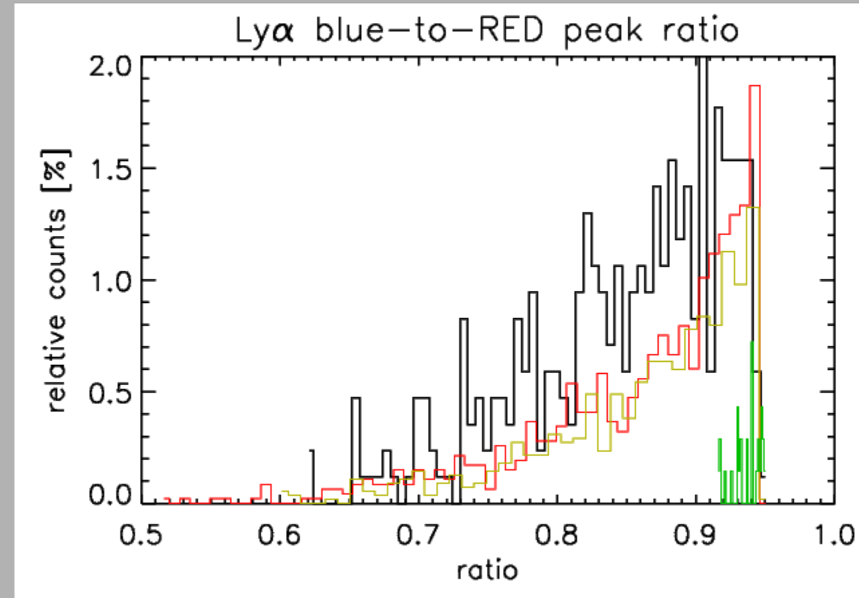
Mo9.5E−5_9000_Bxo6_po2.5E−2, 10 threads
μ=1.0000000

Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=1.0000000

Model_A4_Mo4E−6_po0.03, 10 threads
μ=1.0000000

very low sensitivity to μ from interval 0.5 – 1 !!!!





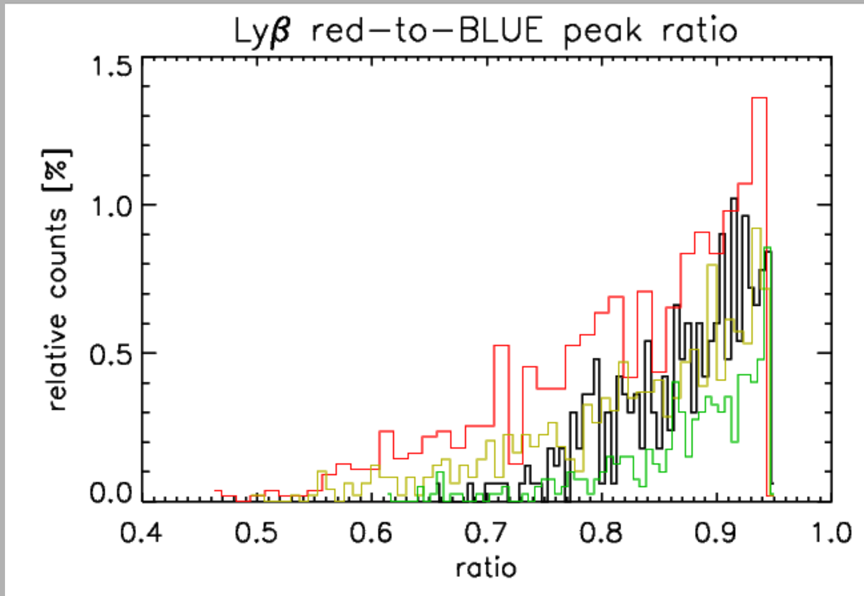
observations

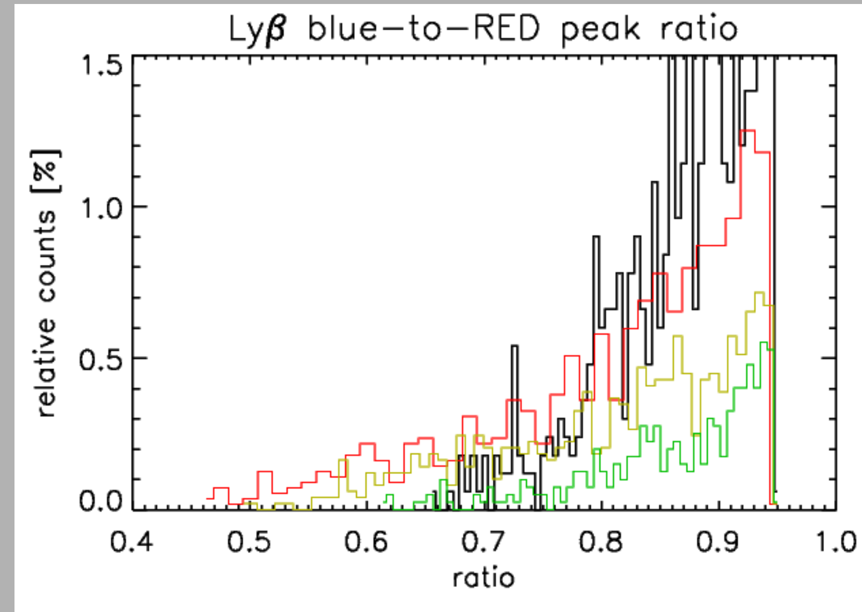
Mo9.5E–5_9000_Bxo6_po2.5E–2, 10 threads
μ=1.0000000

Model1_8000_Mo8.5E–5_Bxo7_po2E–2, 10 threads
μ=1.0000000

Model_A4_Mo4E–6_po0.03, 10 threads
μ=1.0000000

very low sensitivity to μ from interval 0.5 – 1 !!!!





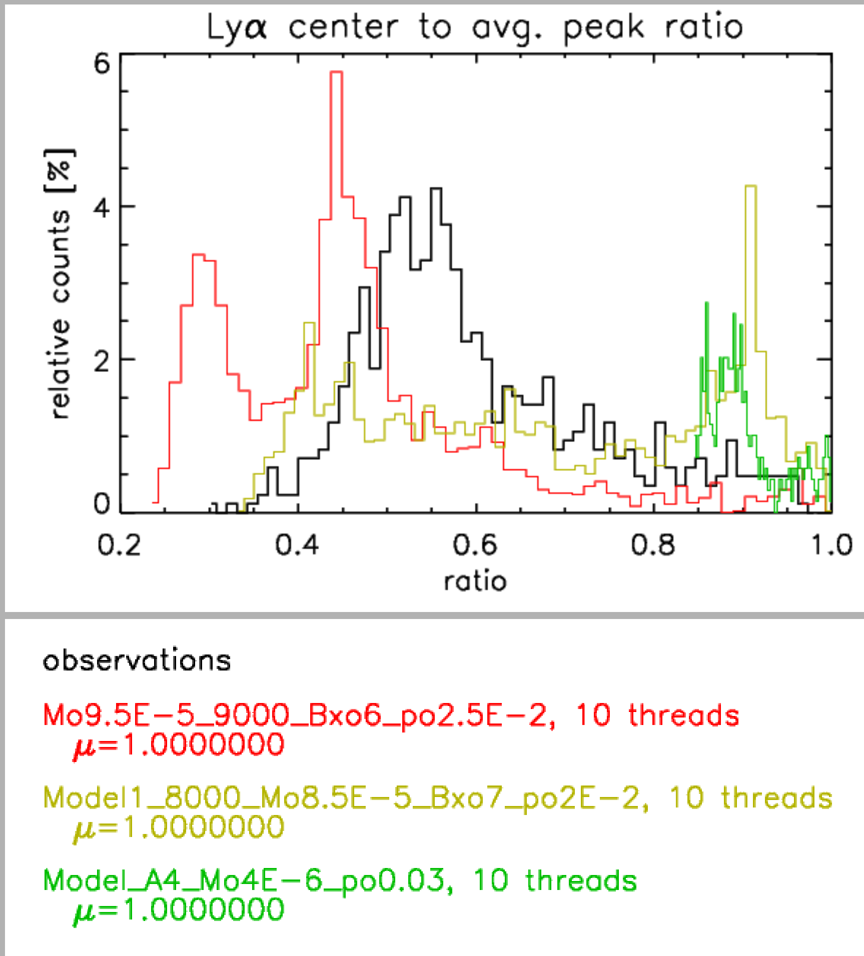
observations

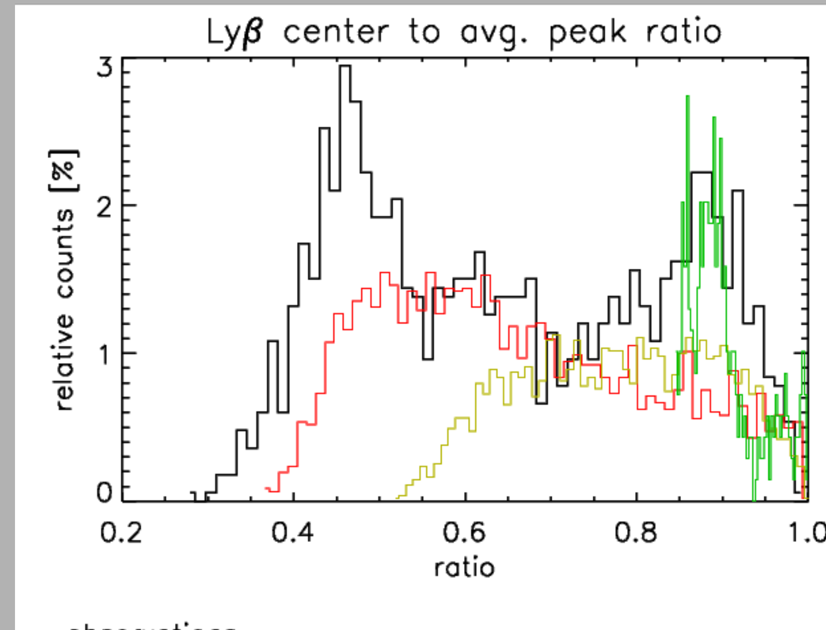
Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=1.0000000

Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=0.86600000

Model1_8000_Mo8.5E−5_Bxo7_po2E−2, 10 threads
μ=0.50000000

similar also for higher Lyman lines





very low sensitivity to μ from interval 0.5 – 1 !!!!

similar as Lyβ also for higher Lyman lines

Conclusions

Models of one thread close to MODEL1 used in model of prominence fine structure are suitable for modelling of prominences with majority of reversed profiles of Lyβ – Lyδ (prominences of 25 May and 18 May 2005):

Mo9.5E-5_9000_Bxo6_po2.5E-2	T_0=9000 K; M_0=9.5 × 10^{-5} g cm^{-2};	$B_x(0)$=6 Gauss; p_0=0.025 dyn cm^{-2};	γ_1=10 γ_2=60
Model1_8000_Mo8.5E-5_Bxo7_po2E-2	T_0=8000 K; M_0=8.5 × 10^{-5} g cm^{-2};	$B_x(0)$=7 Gauss; p_0=0.02 dyn cm^{-2};	γ_1=10 γ_2=60
MODEL1	T_0=7000 K; M_0=1.1 × 10^{-4} g cm^{-2};	$B_x(0)$=6 Gauss; p_0=0.015 dyn cm^{-2}	γ_1=10 γ_2=60

Purely emissive profiles of the lines Lβ – Lδ observed at theprominen-ce on 26 April 2007, are due to lower column mass not due magn. field orientation: purely emissive profiles calculated using the MODEL1 with M_o=1.1×10^{-4} g cm^{-2} for one thread, occurs at μ almost equal to 0 only (below 0.009 for Lβ, below 0.052 for Lγ and below 0.017 for Lδ) ⇒ very low probability to observe the prominence with magnetic field oriented almost or even strictly to the observer. Synthetic profiles of Lβ – Lδ computed using MODEL1 at μ=0 are 2 – 4 times higher than the observed ones Using the model Ax1 with M_o=1×10^{-5} g cm^{-2}, purely emissive profiles can be obtained even at μ=0.5 or lower. These synthetic profiles resemble better observed profiles.

Conclusions – continuation

There is problem with values of reversal depth in modelling the Lyman line profiles – intensities at the reversals are OK, but peaks of synthetic profiles are higher. Including the effect of mutual irradiations of threads made the problem even worse. Even after improvements of the multi-thread model (numerics, using atlas spectrum of BG radiation for IR lines) the problem still persists mainly for the Lyα line

Assuming that optical thickness at the Hα center is around unity, intensity in the linecenter can be used to estimate number of the threads in the observed are of the prominence.

By comparison of histograms of some properties of the observed profiles with those of synthetic profiles by the 18 May prominence it can be seen that models close to MODEL1 cannot explain their behaviour completely and that presence of low density threads are also needed.

Question of whether there is one general prominence-corona transition region (PCTR) or each thread has its own or both exist still open – it is to be solved with applying threads with different plasma conditions in the multithread model

Thank for your attention

This work was supported by grant P209/12/0906 of the Grant Agency of The Czech republic and by the project VEGA 2/0108/12 of the Science Grant Agency. P.S. acknowledges support from the Slovak Research and Development Agency project under contract No. APVV-0816-11.