

Weak Anisotropy Approximation

Application to Ba II

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(IAC; Tenerife; Spain)



Scattering Polarization

- The solar radiation is polarized.
- The polarization has lots of features.
- It makes up a diagnosis tool of the atmosphere, particularly of the magnetic field.
- Complex problem (Non-linear, Non-local, polarized)
→ numerical methods
- Solve at the same time the Radiation Transfer and the Statistical Equilibrium Equations (SEE).

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Statistical Equilibrium Equations

$$\frac{d}{dt}\rho_Q^K(J) = \left[\frac{d}{dt}\rho_Q^K(J) \right]_{\text{Hanle}} + \left[\frac{d}{dt}\rho_Q^K(J) \right]_{\text{Rad}} + \left[\frac{d}{dt}\rho_Q^K(J) \right]_{\text{Coll}}$$

- $K = 0, 1, 2, \dots, 2 \cdot J$
- $Q = -K, -K+1, \dots, K-1, K$
- $(2J+1)^2$ unknowns

Statistical Equilibrium Equations

$$\frac{d}{dt}\rho_Q^K(J) = \left[\frac{d}{dt}\rho_Q^K(J) \right]_{\text{Hanle}} + \left[\frac{d}{dt}\rho_Q^K(J) \right]_{\text{Rad}} + \left[\frac{d}{dt}\rho_Q^K(J) \right]_{\text{Coll}}$$

$$\begin{aligned} \left[\frac{d}{dt}\rho_Q^K(J) \right]_{\text{Rad}} &= \sum_{J_\ell K_\ell Q_\ell} \rho_{Q_\ell}^{K_\ell}(J_\ell) \mathbb{T}_A(JKQ, J_\ell K_\ell Q_\ell) \\ &+ \sum_{J_u K_u Q_u} \rho_{Q_u}^{K_u}(J_u) \mathbb{T}_E(JKQ, J_u K_u Q_u) \\ &- \sum_{K'Q'} \rho_{Q'}^{K'}(J) [\mathbb{R}_A(JKQK'Q') + \mathbb{R}_E(JKQK'Q')] \end{aligned}$$

Statistical Equilibrium Equations

$$\begin{aligned}
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 \end{aligned}$$

$$\begin{aligned}
 \mathbb{R}_A(JKQK'Q') &= (2J+1) \sum_{J_u} B_{\ell u} \sum_{K_r Q_r} \sqrt{3(2K+1)(2K'+1)(2K_r+1)} \\
 &\times (-1)^{1+J_u-K+K_r+Q'} \begin{Bmatrix} K & K' & K_r \\ J & J & J \end{Bmatrix} \begin{Bmatrix} 1 & 1 & K_r \\ J & J & J_u \end{Bmatrix} \\
 &\times \begin{pmatrix} K & K' & K_r \\ Q & -Q' & Q_r \end{pmatrix} \frac{1}{2} \left[1 + (-1)^{K+K'+K_r} \right] J_{Q_r}^{K_r}(\nu_{J_u, J})
 \end{aligned}$$

Weak Anisotropy Approximation

- In the solar atmosphere: $J_0^0 \gg J_Q^K$

$$J_0^0 = \frac{1}{4\pi} \int I d\Omega$$

$$J_0^2 = \frac{1}{4\pi} \int \frac{1}{2\sqrt{2}} [(3\mu^2 - 1)I + 3(\mu^2 - 1)Q] d\Omega$$

- Perturbative expansion in $J_Q^K/J_0^0 \rightarrow$ SEE simplified (Landi Degl'Innocenti & Landolfi 2004).

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Weak Anisotropy Approximation Properties

- Independence between different K .

$$K=0 \quad \rho_0^0(J) \propto N$$

$$\left[\frac{d}{dt} N \right]_{\text{Rad}} = \sum_{\ell} B_{\ell u} J_0^0(\nu_{u,\ell}) N(\ell) + \sum_u A_{u\ell} N(u) \\ - \left[\sum_u B_{\ell u} J_0^0(\nu_{u,\ell}) + \sum_l A_{u\ell} \right] N$$

Weak Anisotropy Approximation Properties

- Only $K \leq 2$ (because $\rho^0_0 \gg \rho^{1,2}_Q \gg \rho^{K>2}_Q$).

$K \neq 0$

$$\begin{aligned} \left[\frac{d}{dt} \rho_Q^K(J) \right]_{\text{Rad}} &= \sum_{J_\ell} \rho_Q^K(J_\ell) \mathbb{T}'_A(JKQ, J_\ell KQ) \\ &+ \sum_{J_u} \rho_Q^K(J_u) \mathbb{T}'_E(JKQ, J_u KQ) \\ &- \rho_Q^K(J) [\mathbb{R}'_A(JKQKQ) + \mathbb{R}'_E(JKQKQ)] \end{aligned}$$

Weak Anisotropy Approximation Properties

- Full Term

$$\begin{aligned}
 \mathbb{R}_A(JKQK'Q') &= (2J + 1) \sum_{J_u} B_{\ell u} \sum_{K_r Q_r} \sqrt{3(2K + 1)(2K' + 1)(2K_r + 1)} \\
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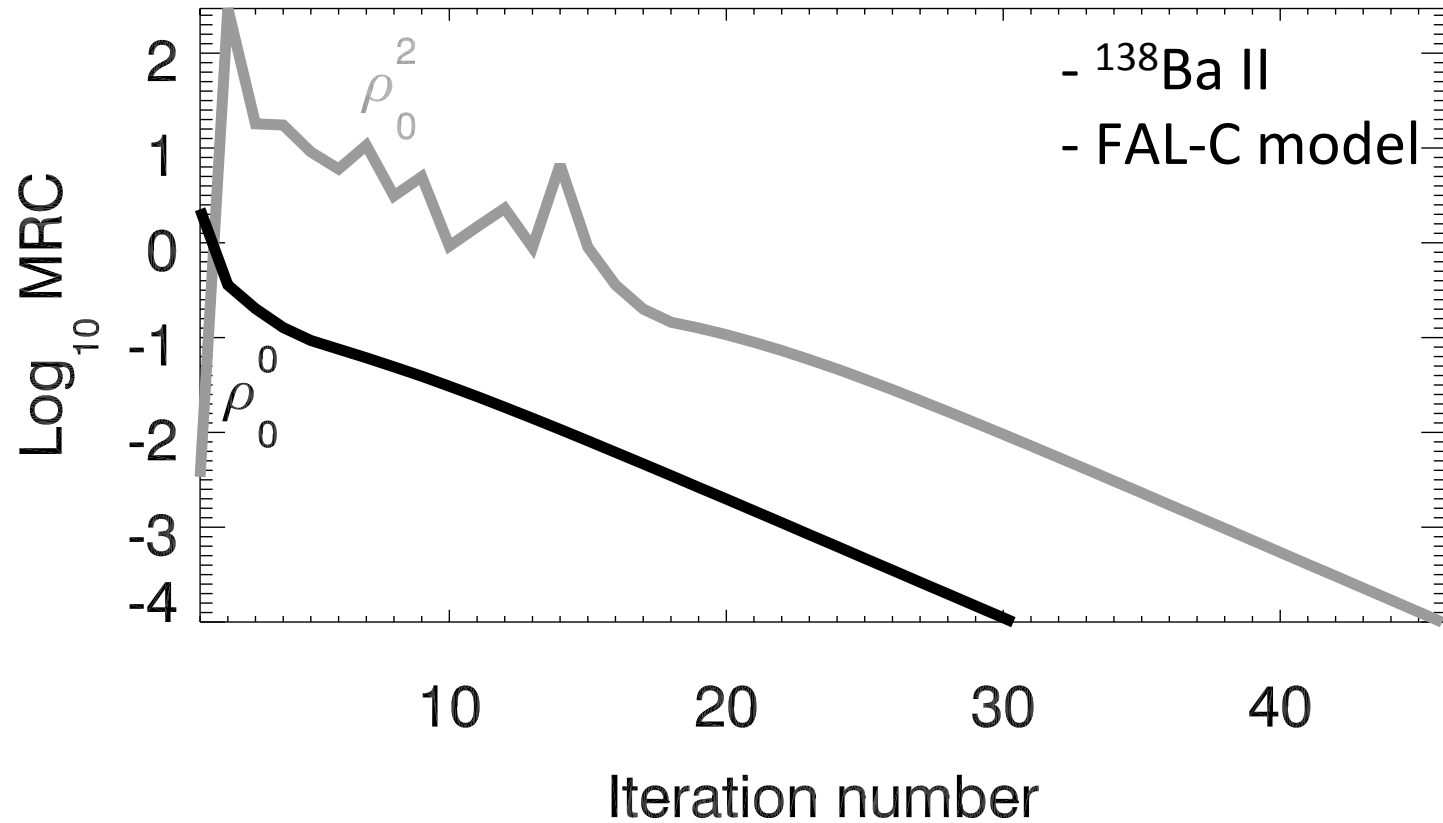
- Weak Anisotropy

$$\mathbb{R}'_A(JKQKQ)\rho_Q^K(J) = \sum_{J_u} B_{\ell u} \left[J_0^0(\nu_{u,\ell})\rho_Q^K(J) + \omega_{JJ_u}^{(K)}(-1)^{K+Q} J_{-Q}^K(\nu_{u,\ell})\rho_0^0(J) \right]$$

Weak Anisotropy Approximation Numerical Scheme

- Multilevel radiation transfer NLTE problem of 2nd kind.
- Diagonal lambda operator (preconditioning) with blends (Rybicki & Hummer 1992).
- Example of convergence rate.

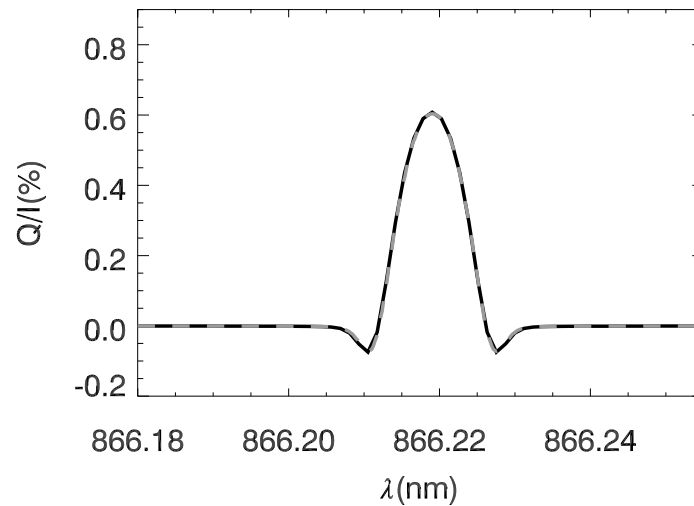
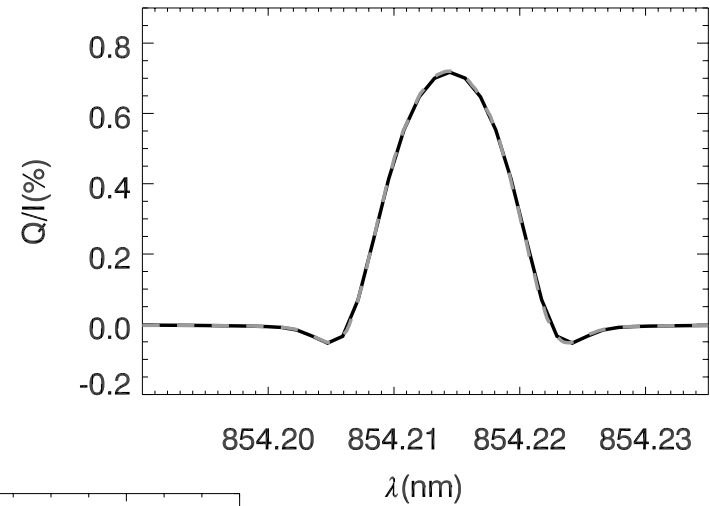
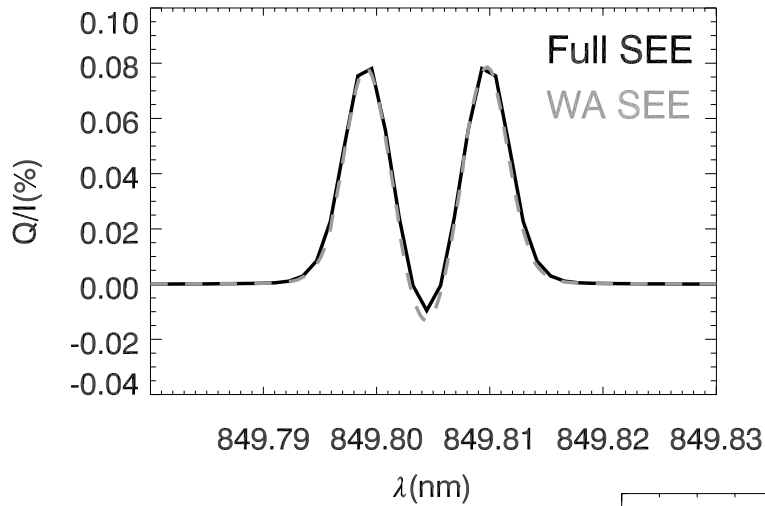
Weak Anisotropy Approximation



Weak Anisotropy Approximation

- Comparison with the general SEE approach:
 - Compare with PORTA (Štěpán & Trujillo Bueno 2013)
 - Ca II atom with five atomic levels.
 - FAL-C model without microturbulence.
 - Emergent profiles of the infrared triplet.

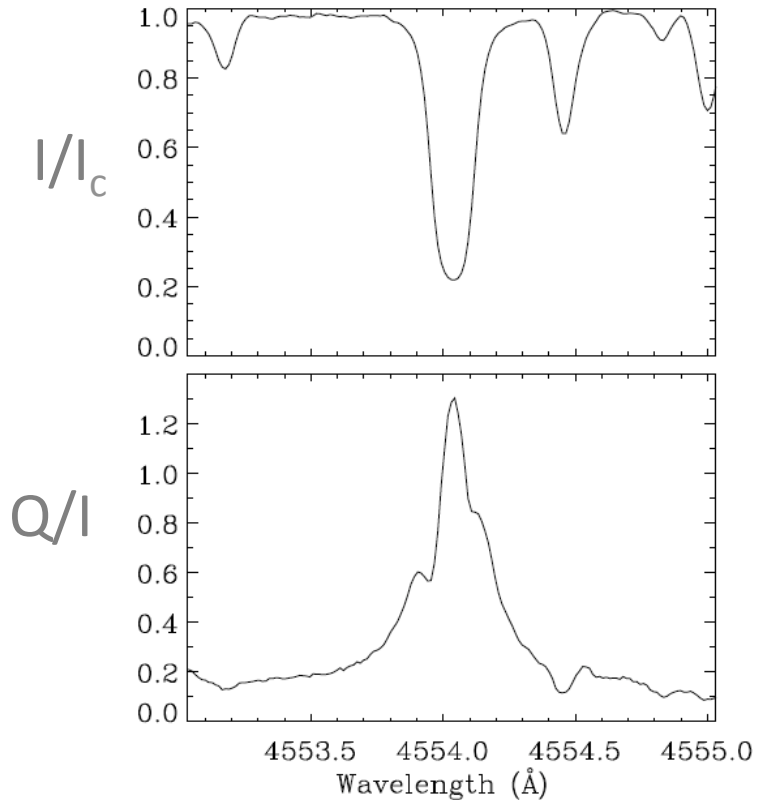
Weak Anisotropy Approximation



Scattering polarization in Ba II Observations

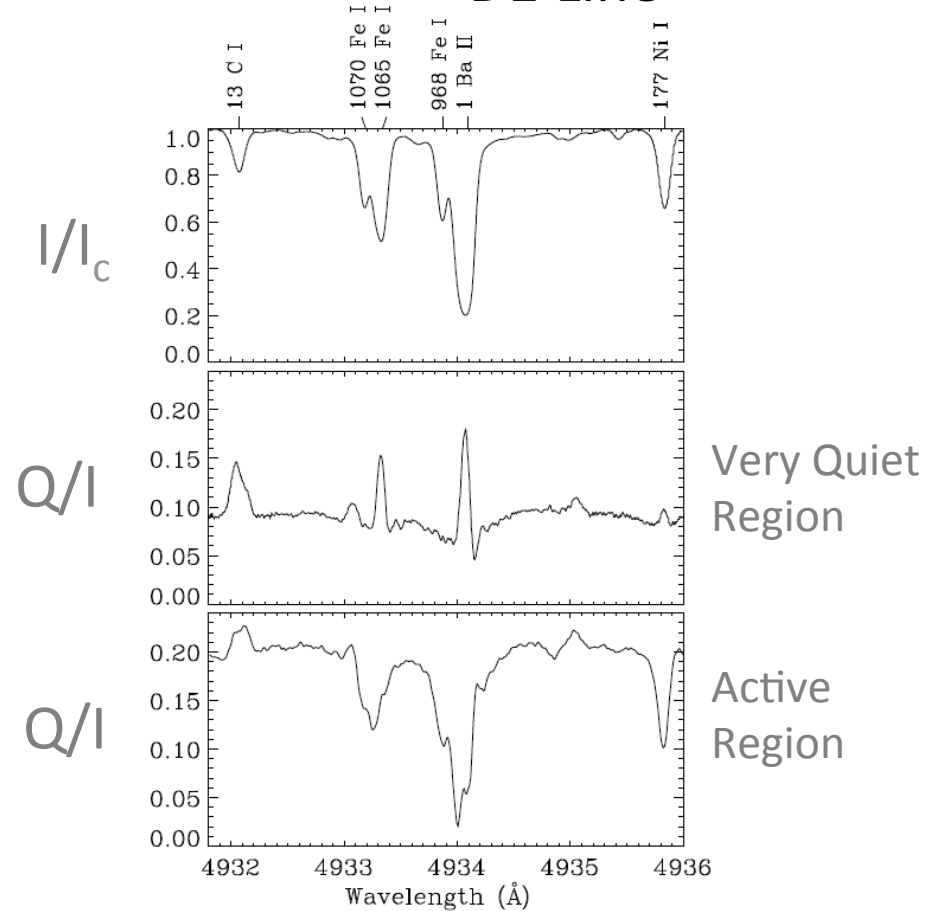
D2 Line

1 Ba II 4554 Å



Stenflo & Keller (1997)

D1 Line

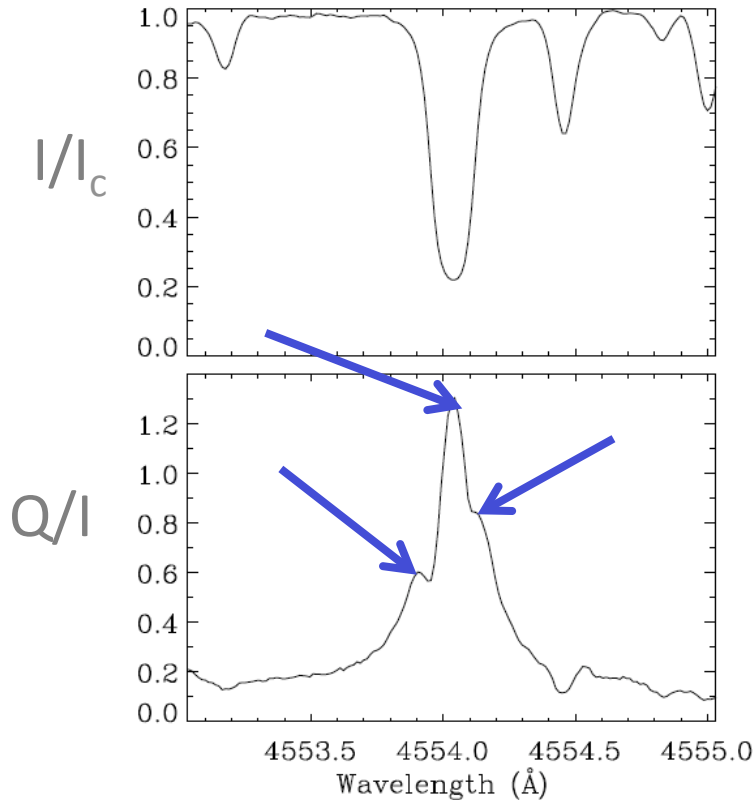


Stenflo et al. (1998)

Scattering polarization in Ba II Observations

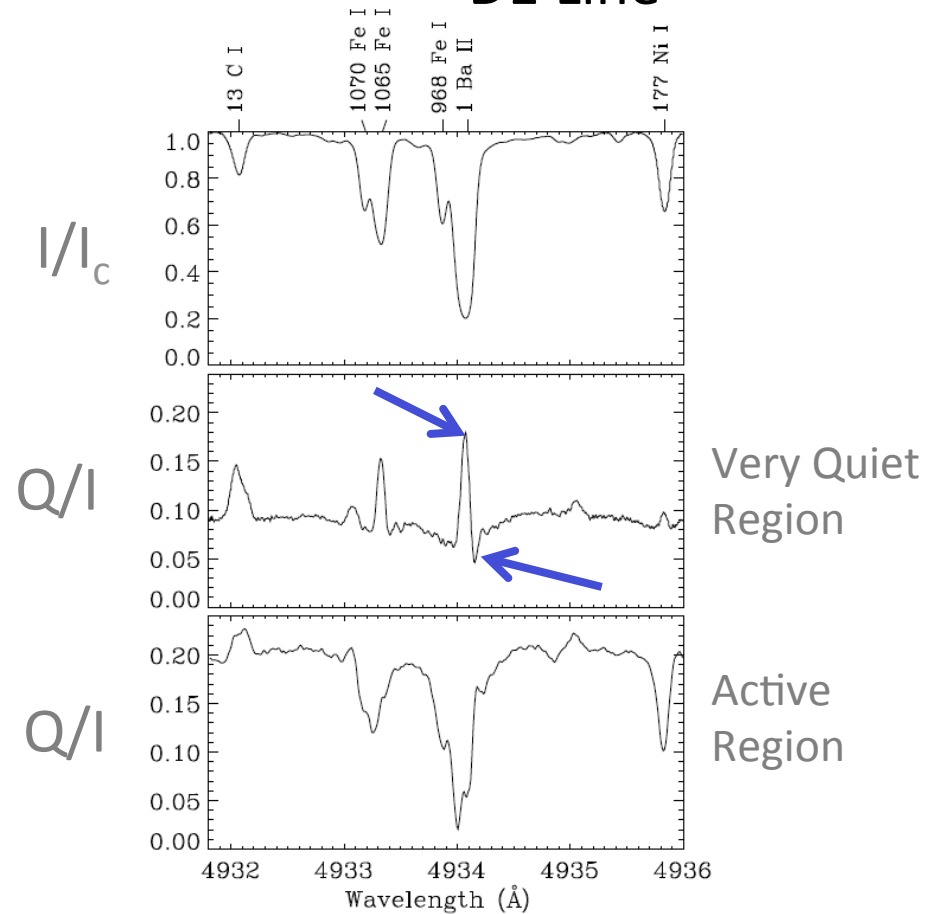
D2 Line

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D1 Line

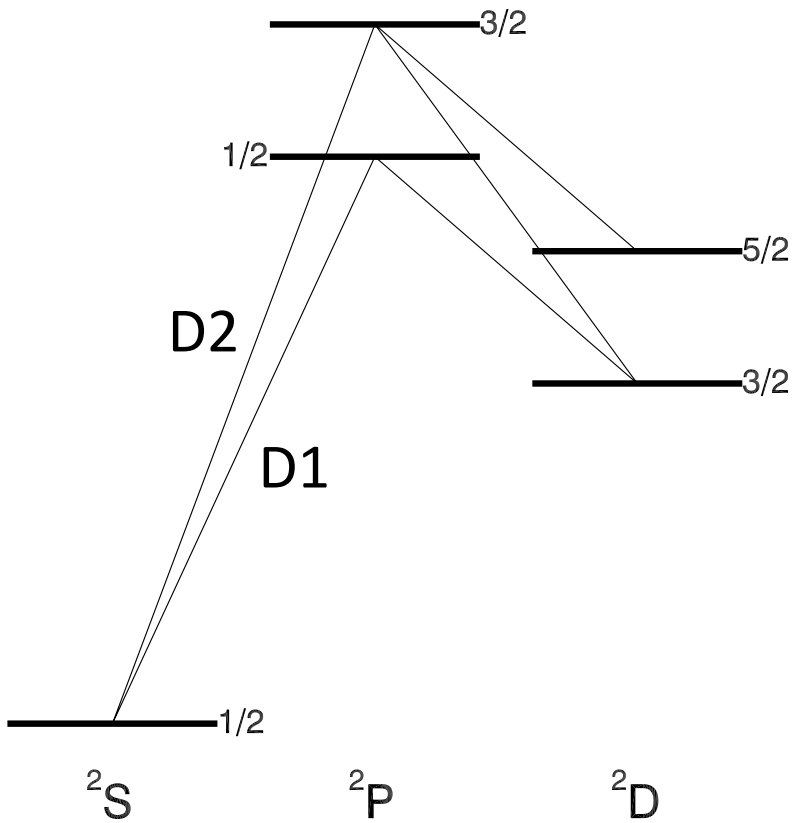


Stenflo et al. (1998)

Scattering polarization in Ba II

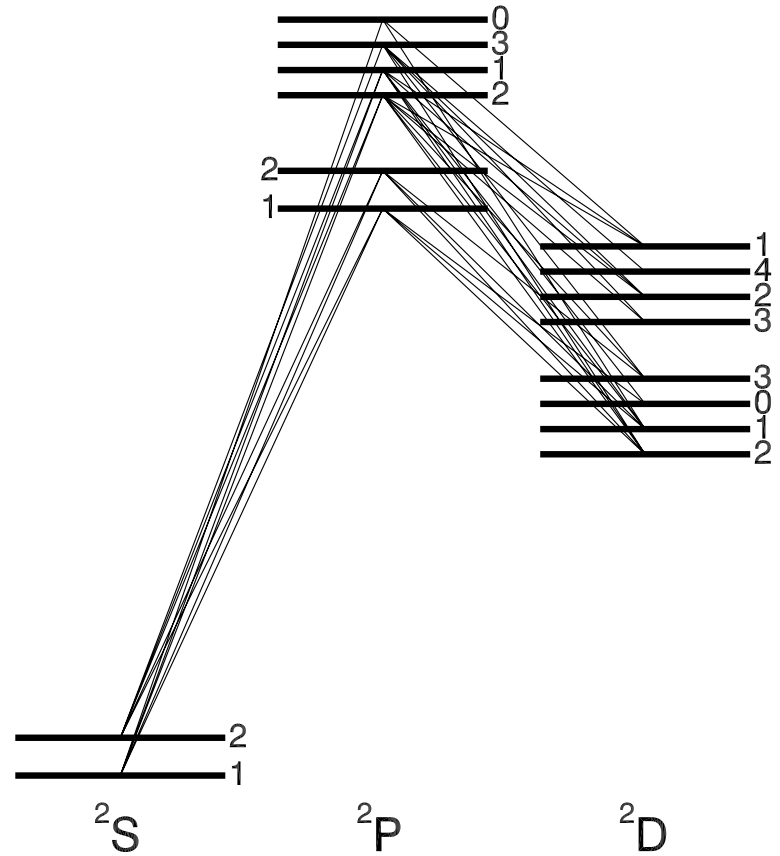
A = 134, 136 & 138

$l = 0$



A = 135 & 137

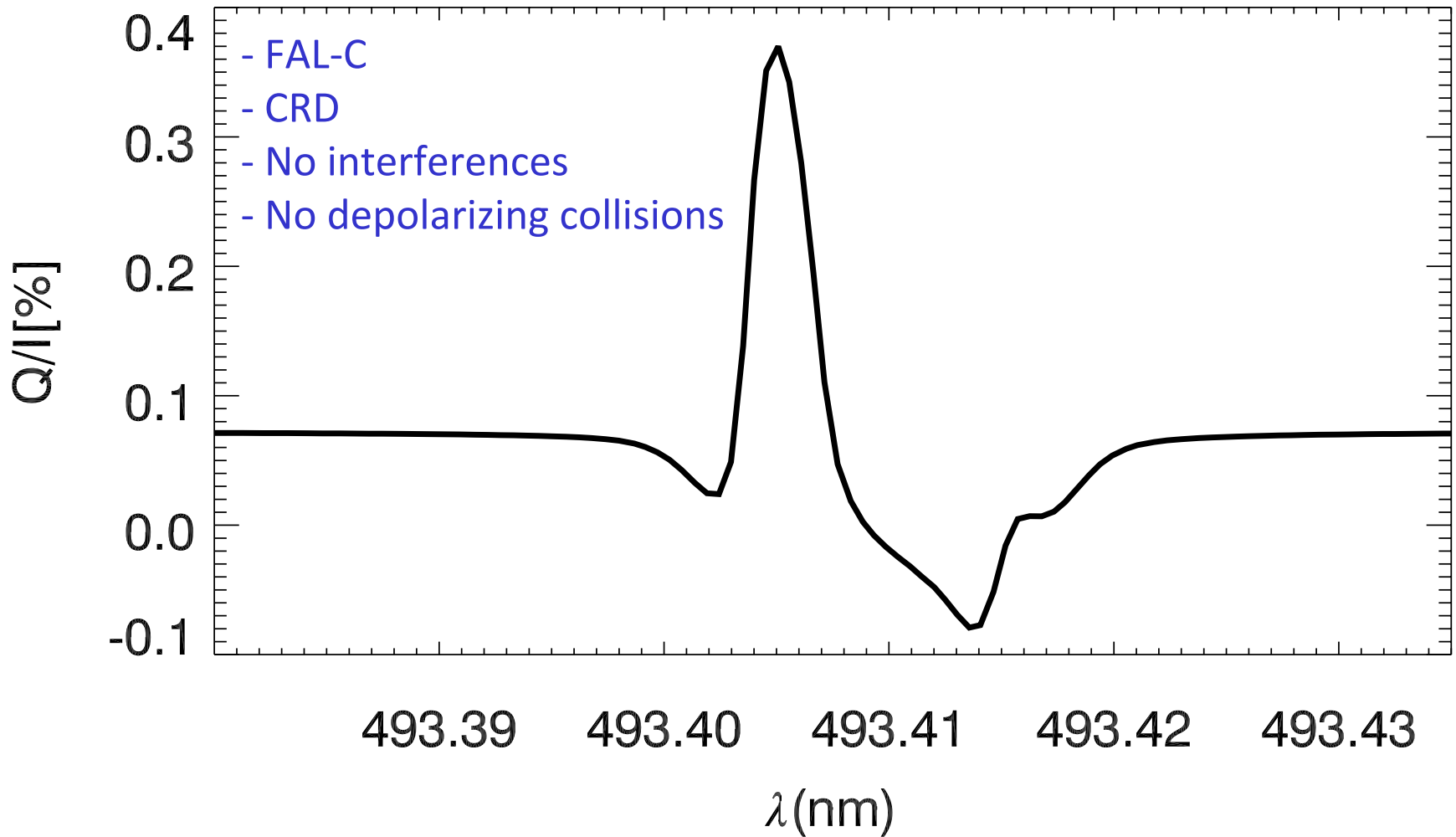
$l = 3/2$



Scattering polarization in Ba II

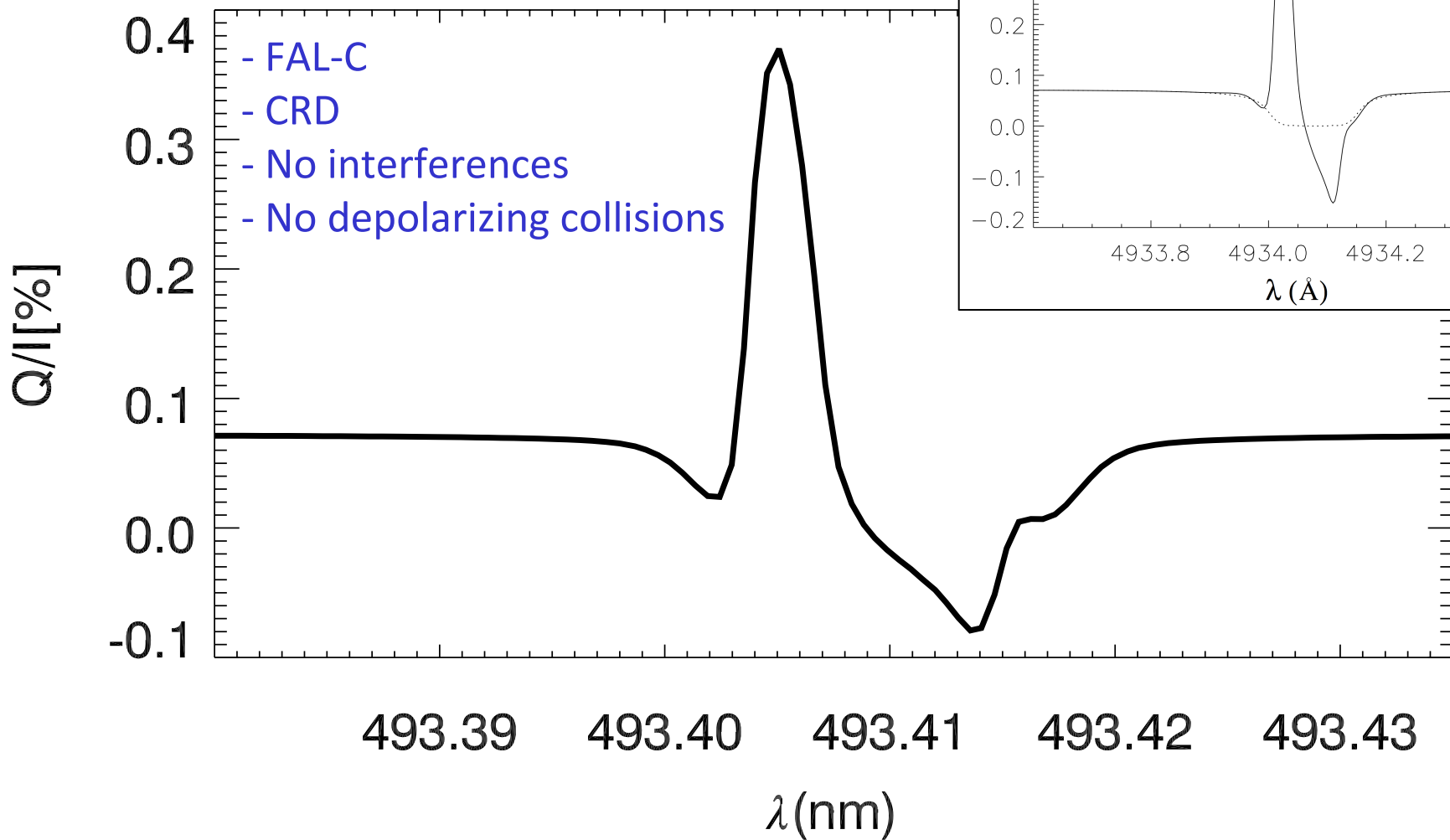
- Reference case
- Are the metastable levels important? (for D lines!)
- Is the polarization of the ground level relevant? (as in Na I) and the metastable levels'? (as in Ca II)
- How sensitive is everything to the atmospheric model? Can we diagnose the plasma?

Ba II D1 Line

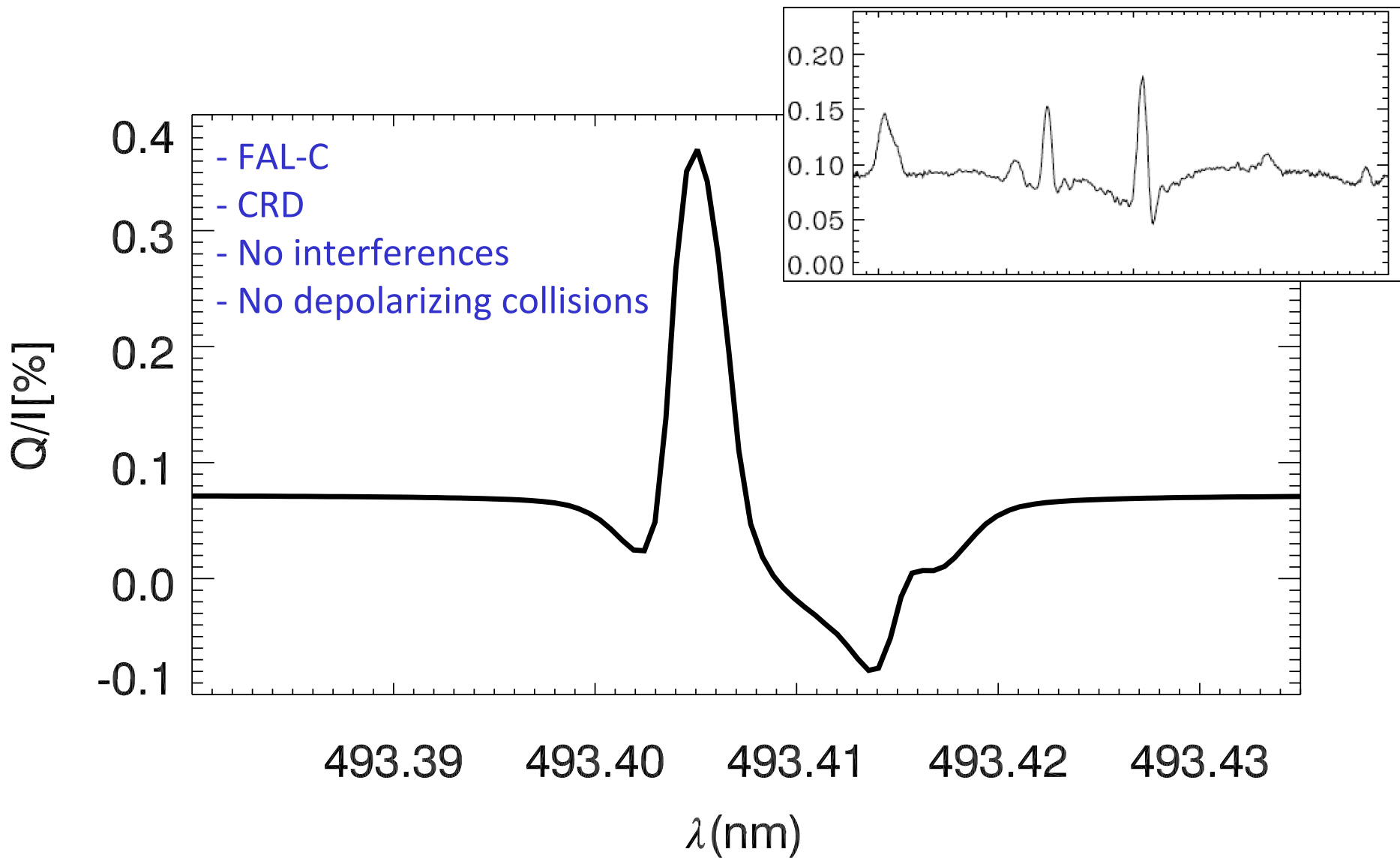


Ba II D1 Line

Belluzzi & Trujillo Bueno (2013)

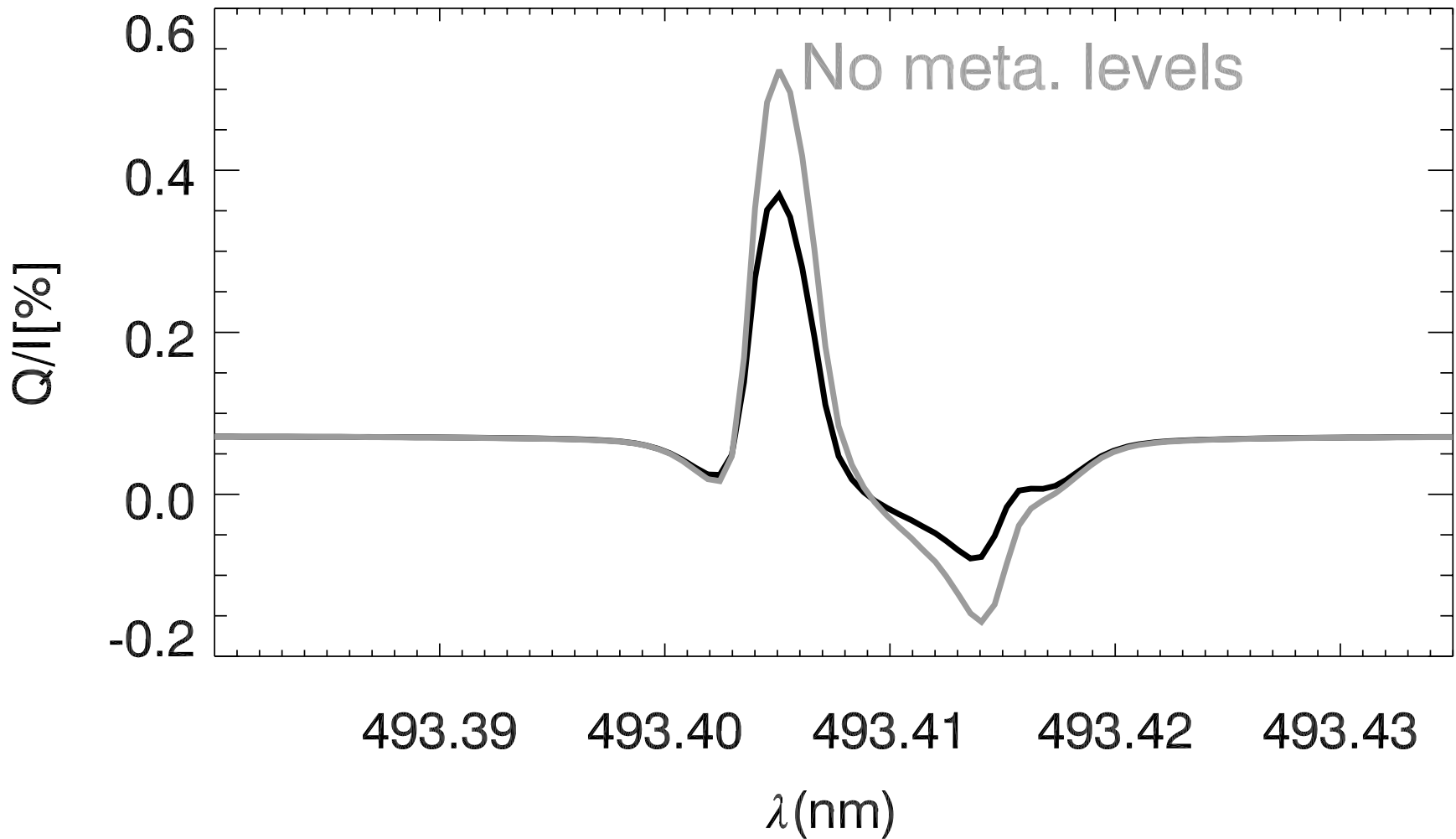


Ba II D1 Line



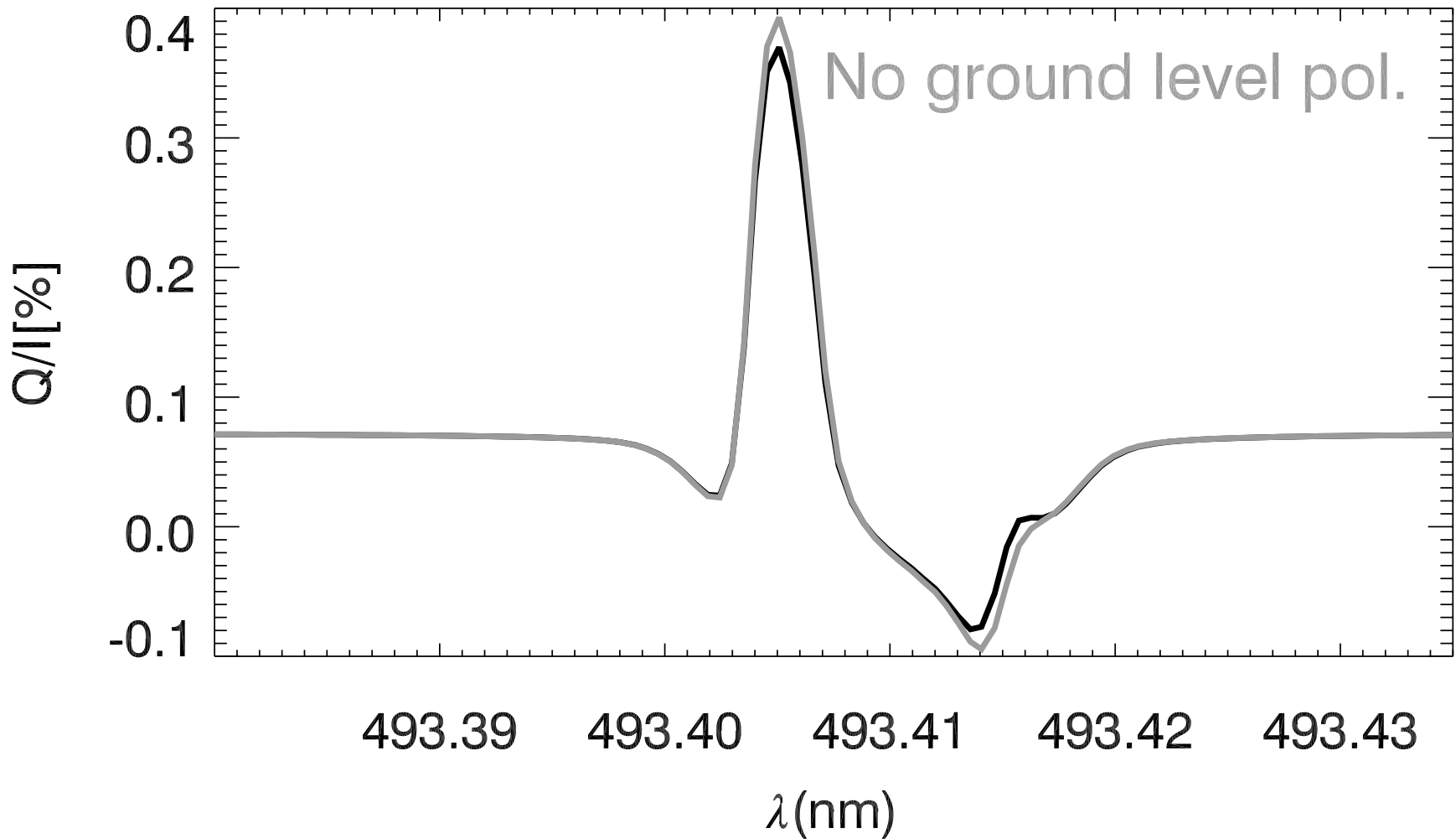
Ba II D1 Line

Metastable Levels



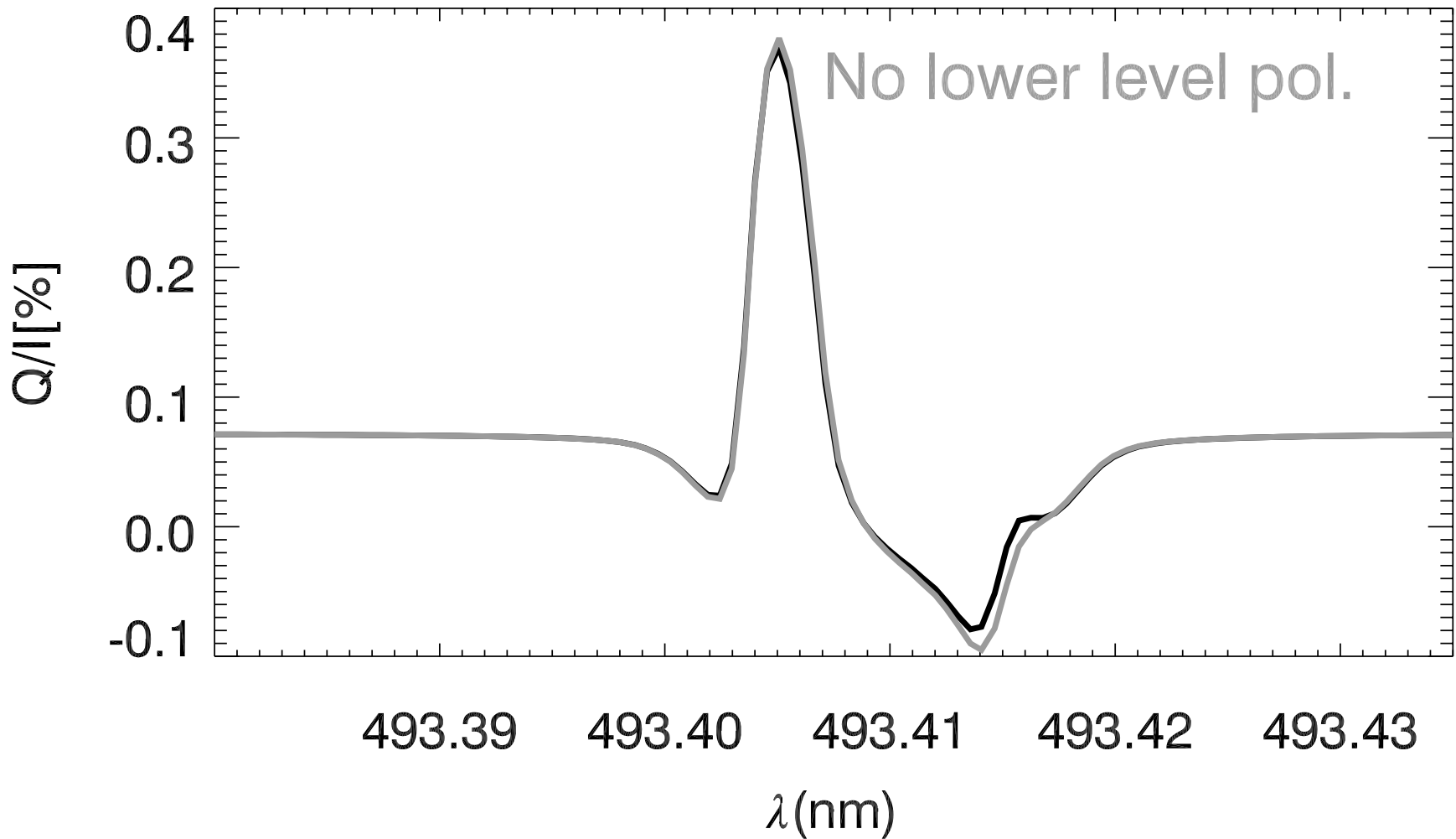
Ba II D1 Line

Ground Level Polarization



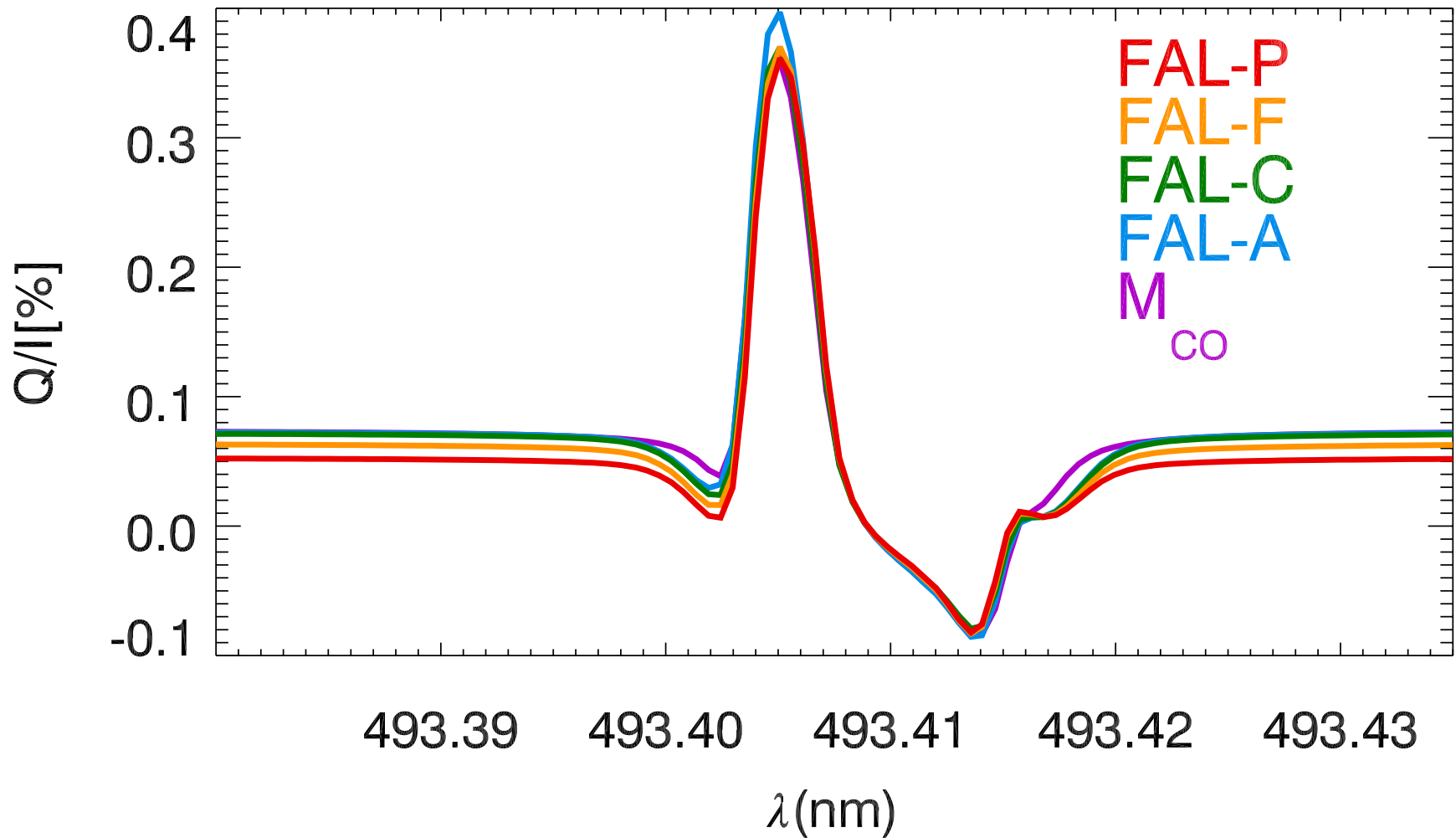
Ba II D1 Line

Lower Level Polarization

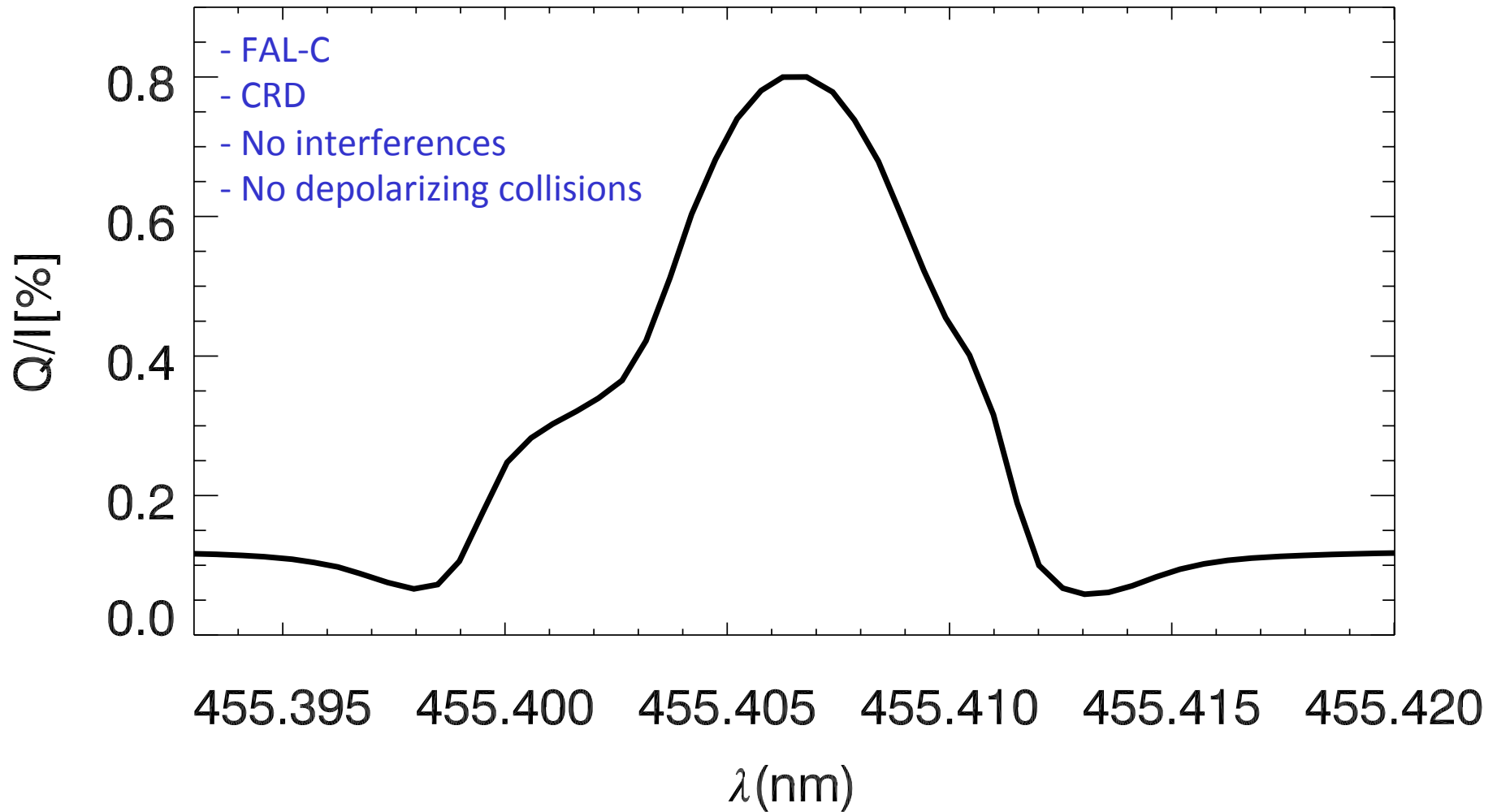


Ba II D1 Line

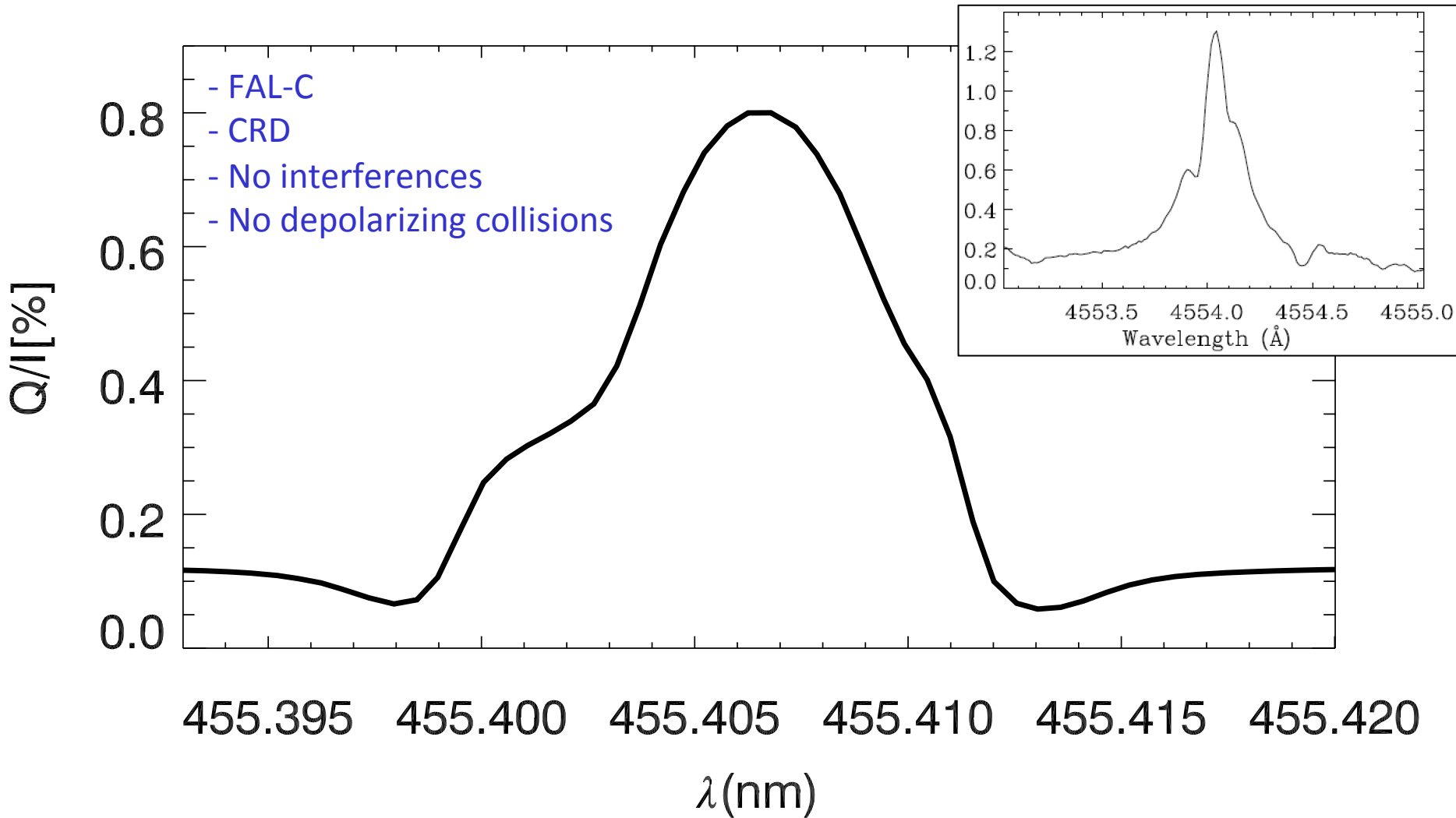
Model Sensitivity



Ba II D2 Line

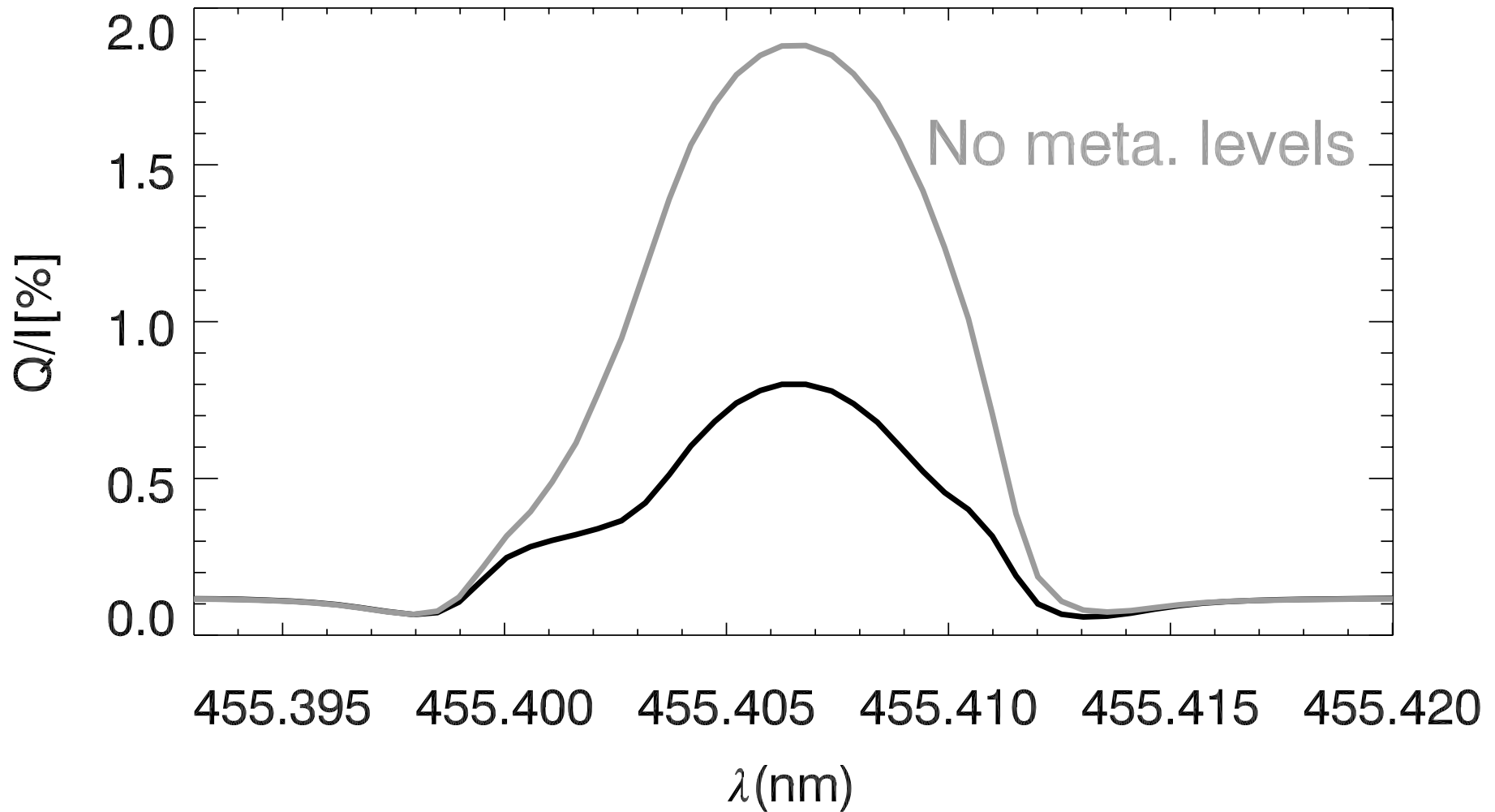


Ba II D2 Line



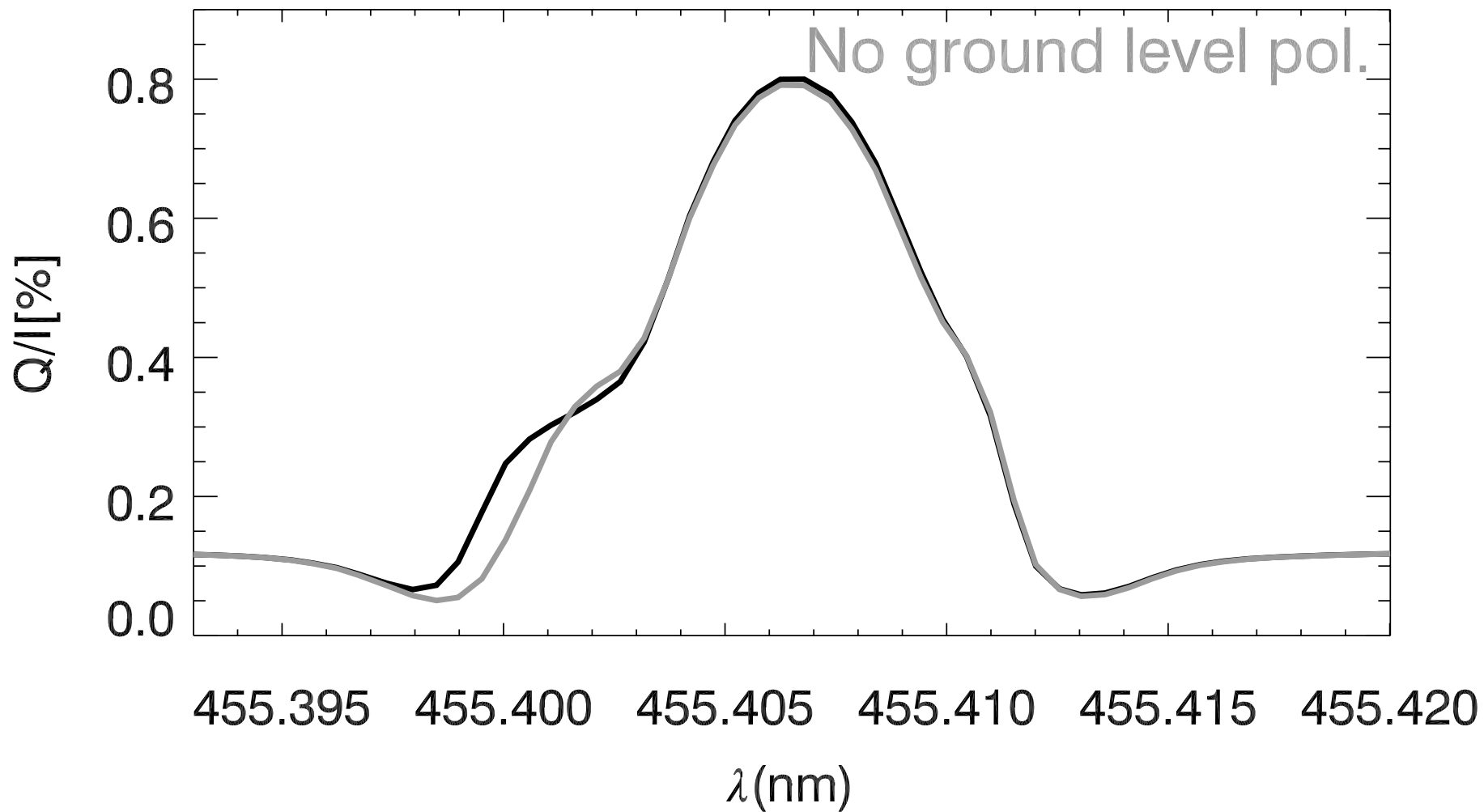
Ba II D2 Line

Metastable Levels



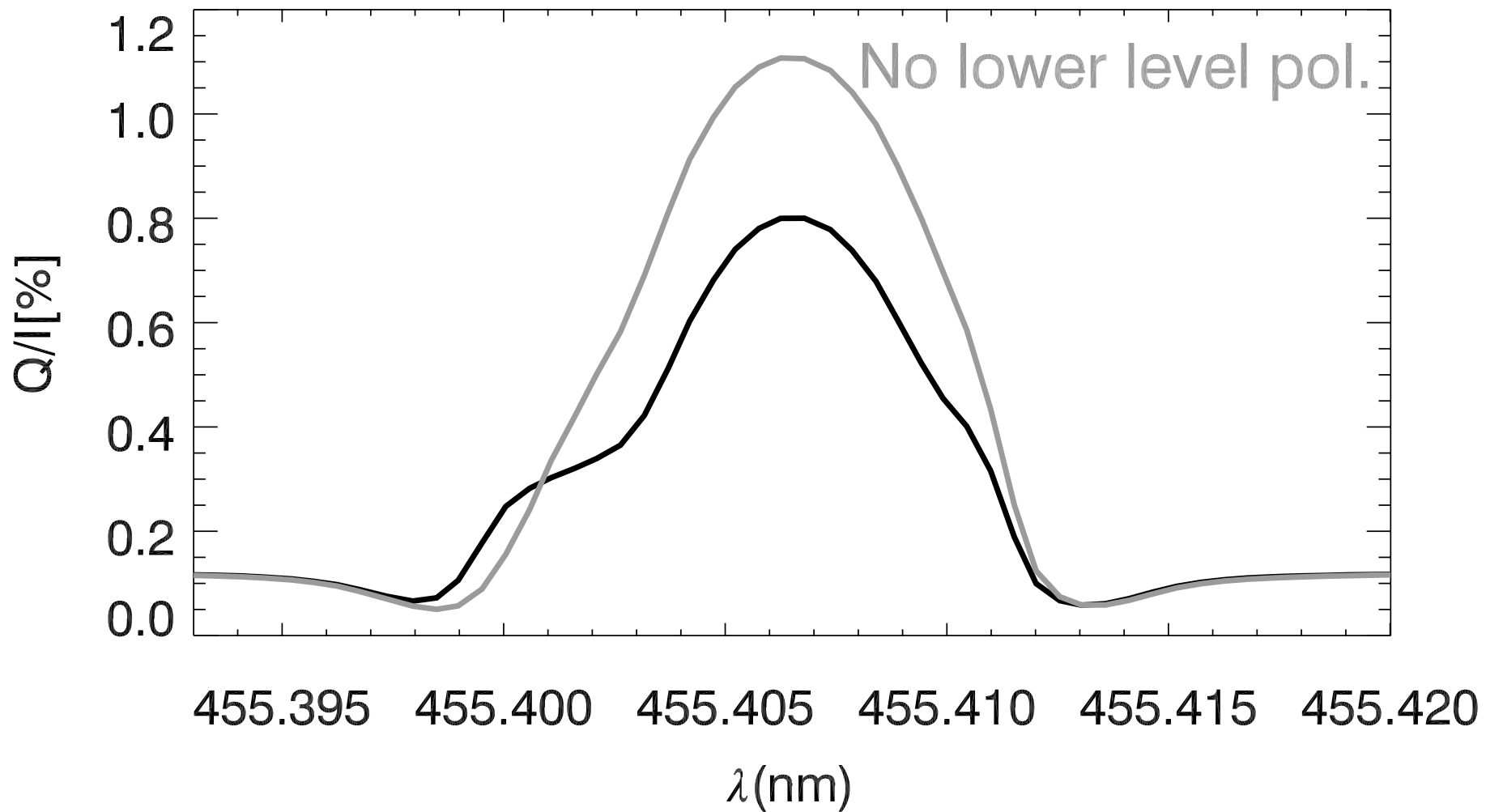
Ba II D2 Line

Ground Level Polarization



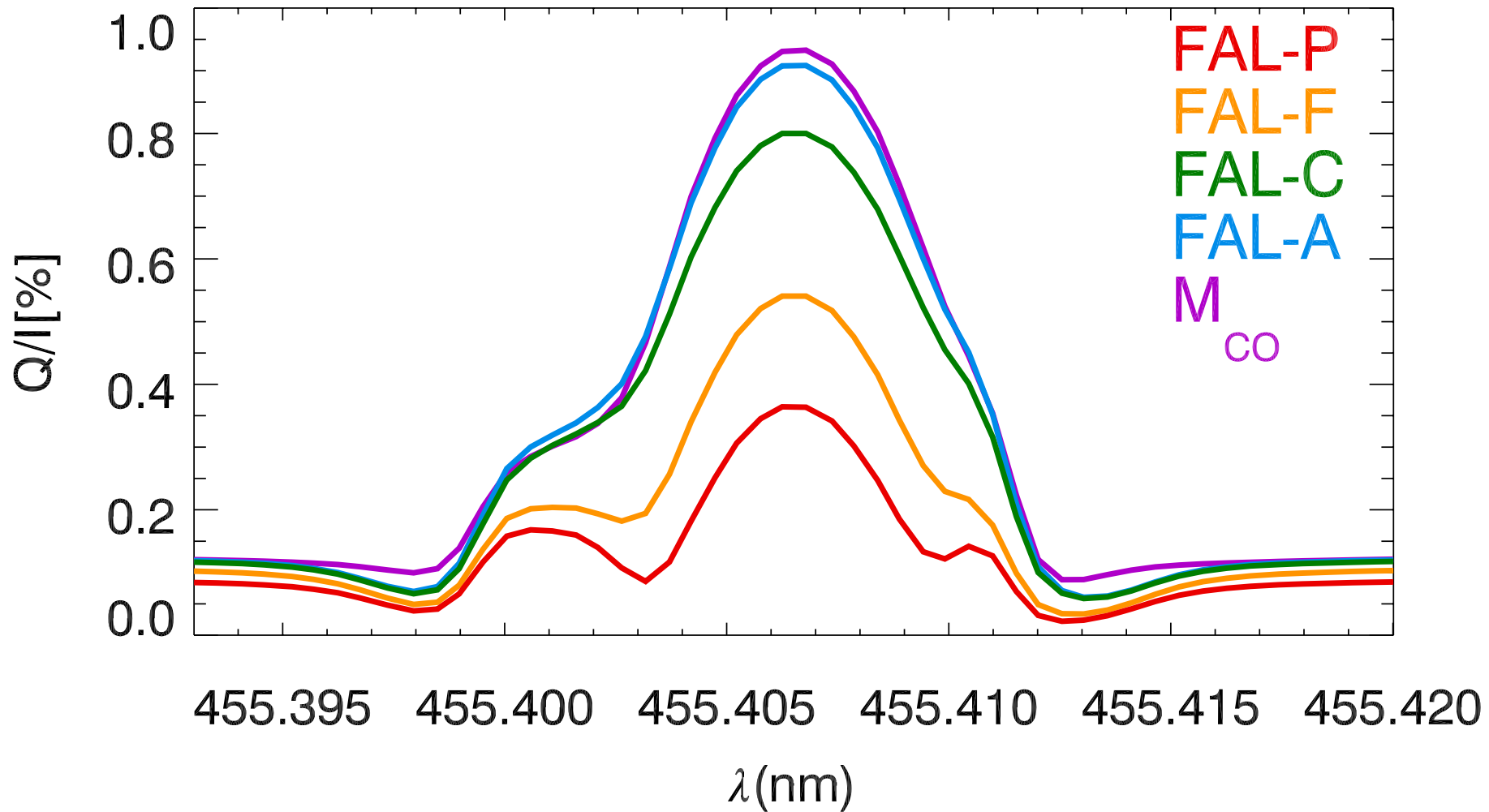
Ba II D2 Line

Lower Level Polarization

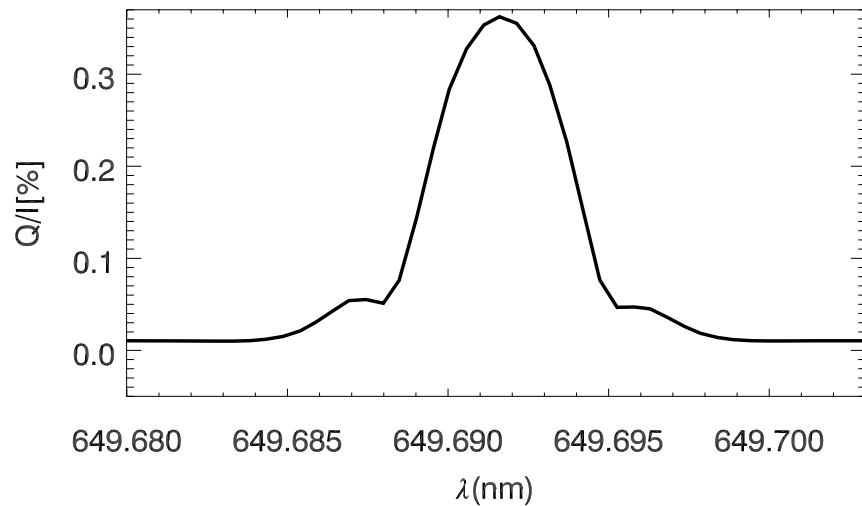
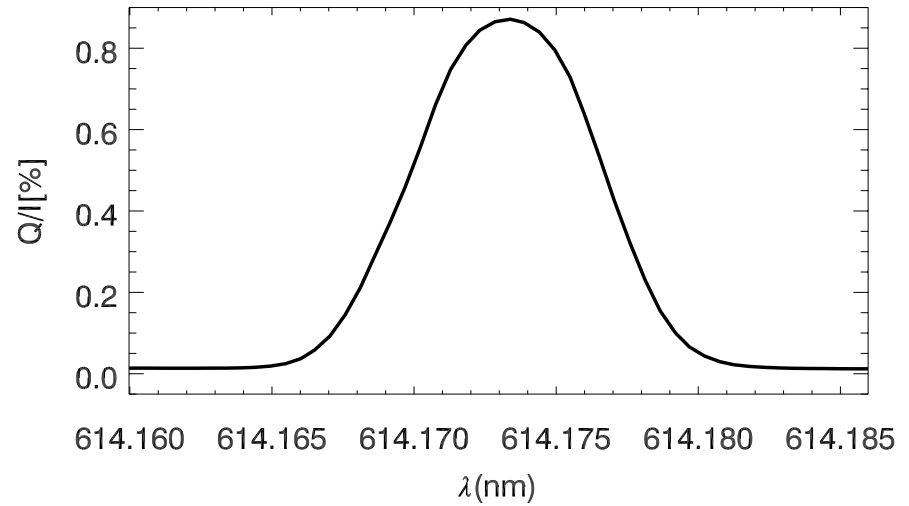
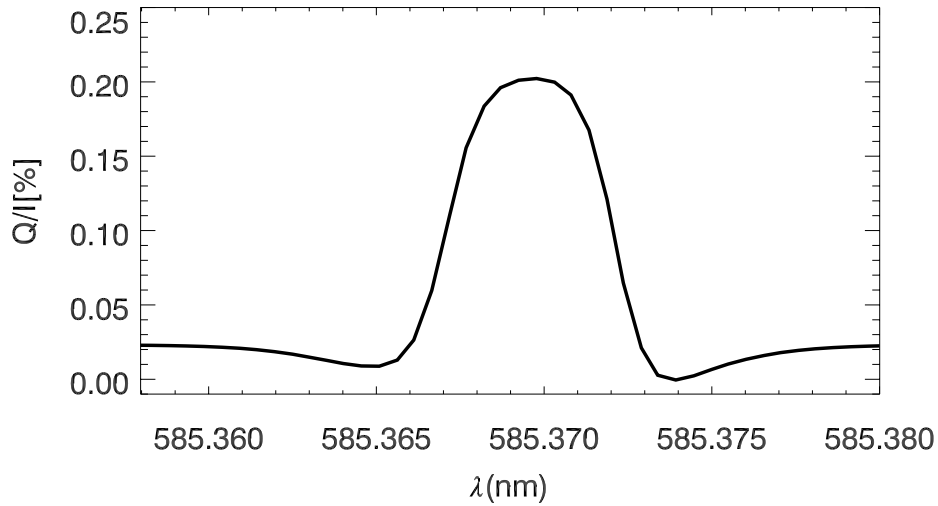


Ba II D2 Line

Model Sensitivity



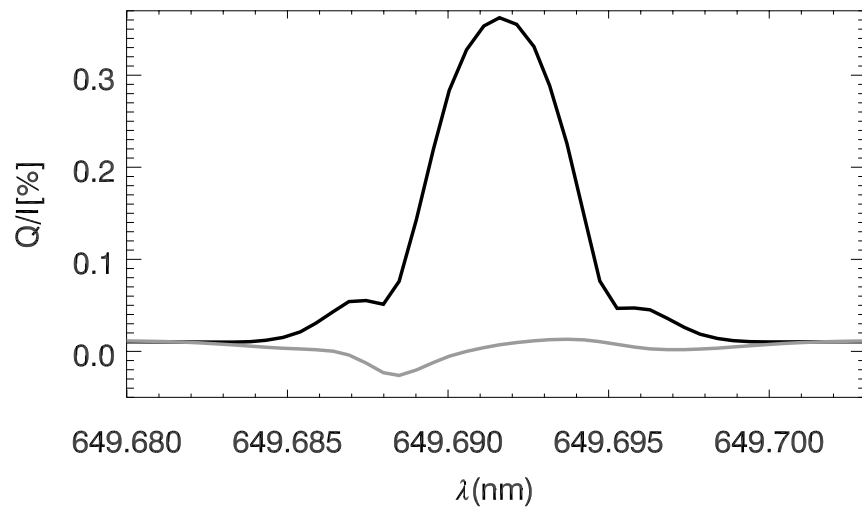
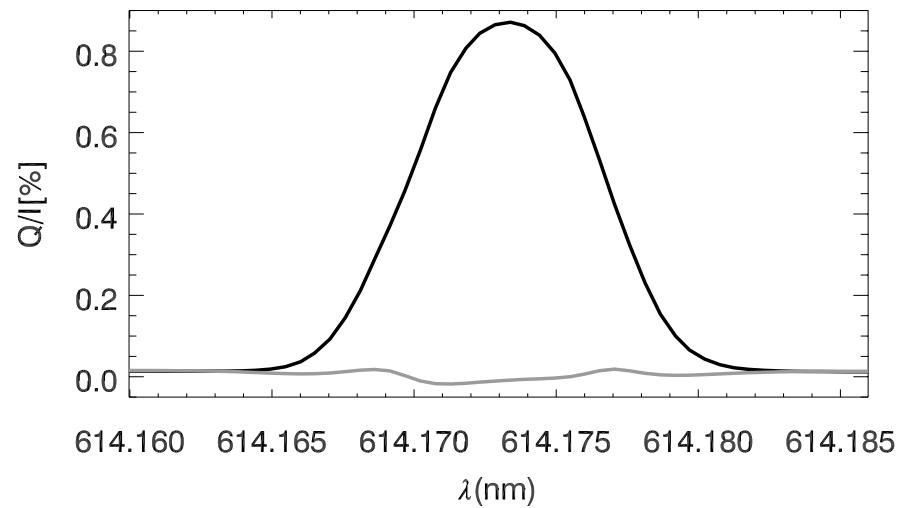
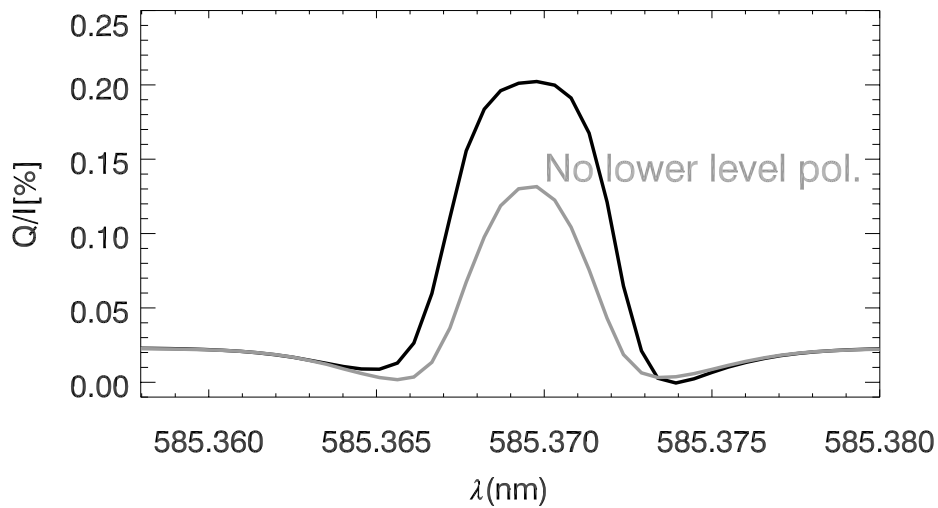
Ba II Triplet



- FAL-C
- CRD
- No interferences
- No depolarizing collisions

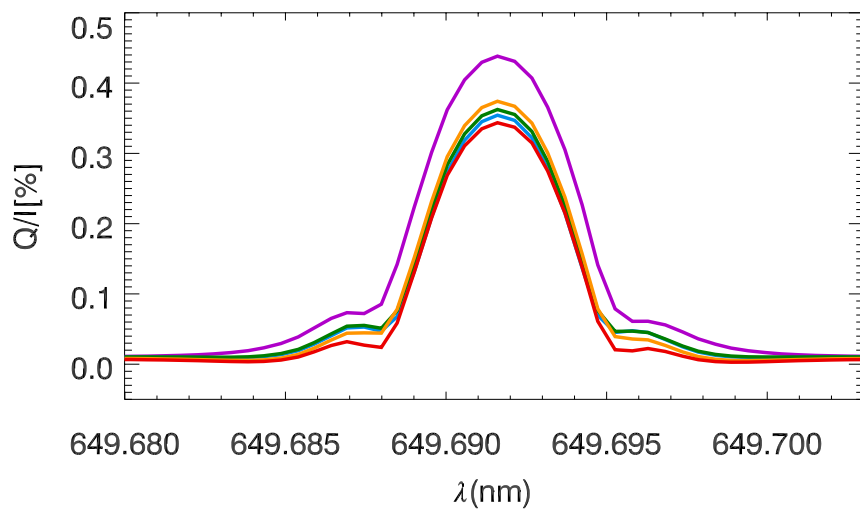
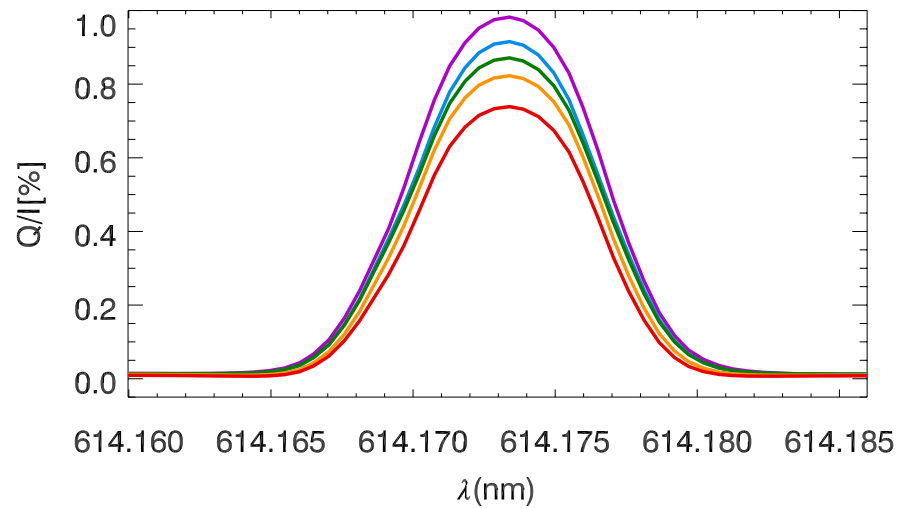
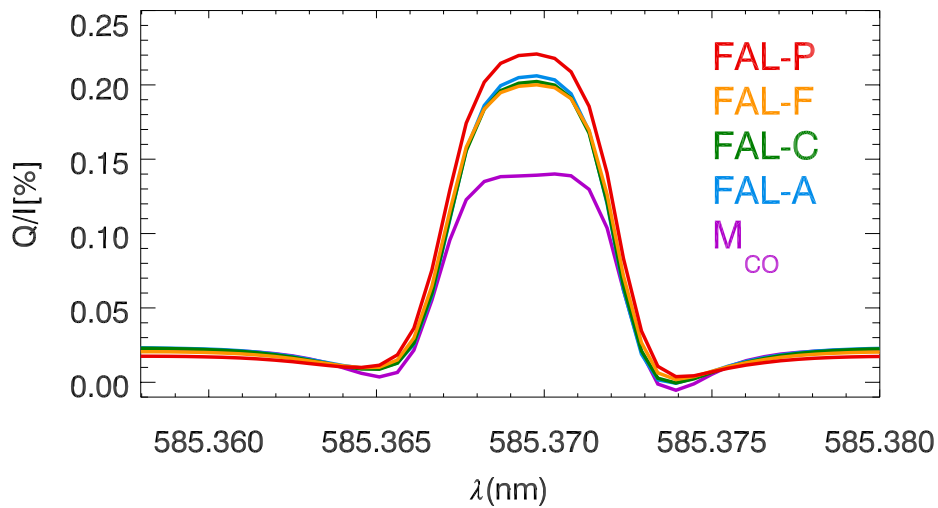
Ba II Triplet

Lower Level Polarization



Ba II Triplet

Model Sensitivity

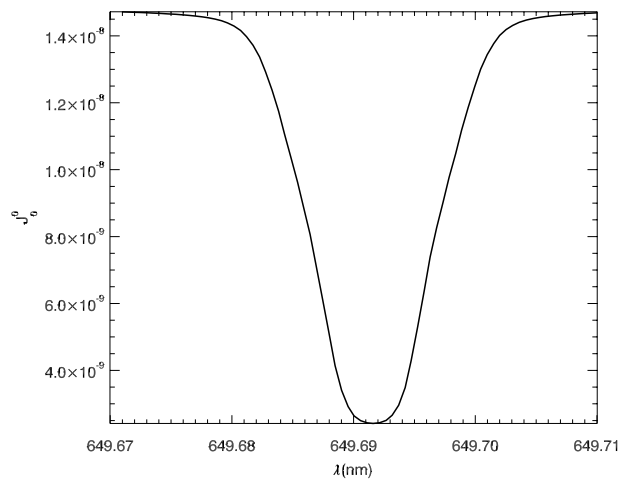
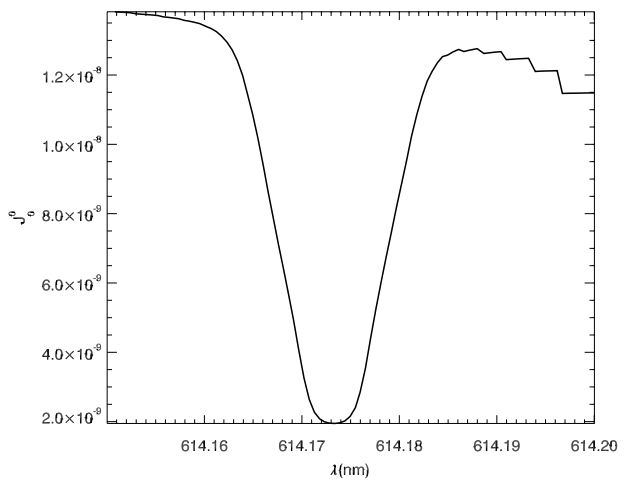
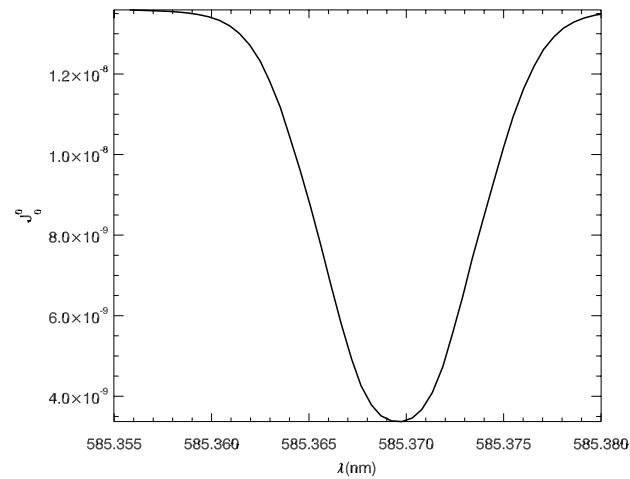
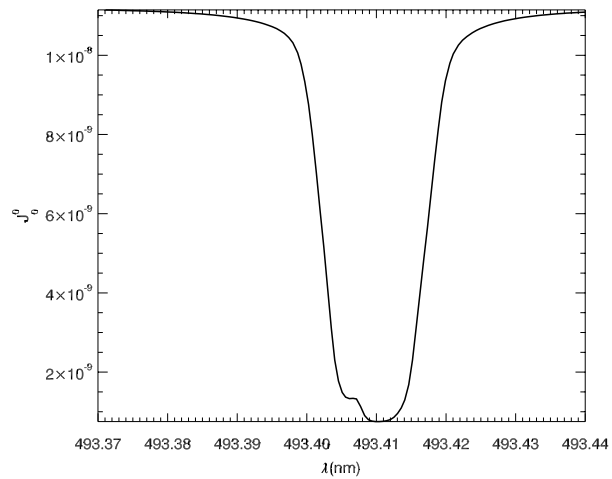
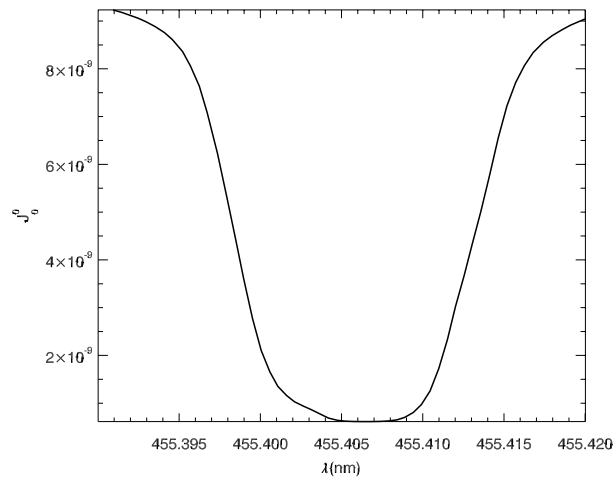


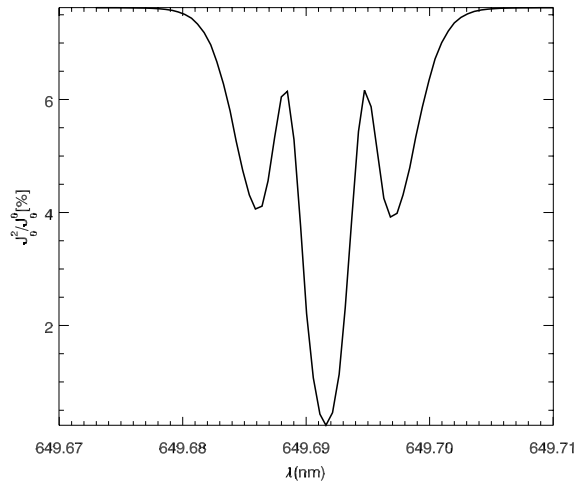
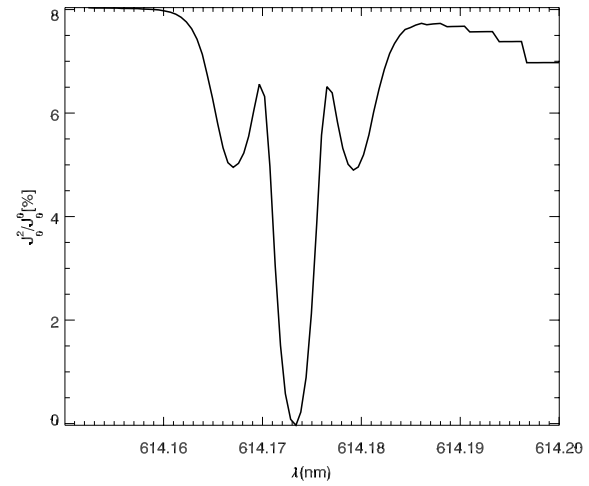
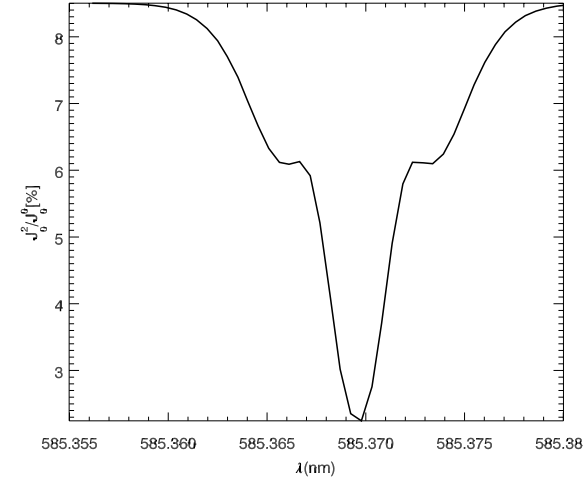
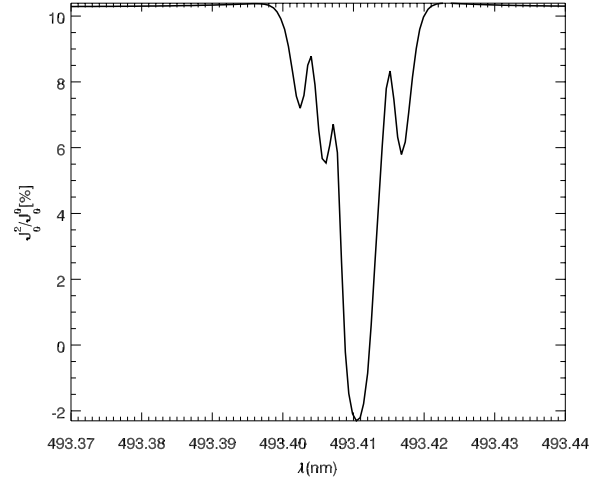
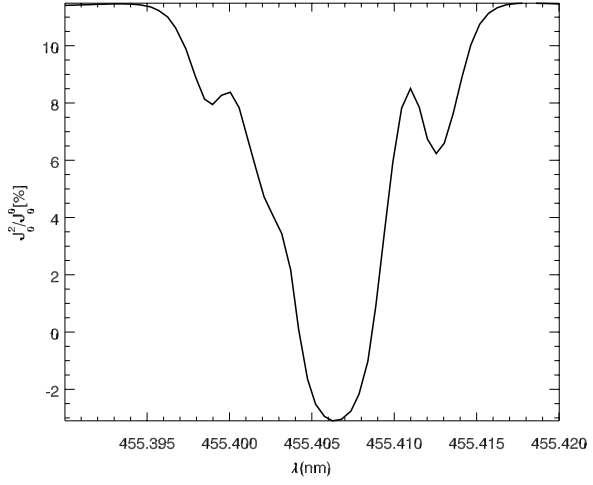
Conclusions

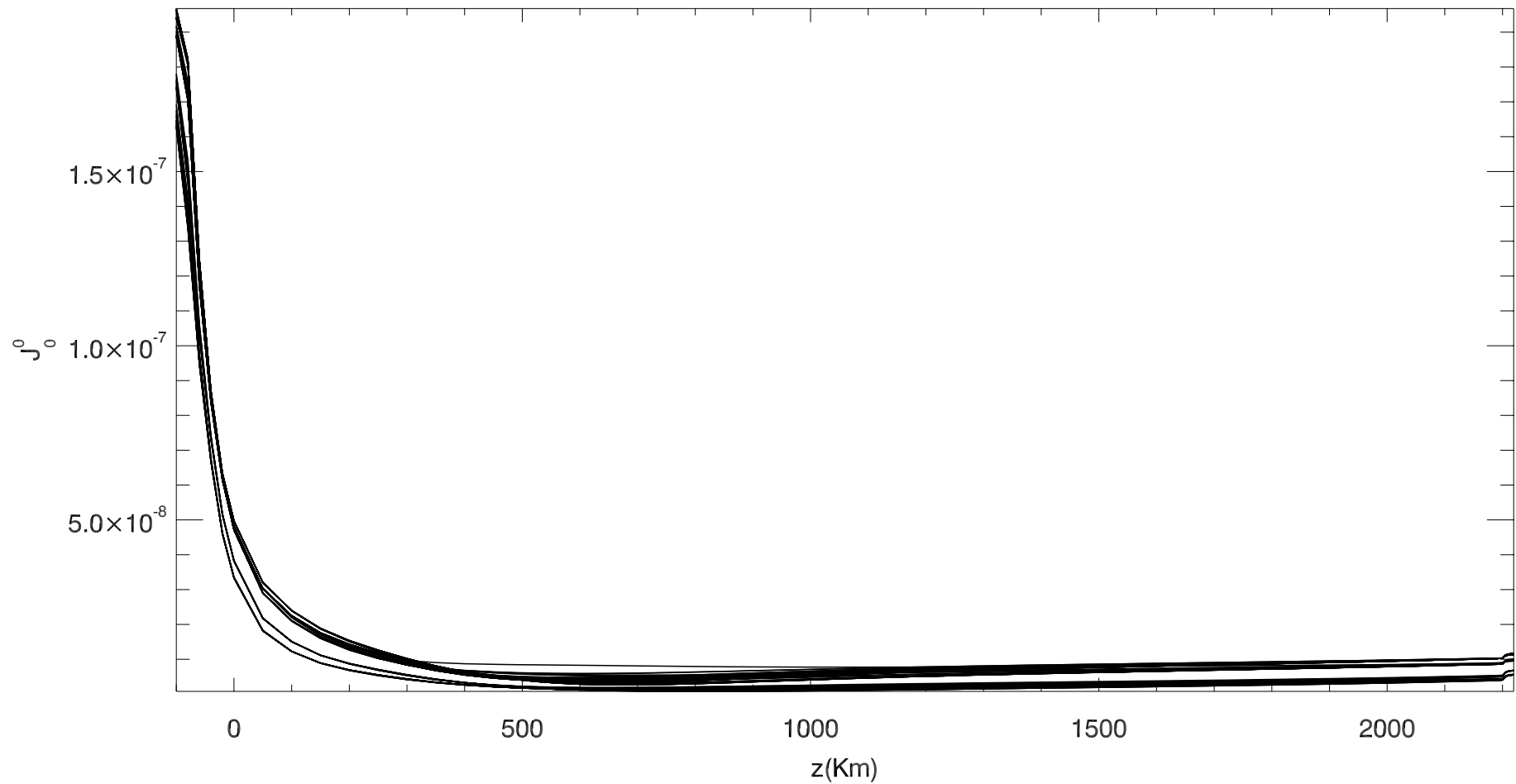
- The **Weak Anisotropy approximation is excellent** for modeling scattering polarization in the solar atmosphere.
- The flat spectrum approximation is not very good: **the spectral structure between the components of the lines is key for D1** (Belluzzi & Trujillo Bueno 2013).
- **D1 and D2 lines are a five-level problem** (in fact a 16 levels one!).
- The polarization of **the ground level is not very significant**, but the polarization of the **metastable levels is**.
- The D2 line and the triplet lines are very sensitive to the thermal structure.
- **More observations** of the Ba II triplet are needed!

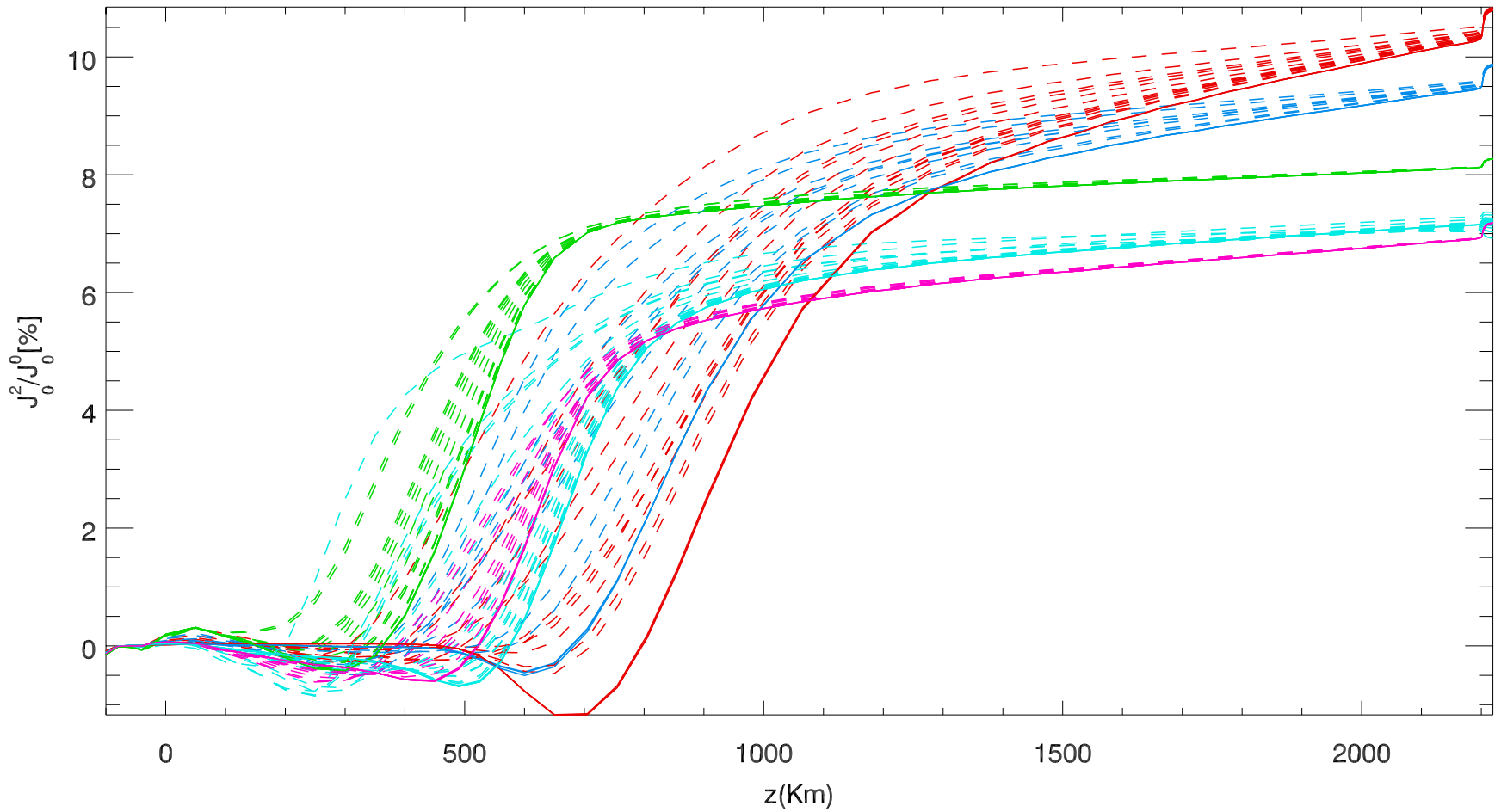
Thank You

Questions?

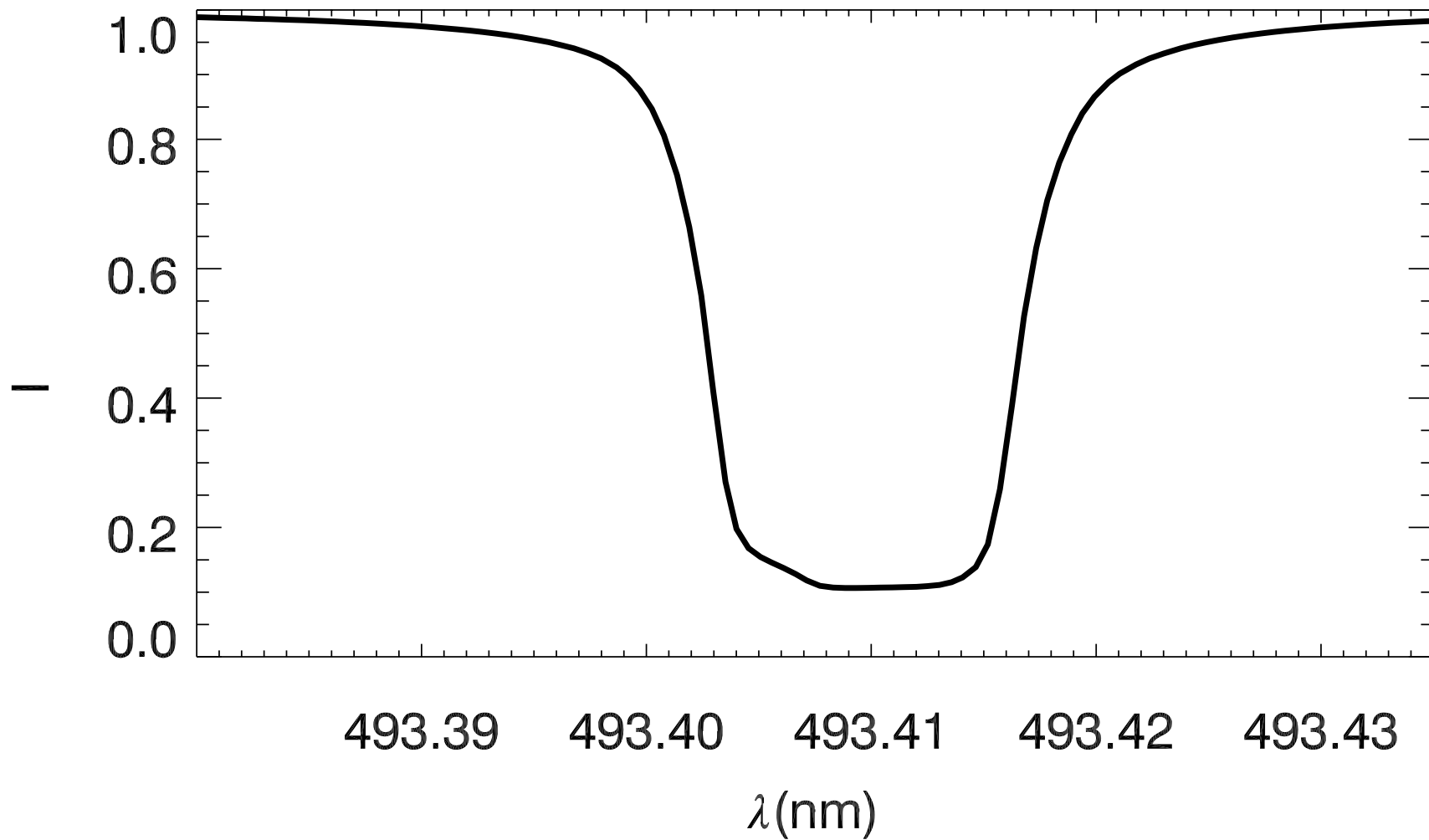






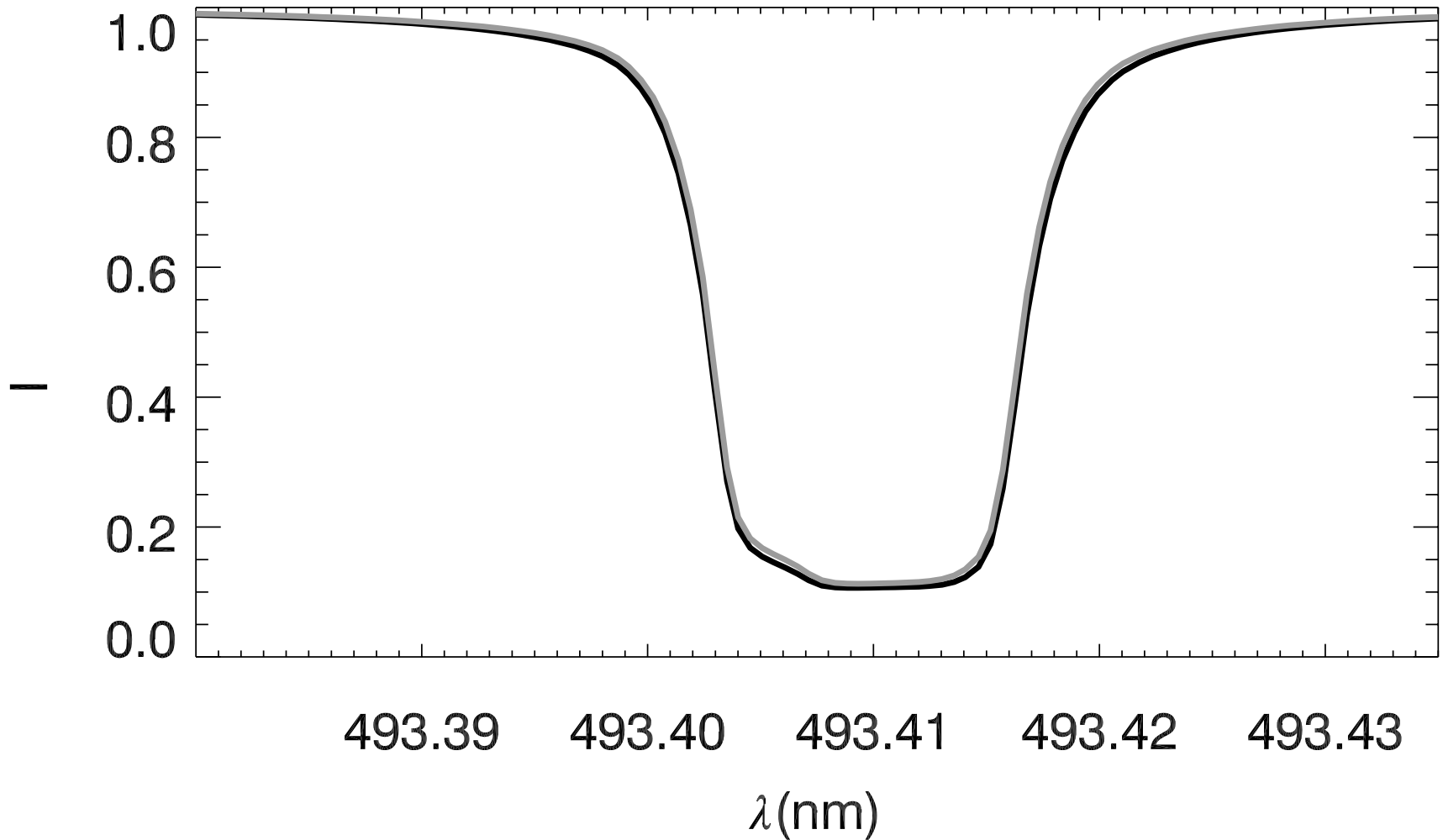


Ba II D1 Line



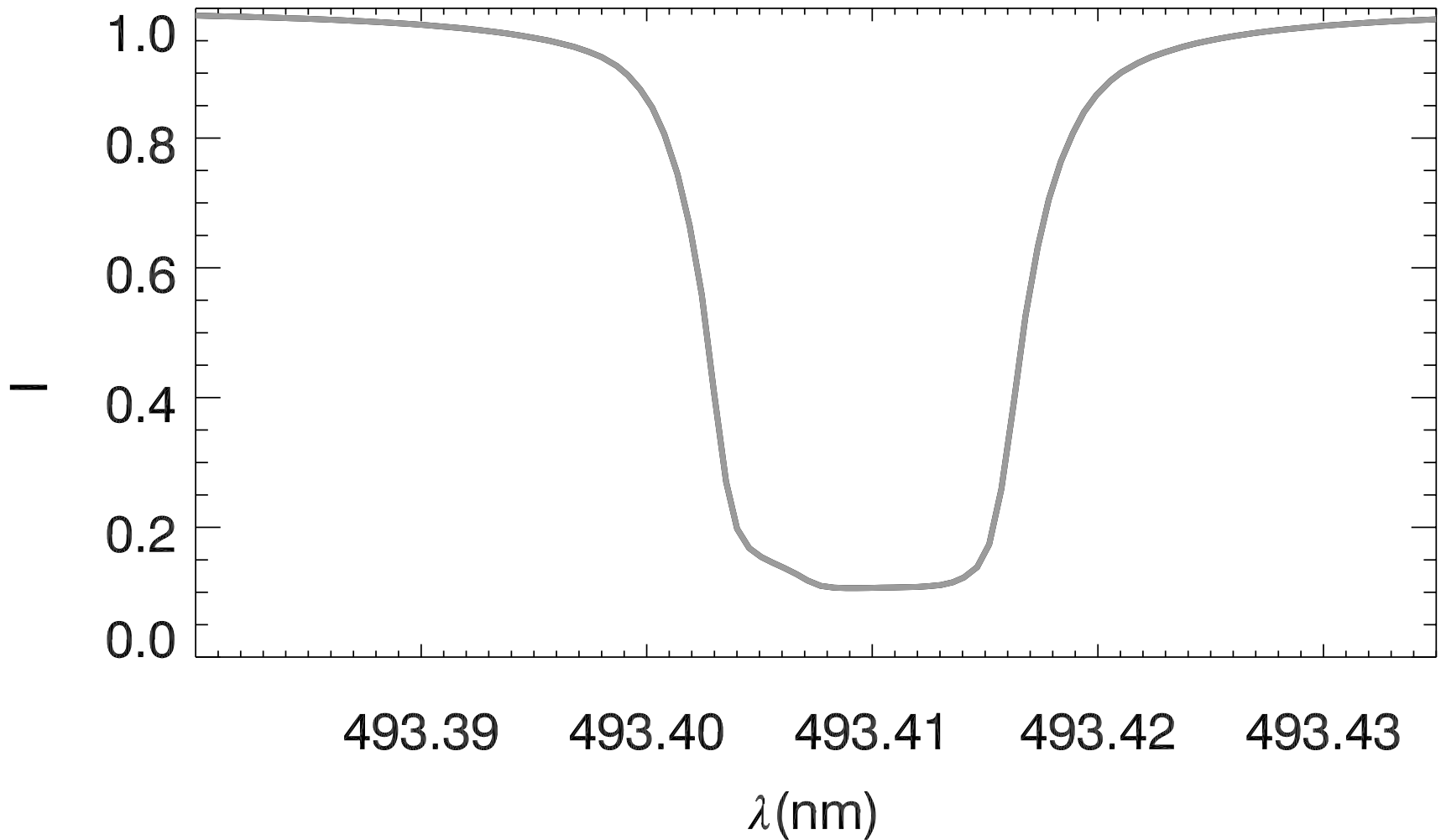
Ba II D1 Line

Metastable Levels



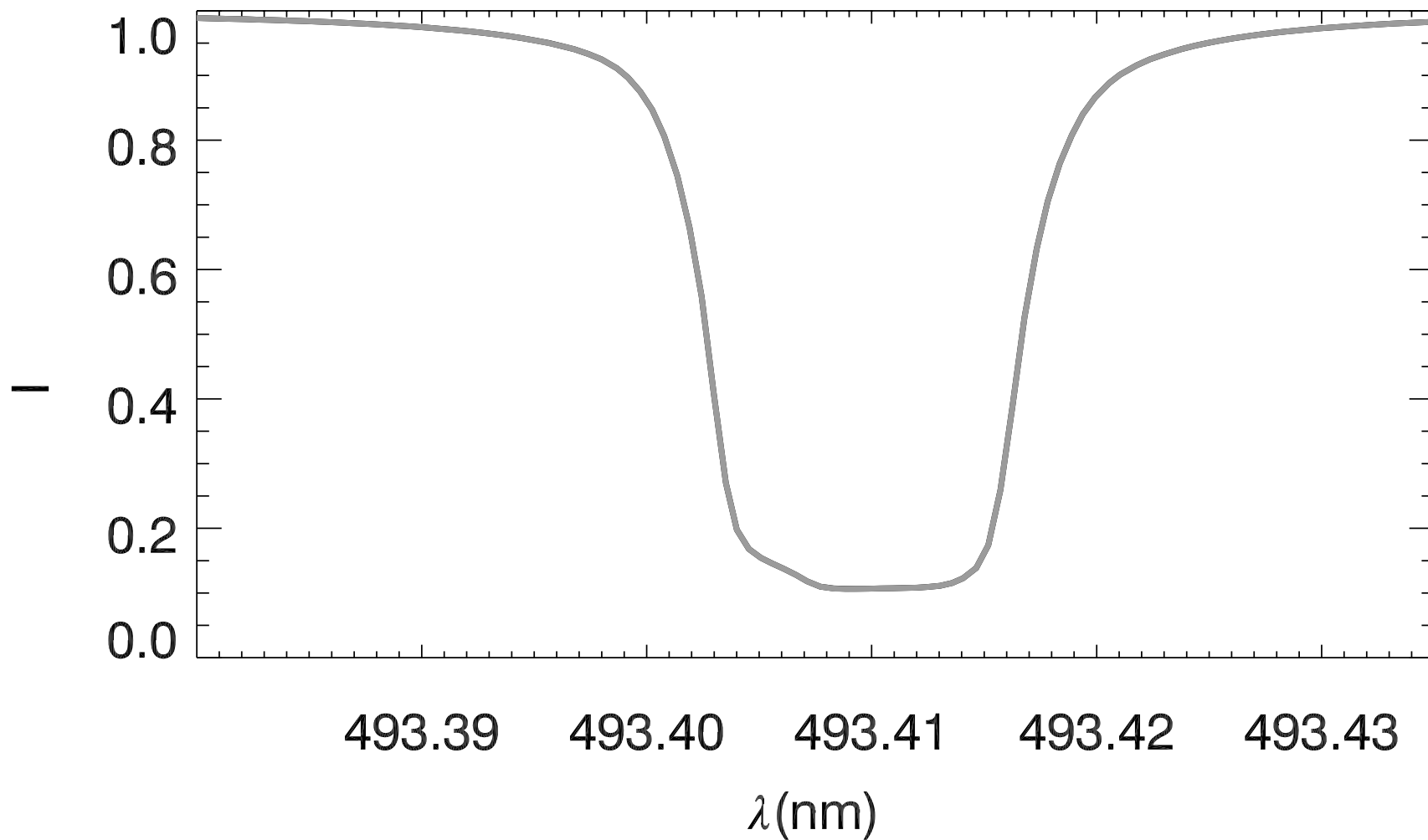
Ba II D1 Line

Ground Level Polarization



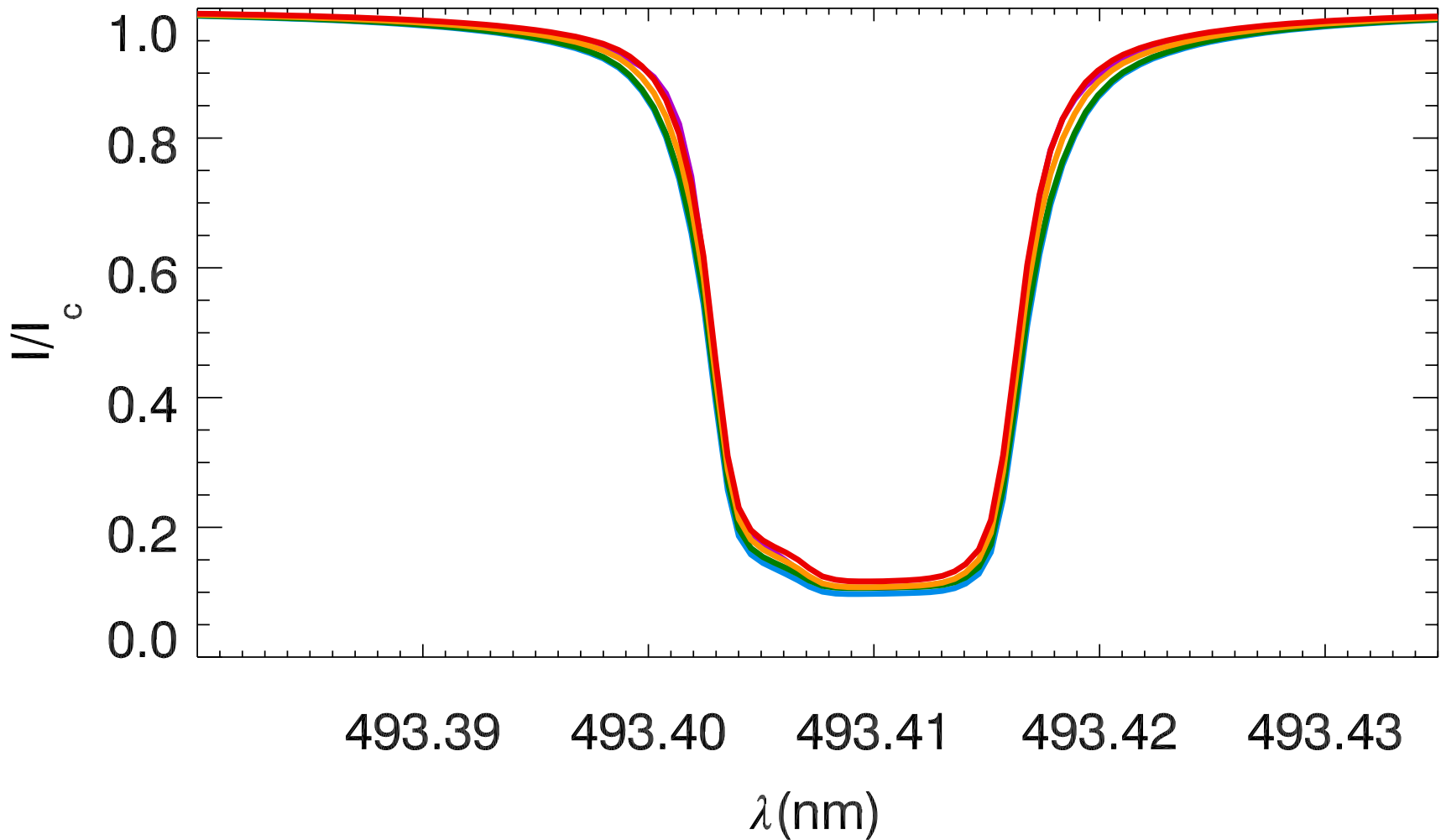
Ba II D1 Line

Lower Level Polarization

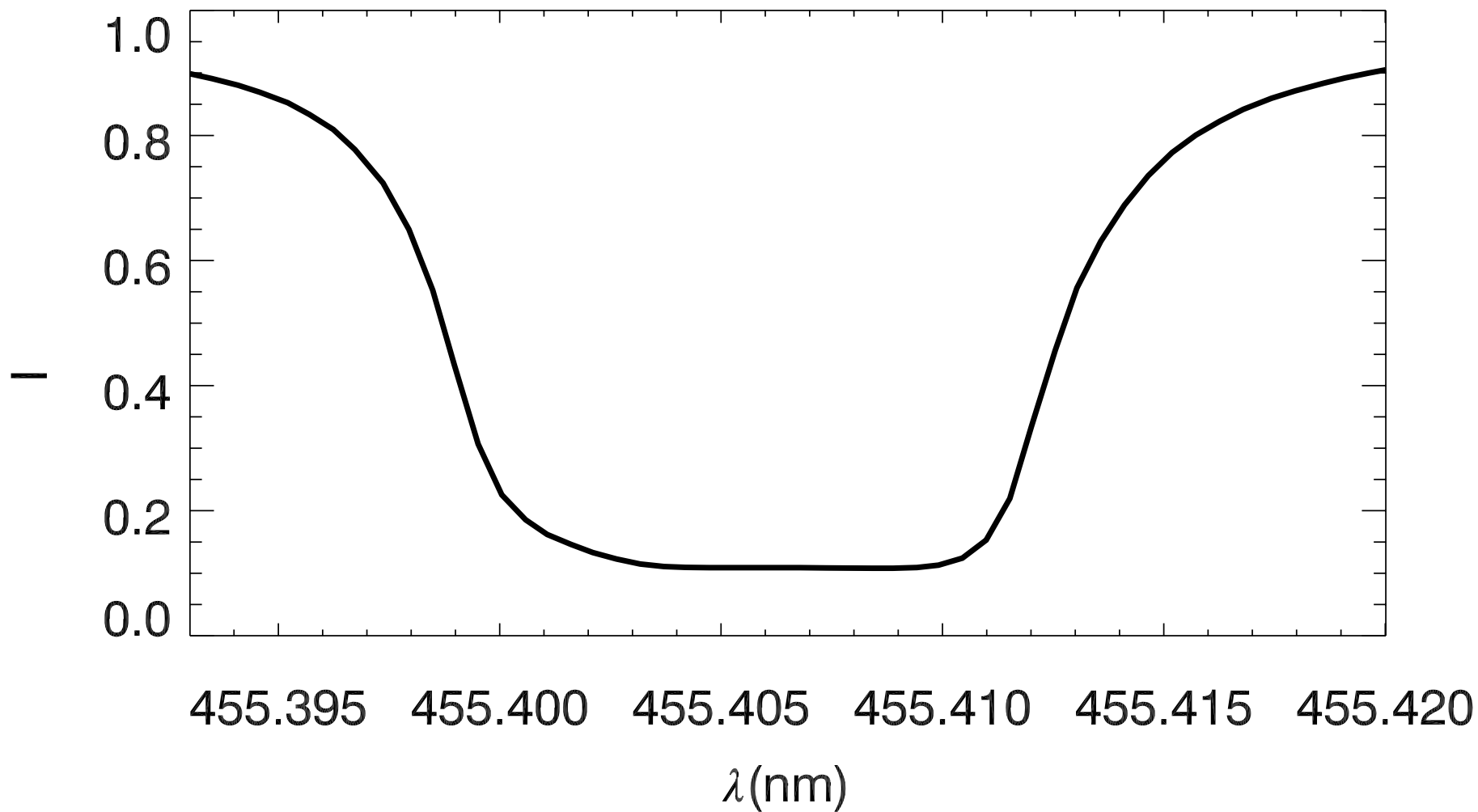


Ba II D1 Line

Model Sensitivity

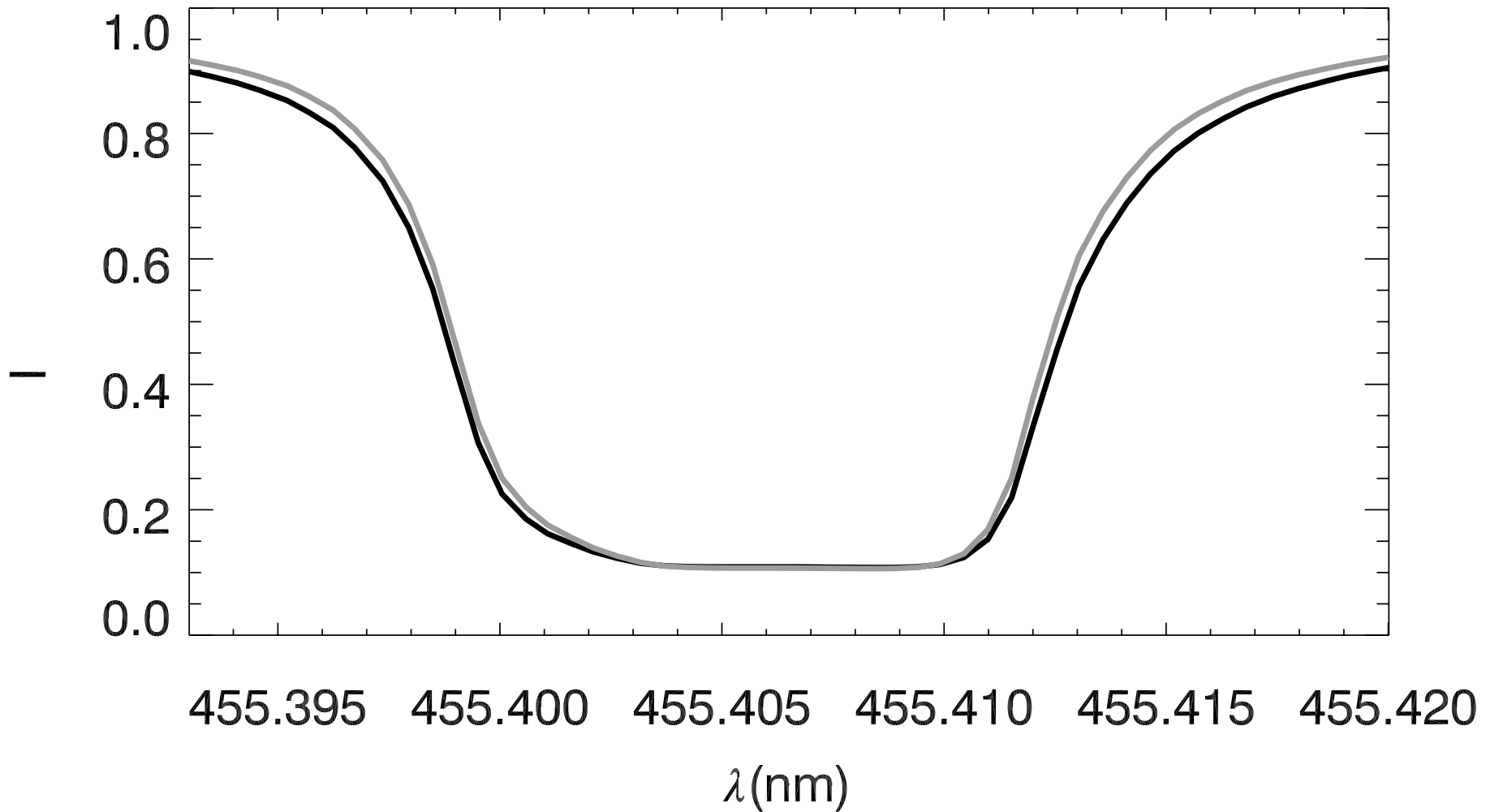


Ba II D2 Line



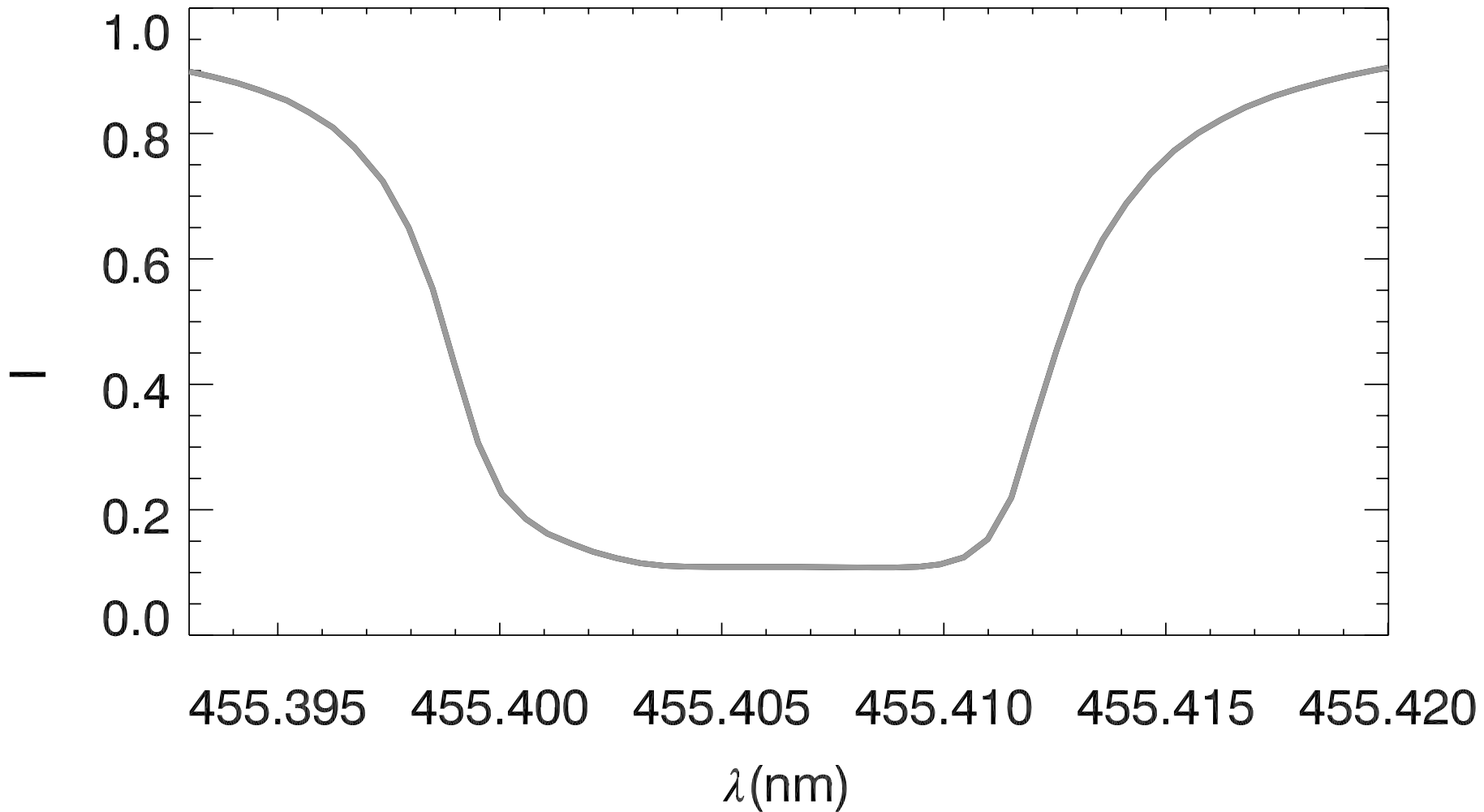
Ba II D2 Line

Metastable Levels



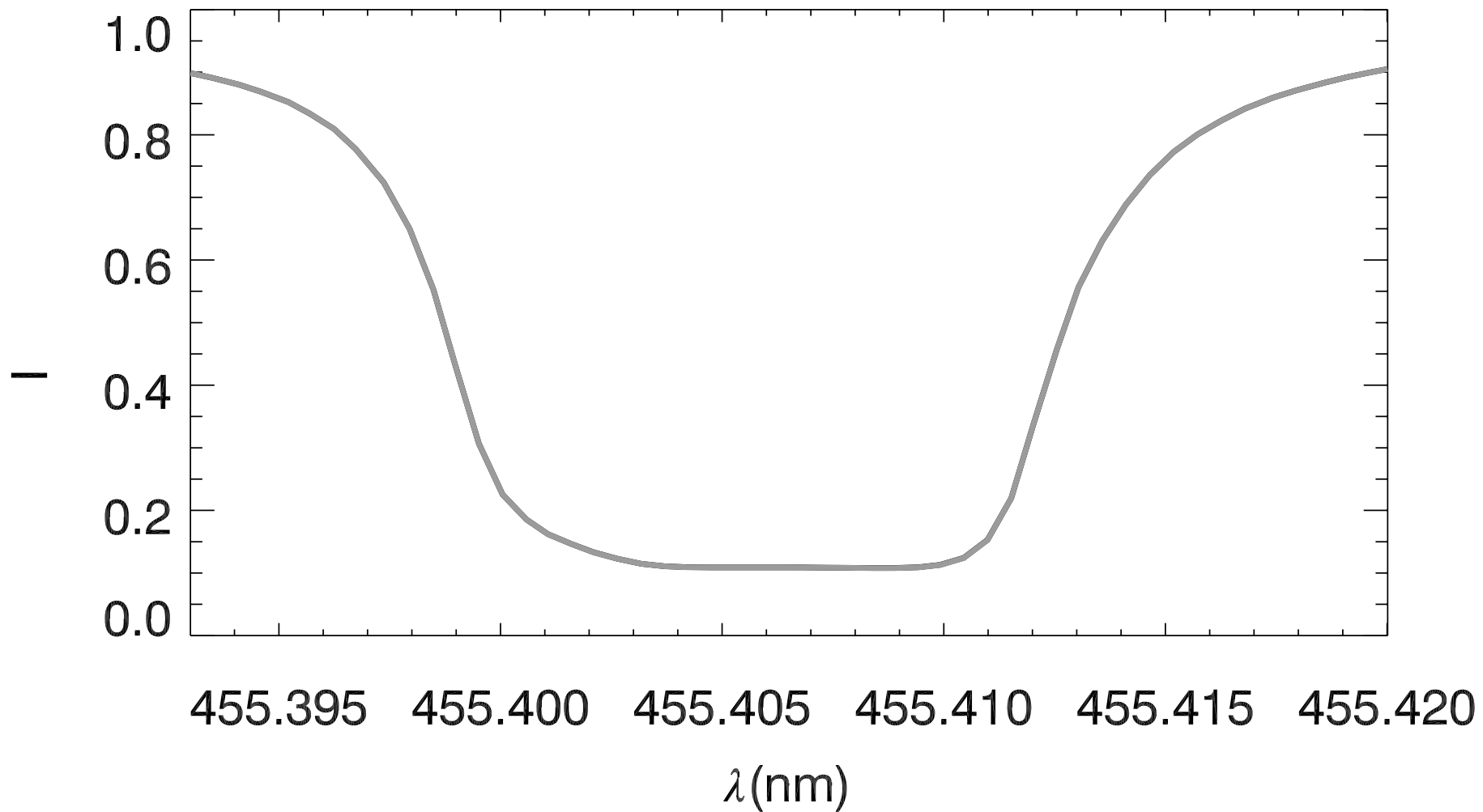
Ba II D2 Line

Ground Level Polarization



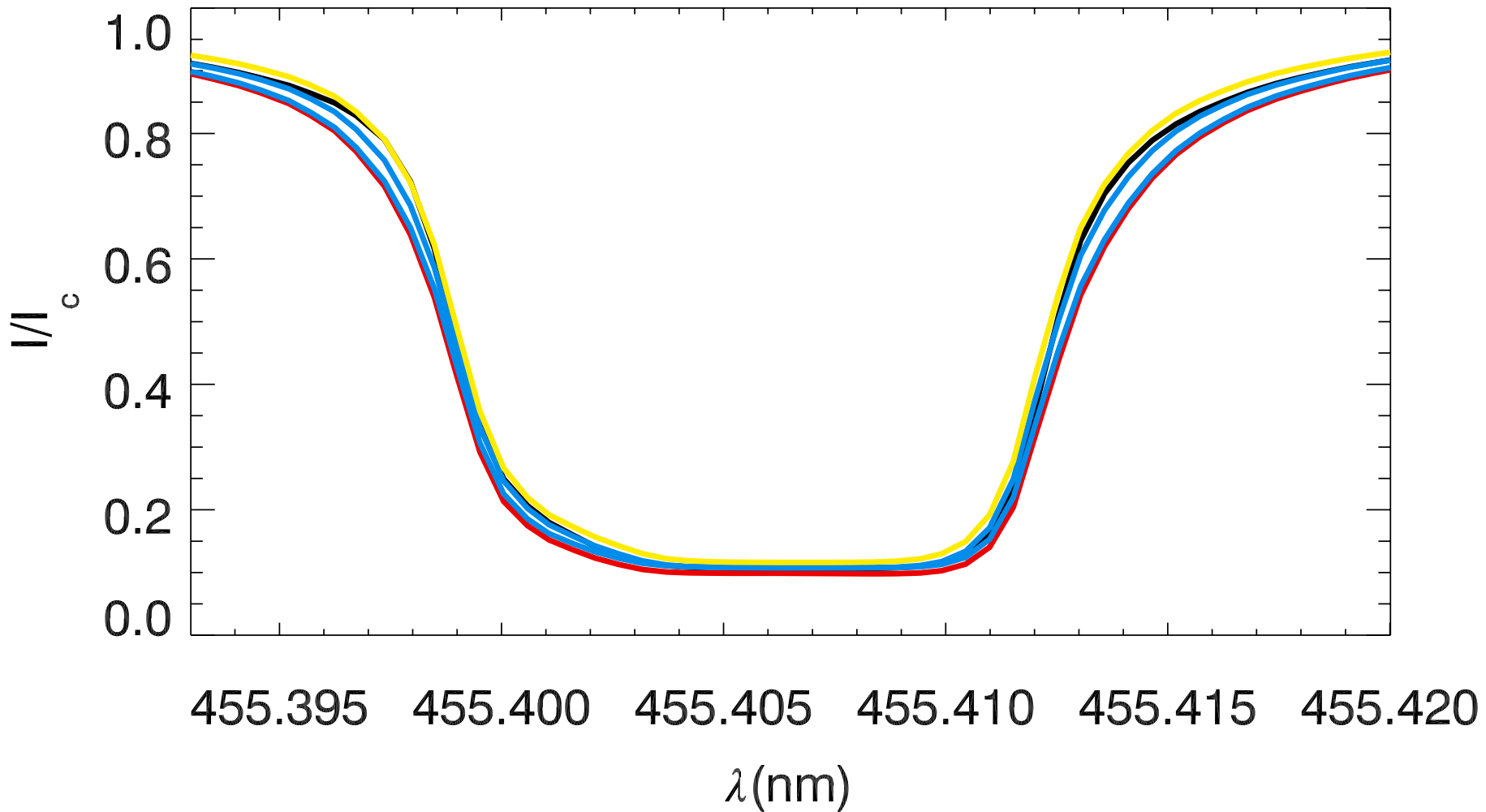
Ba II D2 Line

Lower Level Polarization

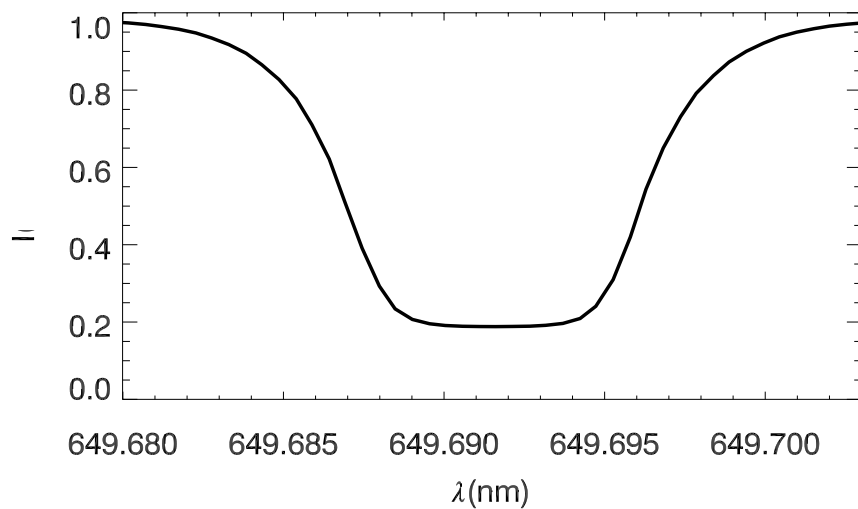
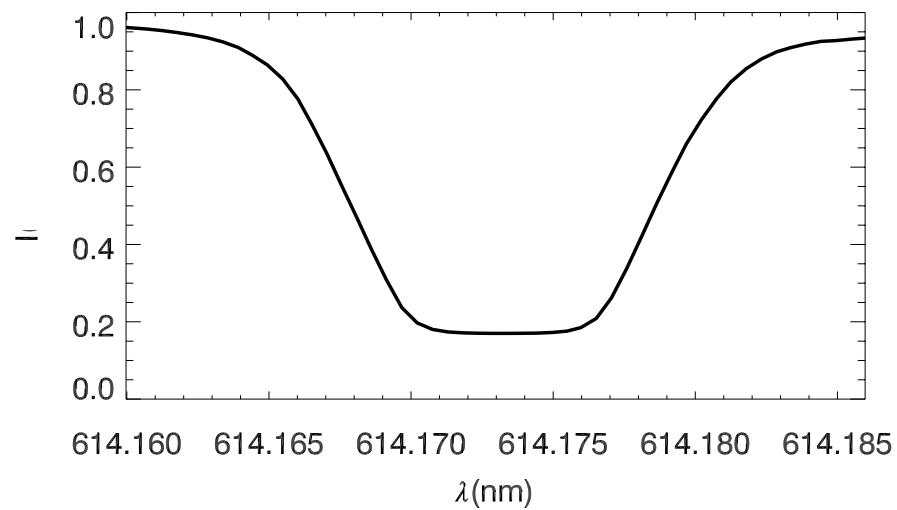
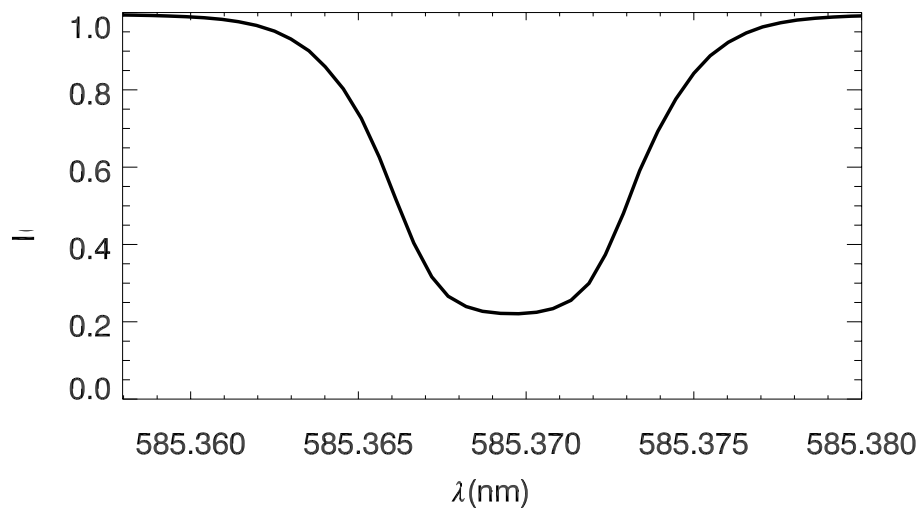


Ba II D2 Line

Model Sensitivity

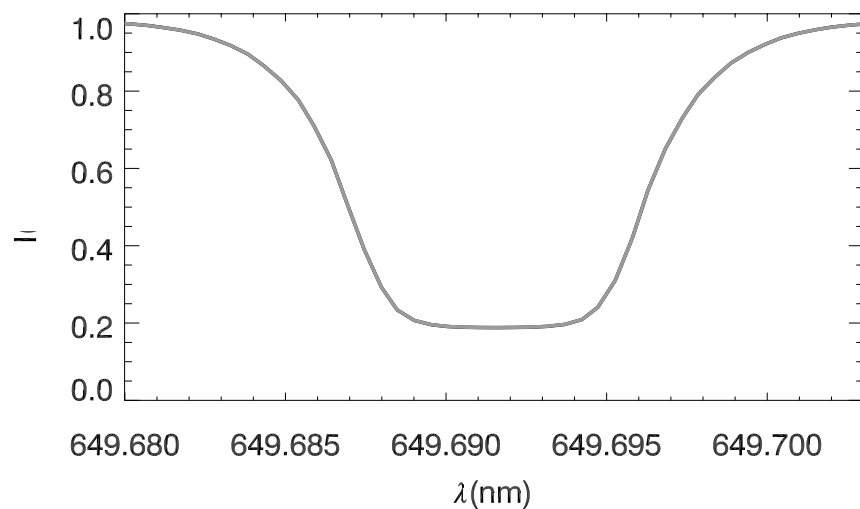
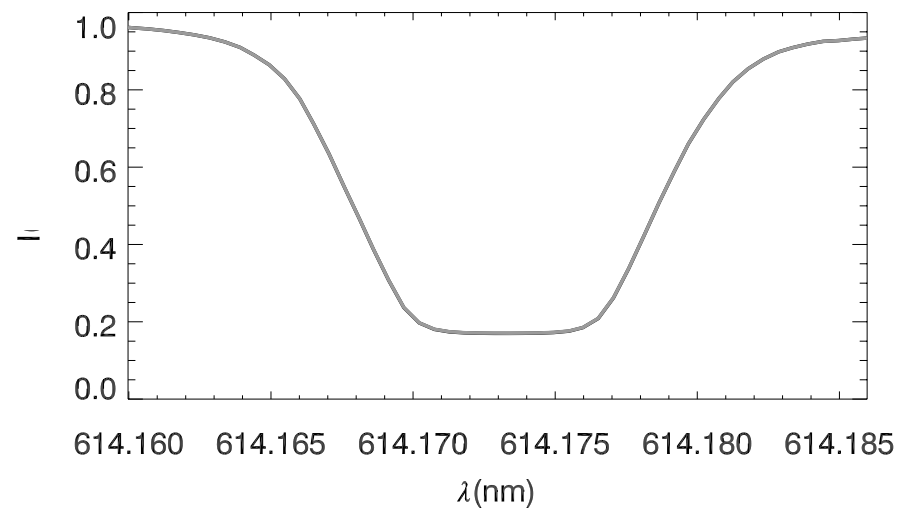
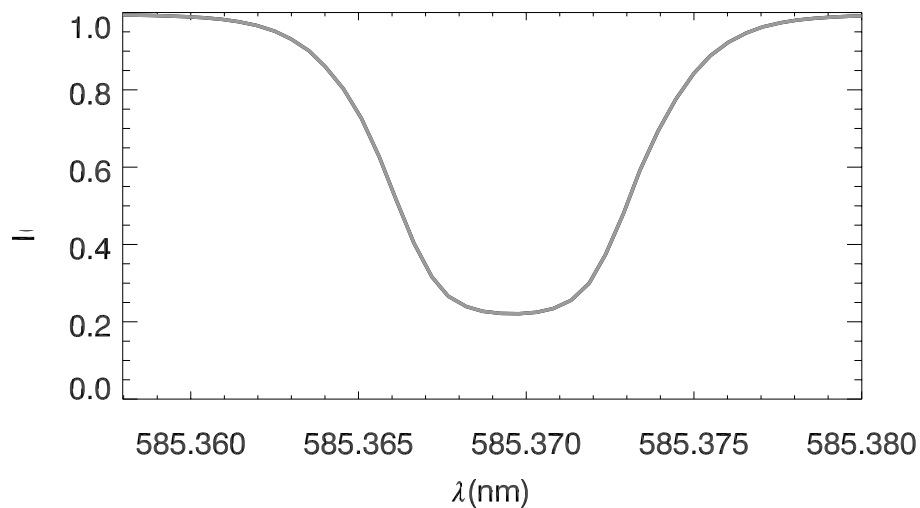


Ba II Triplet



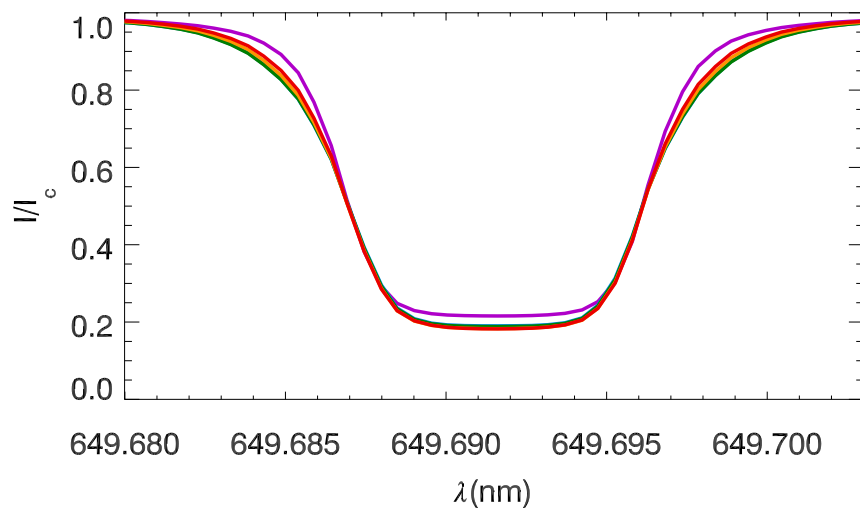
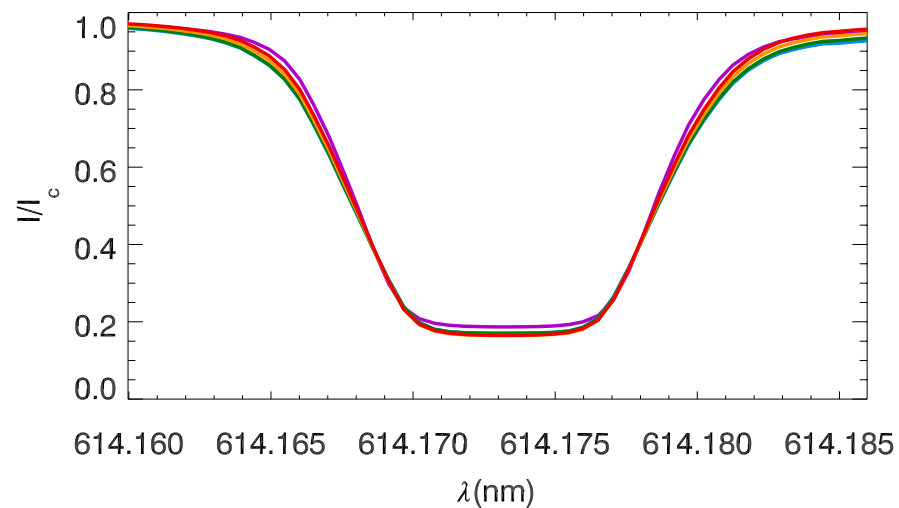
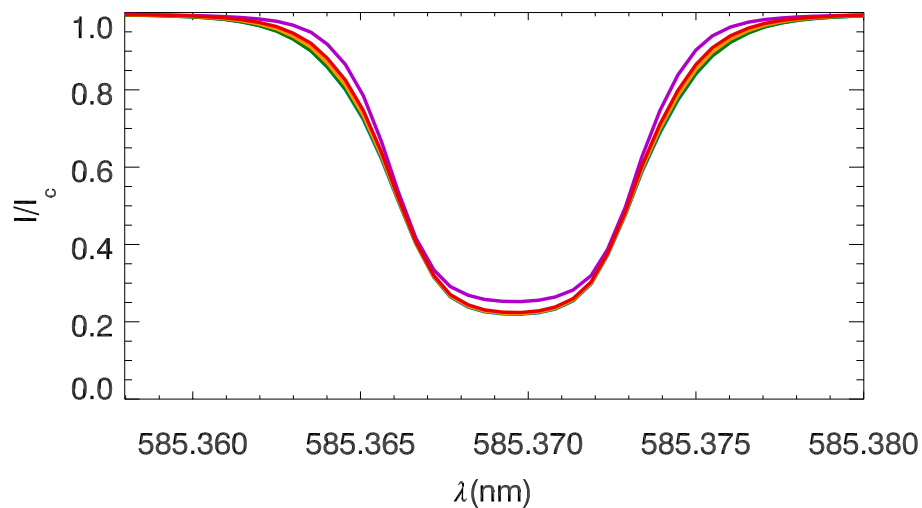
Ba II Triplet

Lower Level Polarization



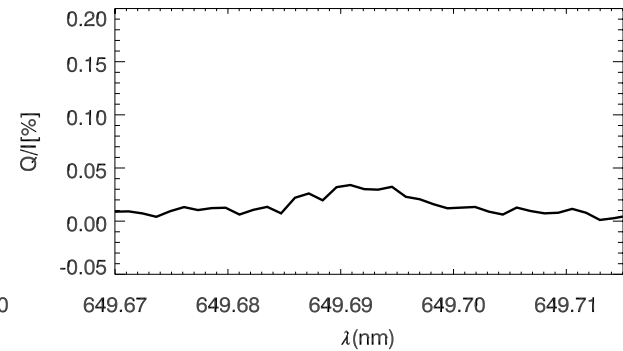
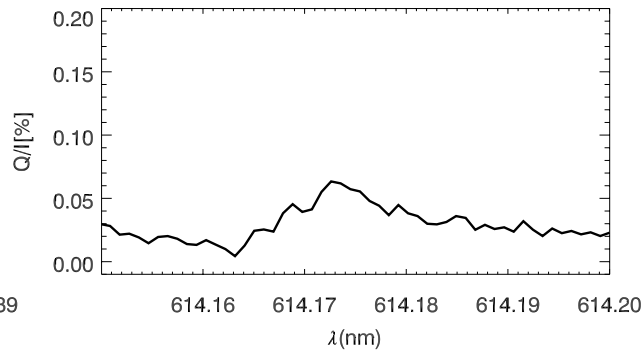
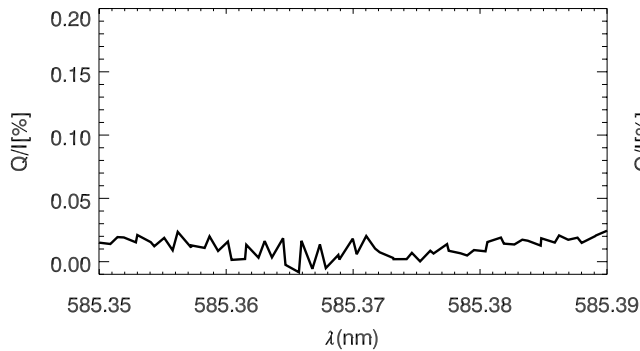
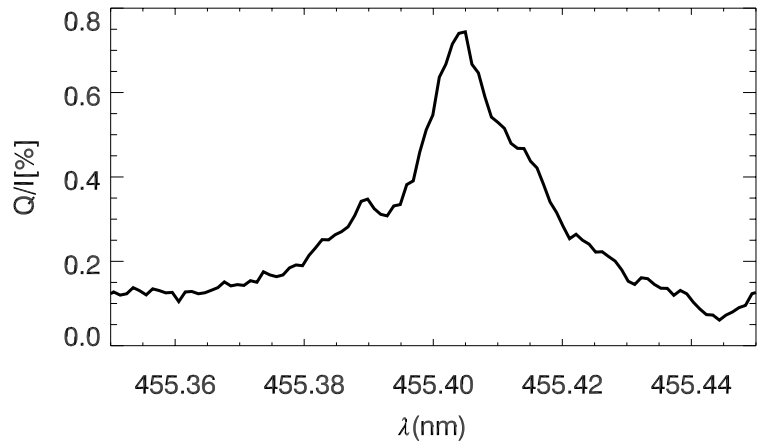
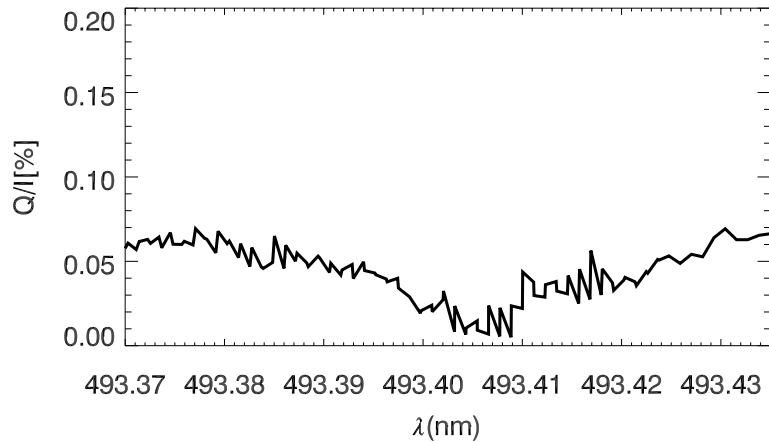
Ba II Triplet

Model Sensitivity



Application to Ba II

Observations during maximum of solar cycle



Gandorfer (2000, 2002, 2005)

Scattering Polarization

- Diagnosis tool. Magnetic field.
- Extract the information encoded in the Stokes parameters.
- To predict the profile of a spectral line of a complex atom.
- Complex problem (Non-linear, Non-local, polarized)
→ numerical methods
- Solve at the same time the Radiation Transfer and the Statistical Equilibrium Equations (SEE).

Conclusions

- The Weak Anisotropy approximation is excellent for the solar atmosphere.
- The mechanism pointed out by Belluzzi & Trujillo Bueno (2013) plays indeed a key role on the linear polarization of the D1 line of Ba II.
- D1 and D2 lines are a five levels problem.
- The polarization of the ground level is not very significant, but the polarization of the metastable levels is very important.
- The D2 line and the triplet lines are very sensitive to the thermal structure.
- In collaboration with our IRSOL colleagues we will obtain new spectropolarimetric observations, especially in the D1 and triplet lines of Ba II.