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A new tool for investigating the magnetism of the solar chromosphere

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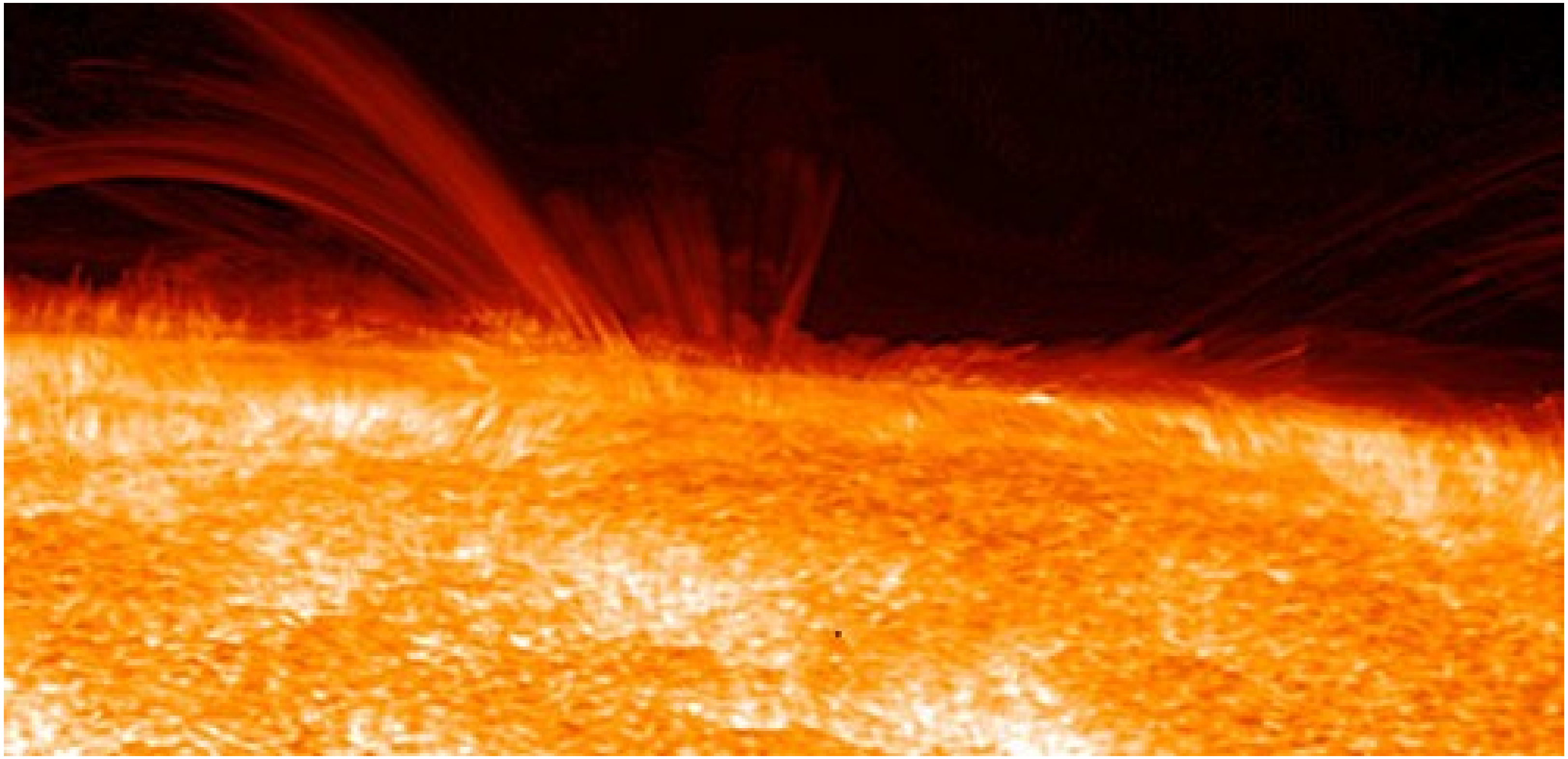
Windisch, May 15-16, 2023

Outline

- Introduction
- Computational challenges
- Solution strategy
- First tests

Introduction

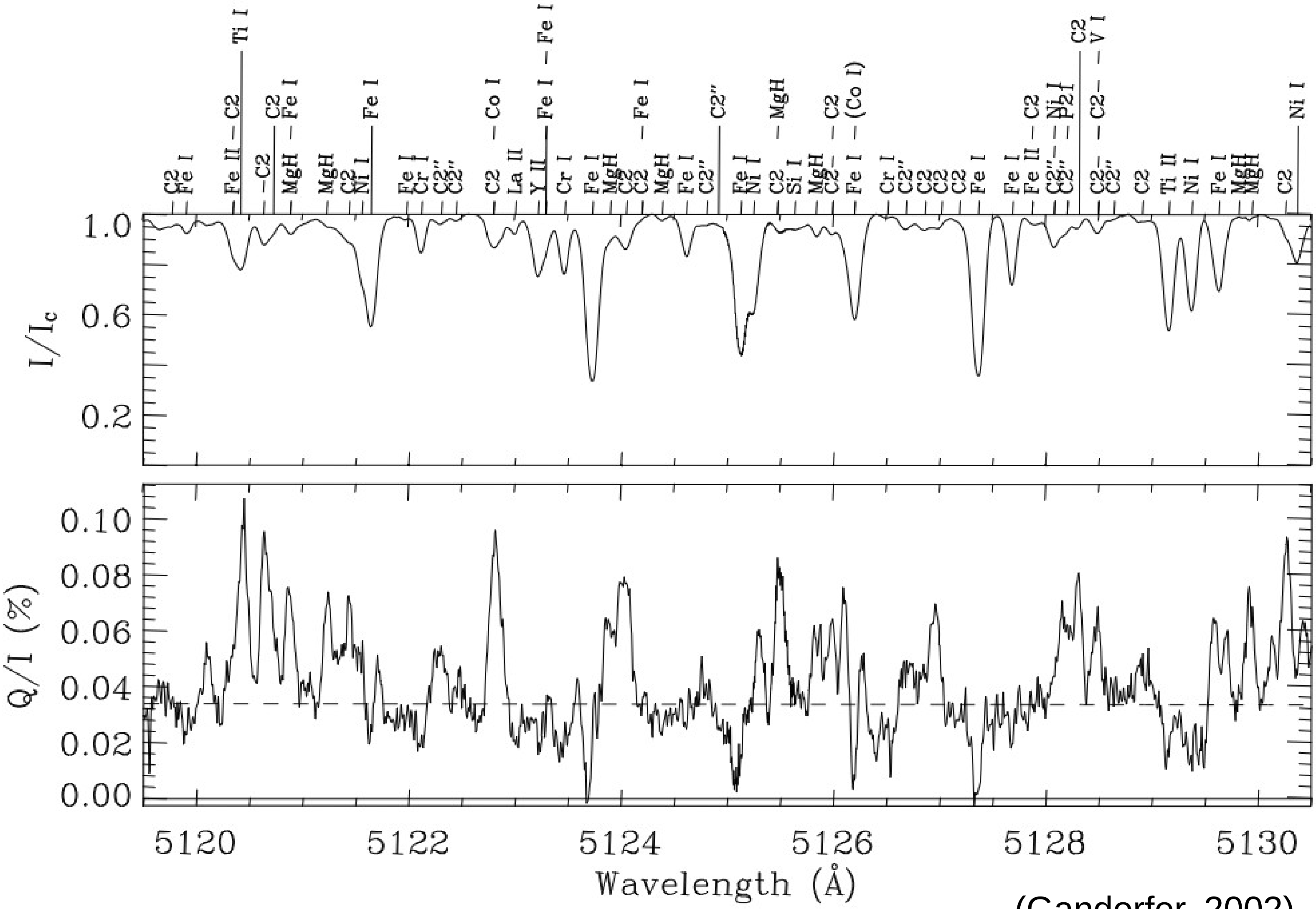
Scientific goal: infer new information on chromospheric magnetic fields



Hinode JAXA/NASA

Introduction

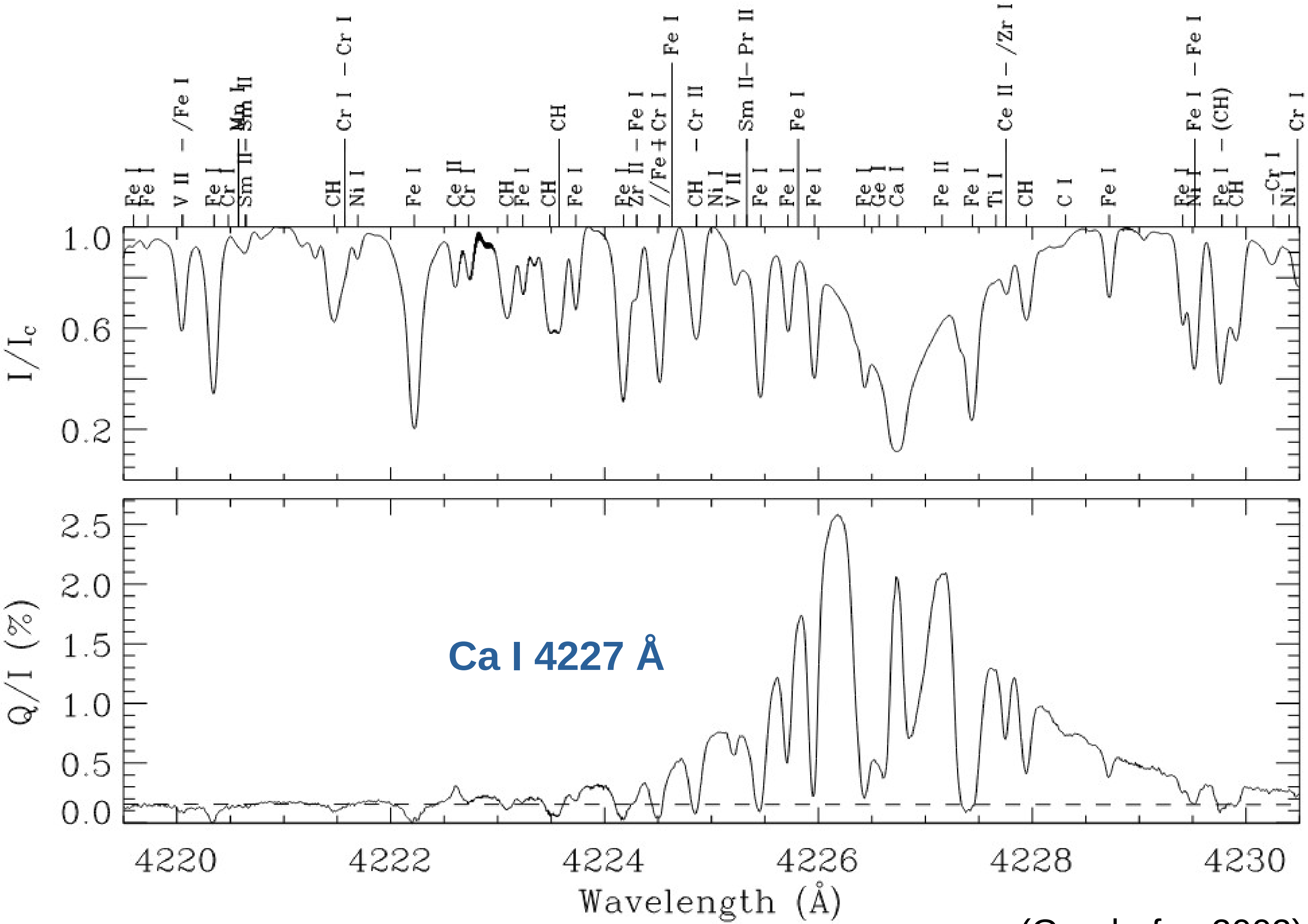
Zeeman effect + magnetic sensitivity of scattering polarization



(Gandorfer, 2002)

Introduction

Zeeman effect + magnetic sensitivity of scattering polarization

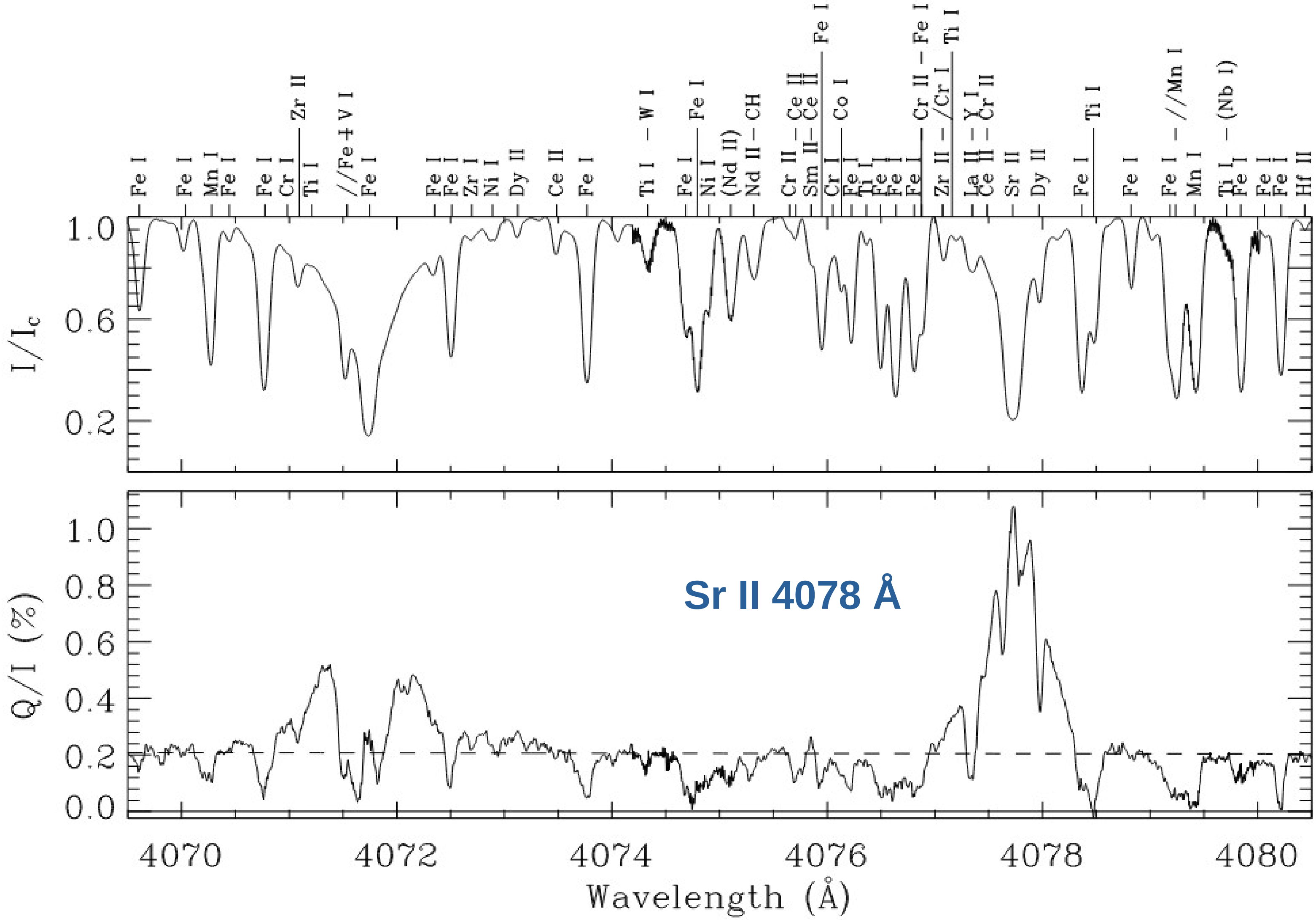


Ca I 4227 Å

(Gandorfer, 2002)

Introduction

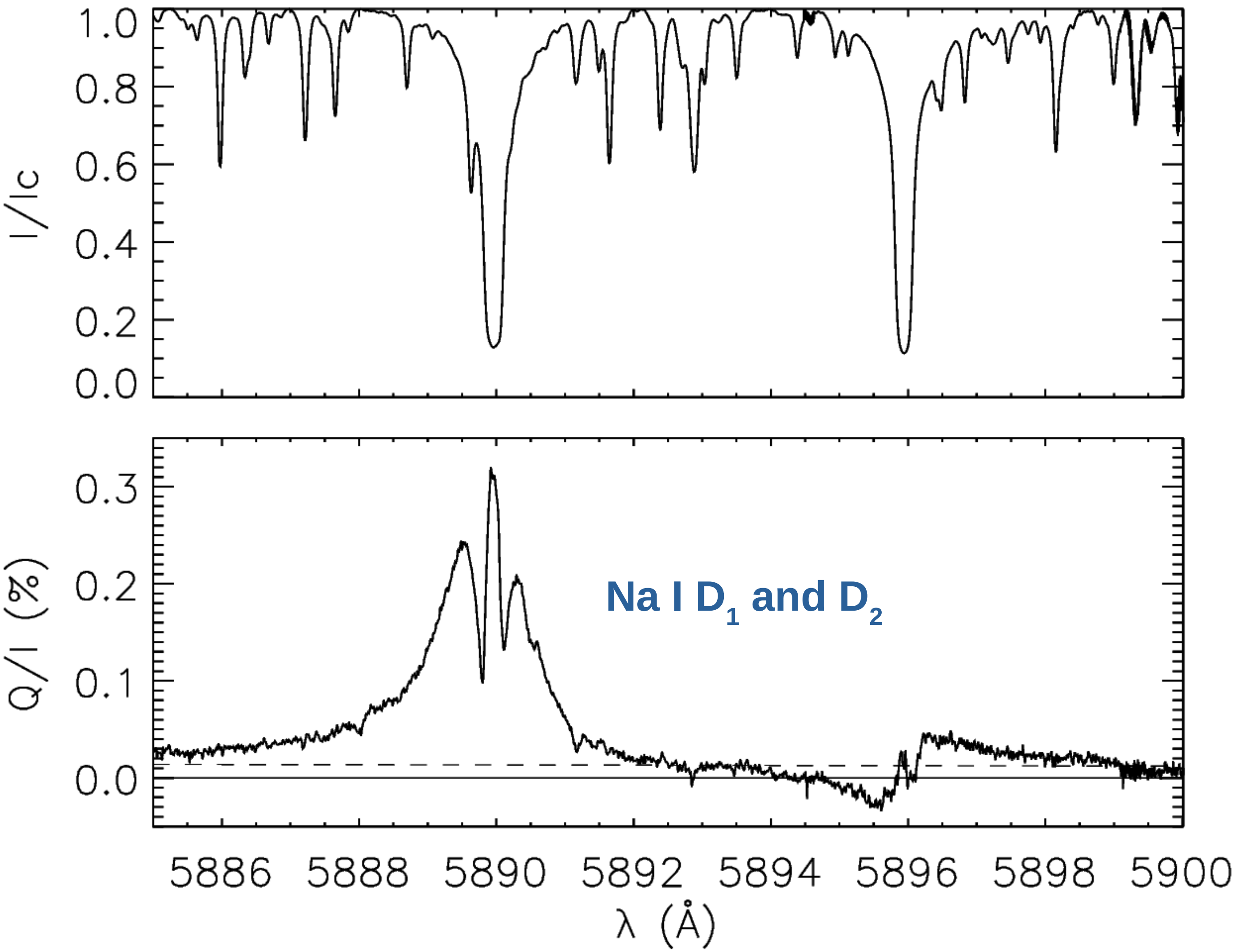
Zeeman effect + magnetic sensitivity of scattering polarization



(Gandorfer, 2002)

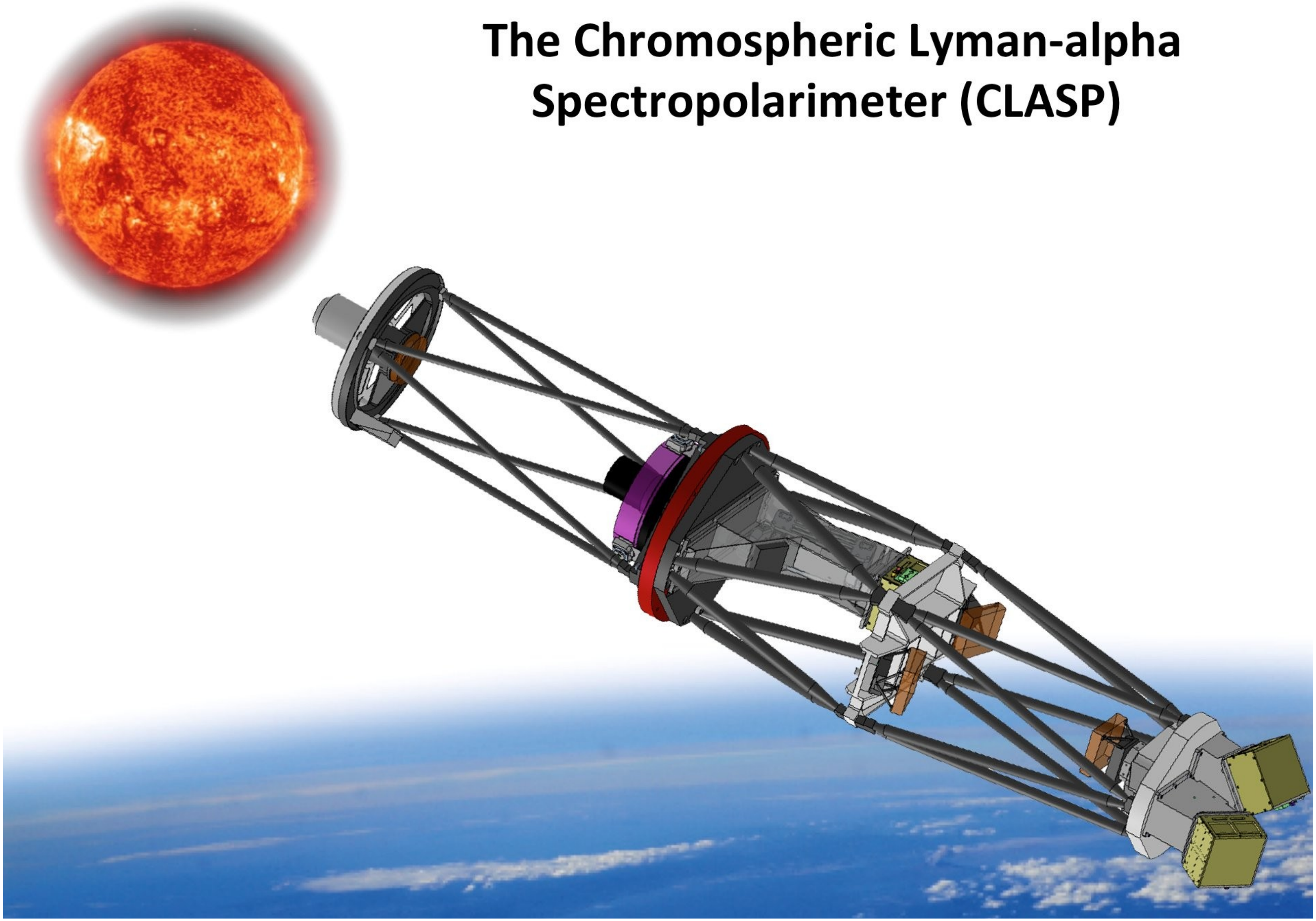
Introduction

Zeeman effect + magnetic sensitivity of scattering polarization



(Gandorfer, 2002)

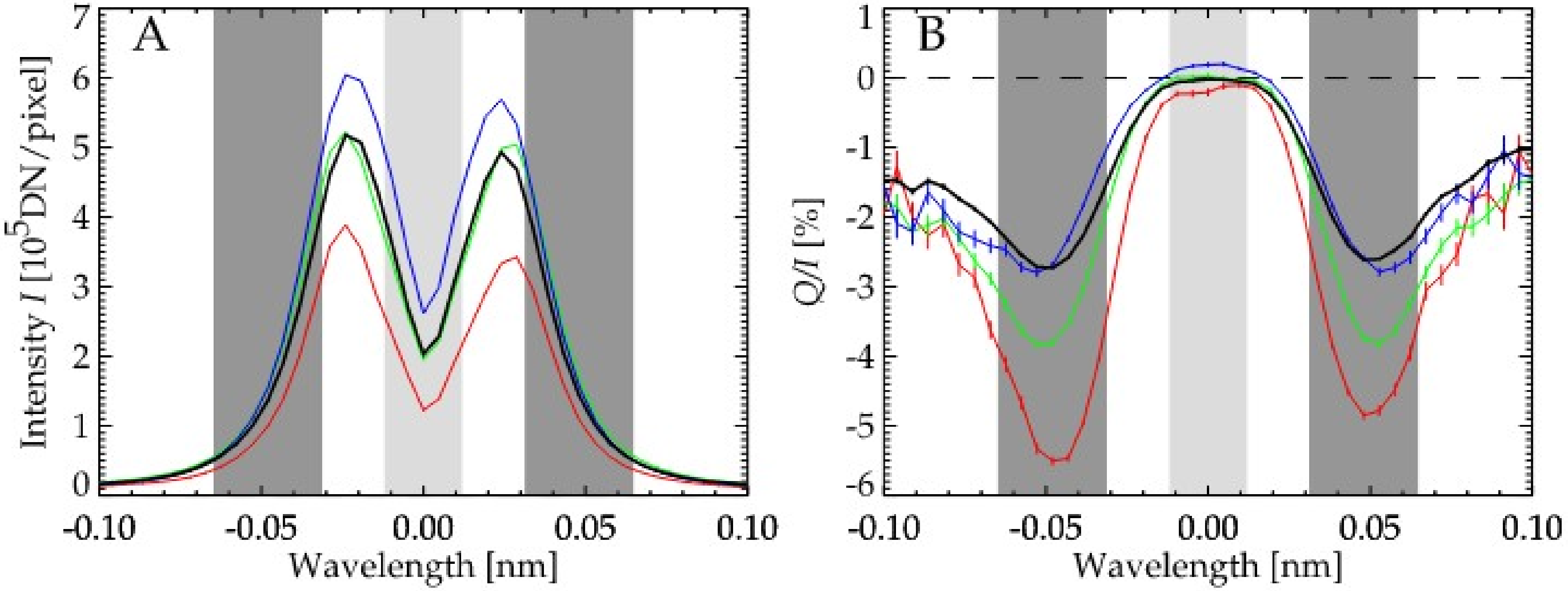
Introduction



The Chromospheric Lyman-alpha Spectropolarimeter (CLASP)

Introduction

H I Ly-α 1215 Å

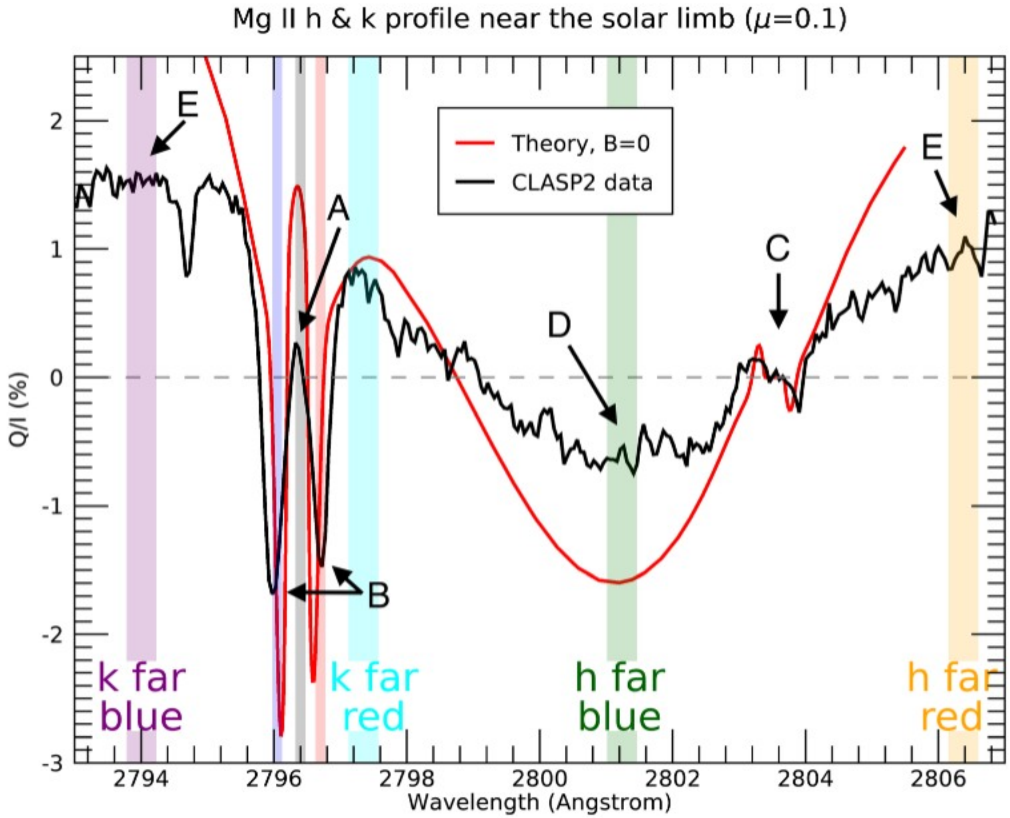


CLASP sounding rocket experiment (2015)

(Kano et al. 2017)

Introduction

Mg II h & k 2800 Å

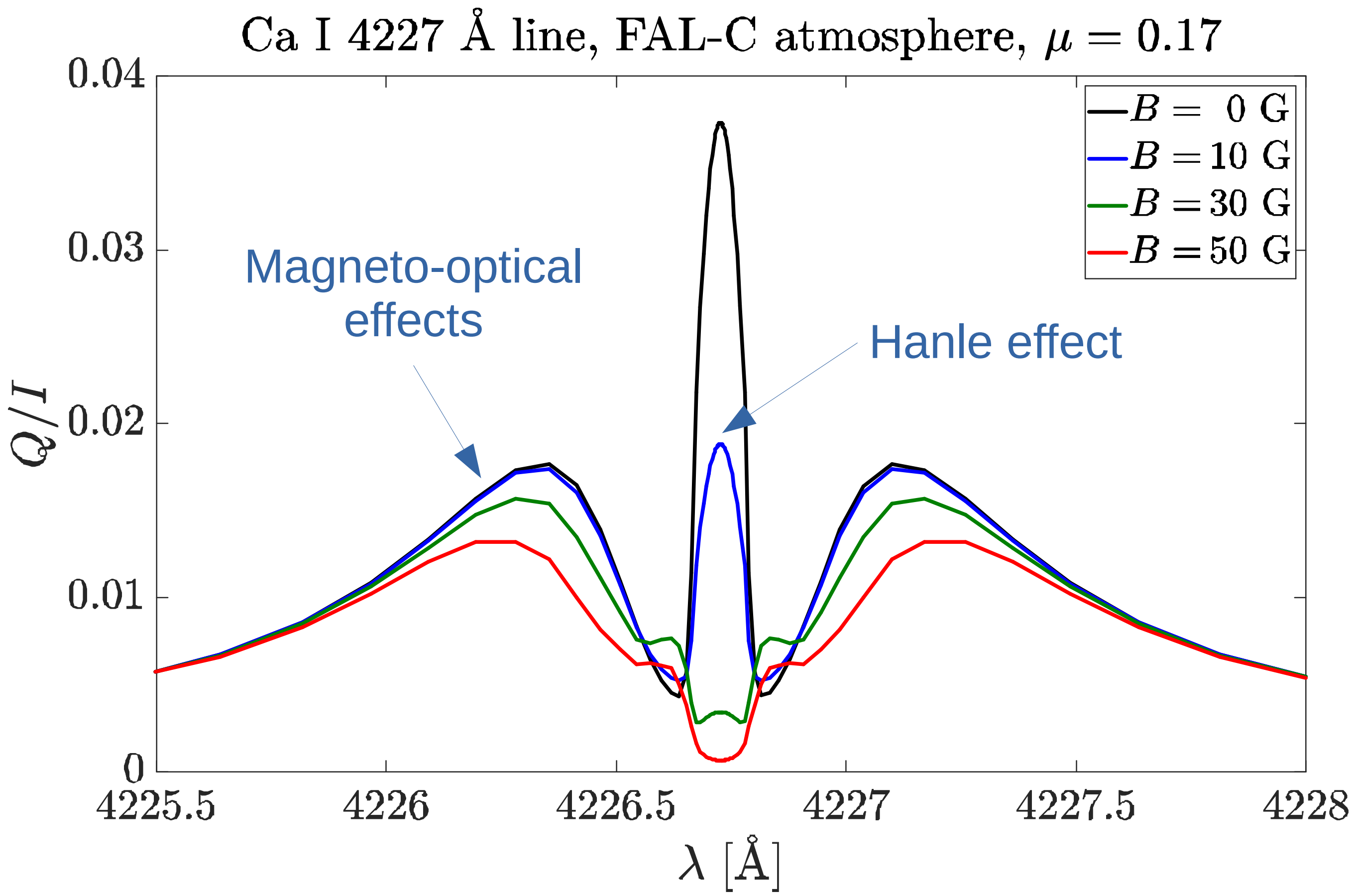


CLASP2 (2019) & CLASP2.1 (2021)

(Rachmeler et al. 2022)

Introduction

Hanle and magneto-optical effects

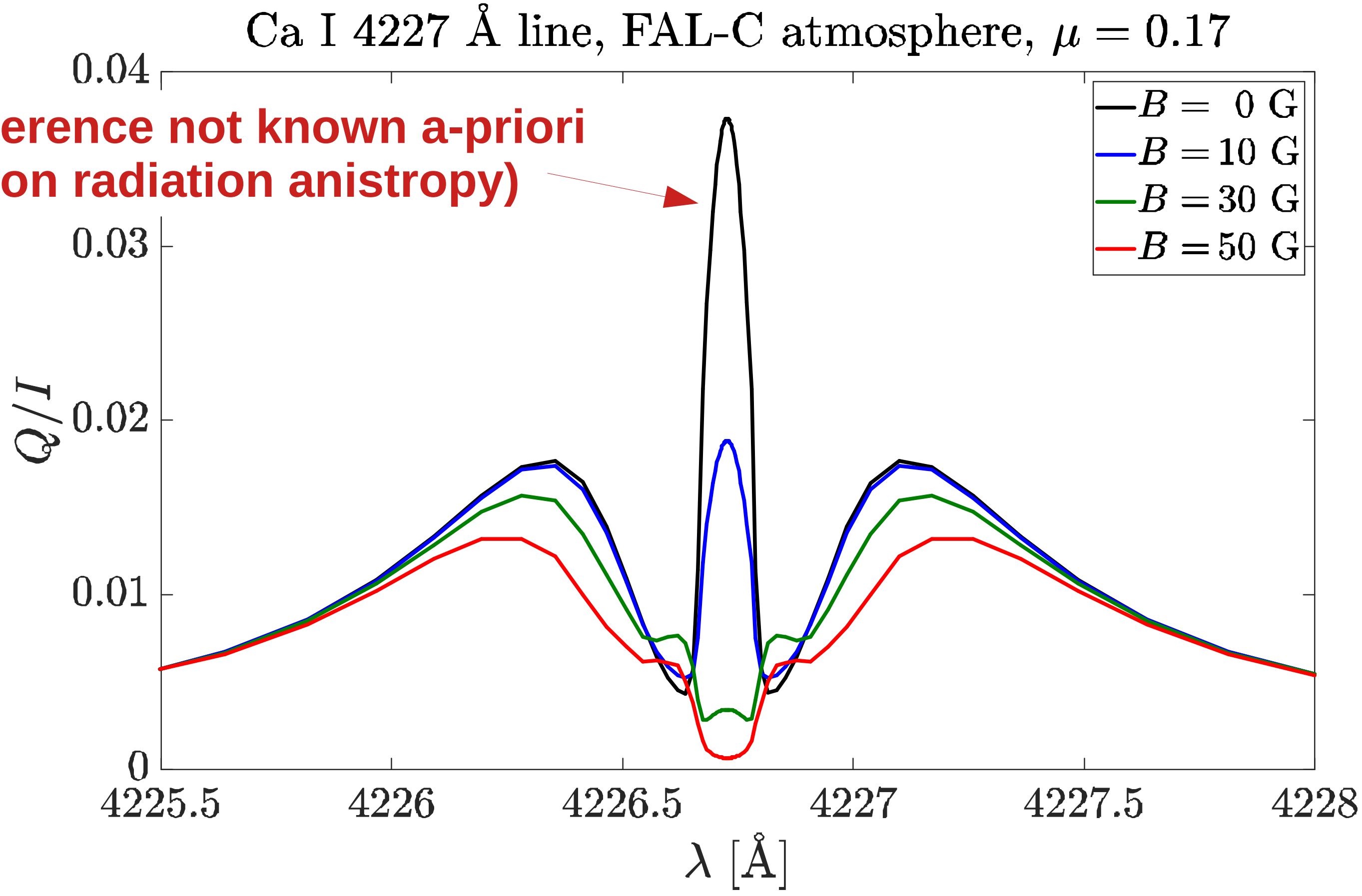


Magneto-optical effects

Hanle effect

Introduction

Hanle and magneto-optical effects



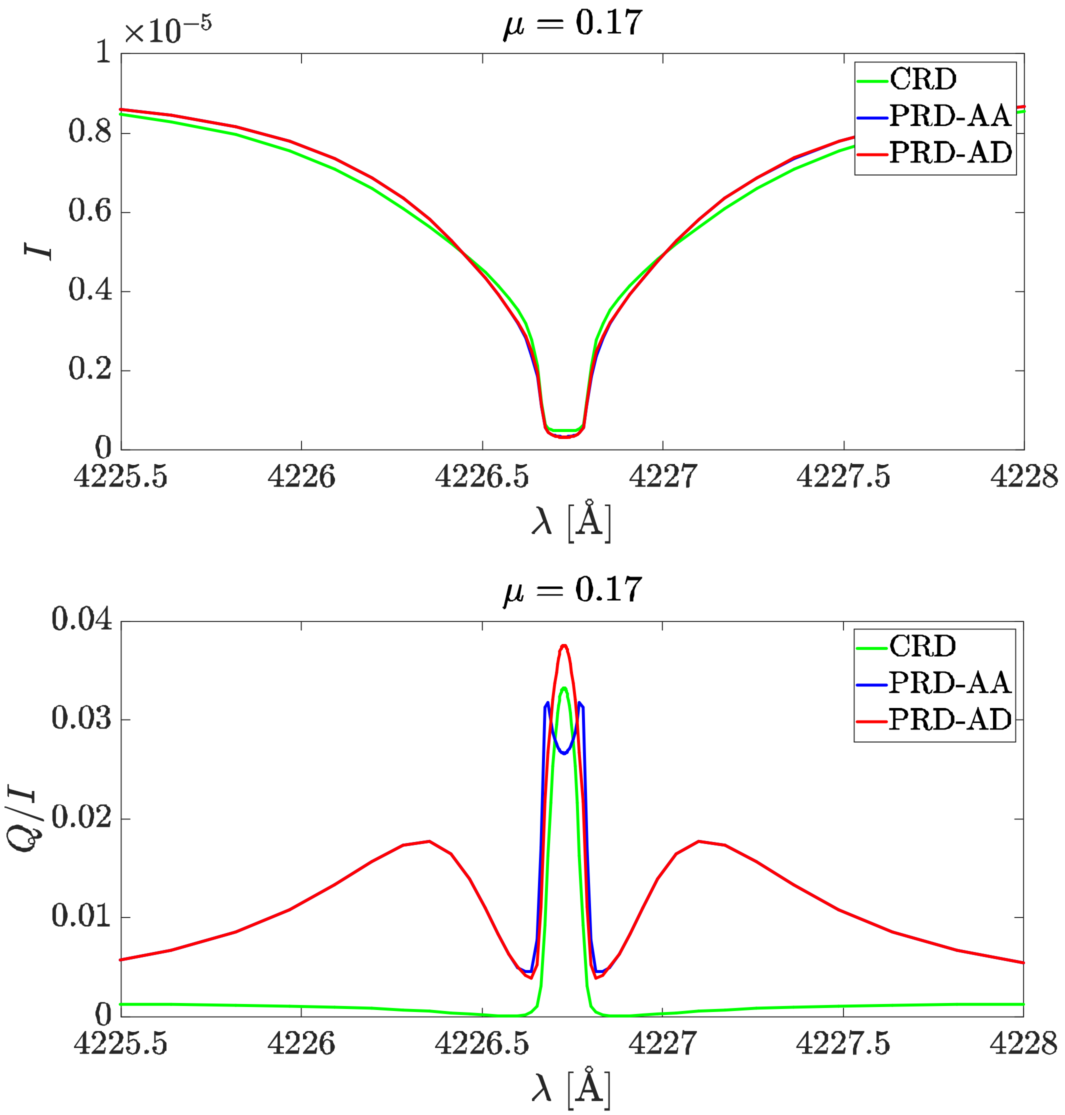
Zero-field reference not known a-priori (depends on radiation anistropy)

Approaches:

- **Differential Hanle effect (e.g., with molecular lines)**
- **Synthetic reference form realistic 3D models of the solar atmosphere**
  (e.g., PORTA code by Stepan & Trujillo Bueno 2013)

Introduction

Importance of PRD effects



CaI 4227 Å line

Run times

CRD: ~ 10 s

PRD: ~ 1 hour

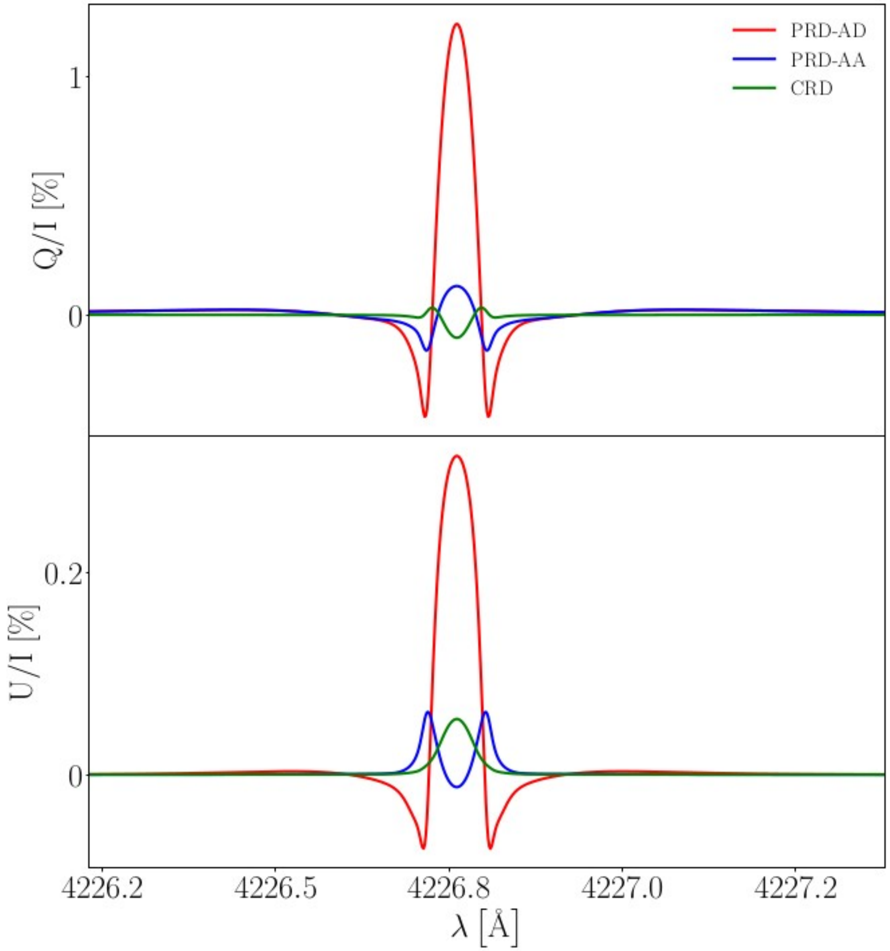
PRD-AA: ~ 1 min

Non-LTE RT calculations in FAL-C, no magnetic fields

Introduction

Importance of PRD effects

μ = 0.966, horizontal magnetic field (20 G)
(forward scattering Hanle effect)



(Belluzzi et al., in prep.)

Project

Goal: solve the non-LTE RT problem for polarized radiation in **3D atmospheric** models accounting for **scattering polarization** and **angle-dependent PRD** effects.

Problem computationally challenging already in 1D!

SNSF *Sinergia* project:
“HPC techniques for 3D modeling of resonance line polarization with PRD”

- Physics of polarization
- Numerical radiative transfer
- Computational sciences

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Model problem

- **Two-level atom** with unpolarized and infinitely-sharp lower level
- **PRD theory of Bommier (1997a,b)**
- **Redistribution matrix formalism**

$$R(\mathbf{r},\mathbf{\Omega}',\mathbf{\Omega},\nu',\nu) = R^{\mathrm{II}}(\mathbf{r},\mathbf{\Omega}',\mathbf{\Omega},\nu',\nu) + R^{\mathrm{III}}(\mathbf{r},\mathbf{\Omega}',\mathbf{\Omega},\nu',\nu)$$

$R^{\mathrm{II}}(\mathbf{r},\mathbf{\Omega}',\mathbf{\Omega},\nu',\nu)$: exact **angle-dependent** expression in the observer's frame

$R^{\mathrm{III}}(\mathbf{r},\mathbf{\Omega}',\mathbf{\Omega},\nu',\nu)$: assumption of totally **incoherent scattering** in the observer's frame

Arbitrary magnetic fields accounted for

Computational challenges

Memory requirements

Need to store the full radiation field: $\boldsymbol{I}(\boldsymbol{r}, \boldsymbol{\Omega}, \nu)$

Problem discretization

$\mathbf{r} \rightarrow N_p$ ~ 500^3 (3D)
$\boldsymbol{\Omega} \rightarrow N_\Omega$ ~ 100
$\nu \rightarrow N_\nu$ ~ 100

→ **40 TB** (CRD: ~ 10 GB)

Solution method

Iterative solution methods successfully applied in CRD or PRD-AA

cannot be easily generalized to PRD-AD (not efficient or too expensive)

Evaluation of scattering integral

$$\varepsilon^{\rm sc}(\boldsymbol{r}, \boldsymbol{\Omega}, \nu) = k_L(\boldsymbol{r}) \int \mathrm{d}\nu' \oint \frac{\mathrm{d}\boldsymbol{\Omega}'}{4\pi} R(\boldsymbol{r}, \boldsymbol{\Omega}', \boldsymbol{\Omega}, \nu', \nu)\, \boldsymbol{I}(\boldsymbol{r}, \boldsymbol{\Omega}', \nu')$$

Computational complexity in the AD case: $O\left(N_p N_\Omega^2 N_\nu^2\right)$

Algebraic formulation

Continuous problem

$$\boldsymbol{\Omega} \cdot \nabla \boldsymbol{I}(\boldsymbol{r}, \boldsymbol{\Omega}, \nu) = -K(\boldsymbol{r}, \boldsymbol{\Omega}, \nu)\, \boldsymbol{I}(\boldsymbol{r}, \boldsymbol{\Omega}, \nu) + \boldsymbol{\varepsilon}(\boldsymbol{r}, \boldsymbol{\Omega}, \nu)$$

$$\boldsymbol{\varepsilon}(\boldsymbol{r}, \boldsymbol{\Omega}, \nu) = k_L(\boldsymbol{r}) \int \mathrm{d}\nu' \oint \frac{\mathrm{d}\boldsymbol{\Omega}'}{4\pi} R(\boldsymbol{r}, \boldsymbol{\Omega}', \boldsymbol{\Omega}, \nu', \nu)\, \boldsymbol{I}(\boldsymbol{r}, \boldsymbol{\Omega}', \nu') \; + \; \boldsymbol{\varepsilon}^{\rm th}(\boldsymbol{r}, \boldsymbol{\Omega}, \nu)$$

Discretized problem

$$\boxed{\mathbf{I} = \Lambda \boldsymbol{\epsilon} + \mathbf{t}} \qquad \Lambda : \mathbb{R}^N \to \mathbb{R}^N$$

Transfer operator (encodes formal solver and K)

$$\boxed{\boldsymbol{\epsilon} = \Sigma \mathbf{I} + \boldsymbol{\epsilon}^{\rm th}} \qquad \Sigma : \mathbb{R}^N \to \mathbb{R}^N$$

Scattering operator (encodes quadratures)

$$N = 4\, N_p\, N_\Omega\, N_\nu$$

$$\boxed{(Id - \Lambda\Sigma)\,\mathbf{I} = \mathbf{b}} \qquad \mathbf{b} = \Lambda \boldsymbol{\epsilon}^{\rm th} + \mathbf{t} \in \mathbb{R}^N$$

References

- Janett et al. 2021, A&A, 655, 87
- Benedusi et al. 2022, A&A, 664, 197

Linearization

Main assumption: lower level population known a-priori and kept fixed
(e.g., pre-calculated with an independent RT code, possibly neglecting polarization)

Pros:

- $(Id - \Lambda\Sigma)\,\mathbf{I} = \mathbf{b}$ linear system → Linearization
- Accurate estimate of lower-level population (e.g., from multi-level atomic models)

Cons:

- Neglect feedback of polarization on lower level population

References

- Janett et al. 2021, A&A, 655, 87

Solution strategy

$$\boxed{(Id - \Lambda\Sigma)\,\mathbf{I} = \mathbf{b}}$$

Preconditioned matrix-free GMRES Krylov solver

(e.g., Nagendra 2009, Anusha & Nagendra 2011, 2012, 2013; Sampoorna 2019)

Preconditioning: $P^{-1}\,(Id - \Lambda\Sigma)\,\mathbf{I} = P^{-1}\mathbf{b}$

Methods successfully applied to CRD and PRD-AA (Jacobi, block-Jacobi, Gauss-Siedel, SOR) ***cannot be easily generalized*** to PRD-AD case (P^{-1} not cheap, or not effective)

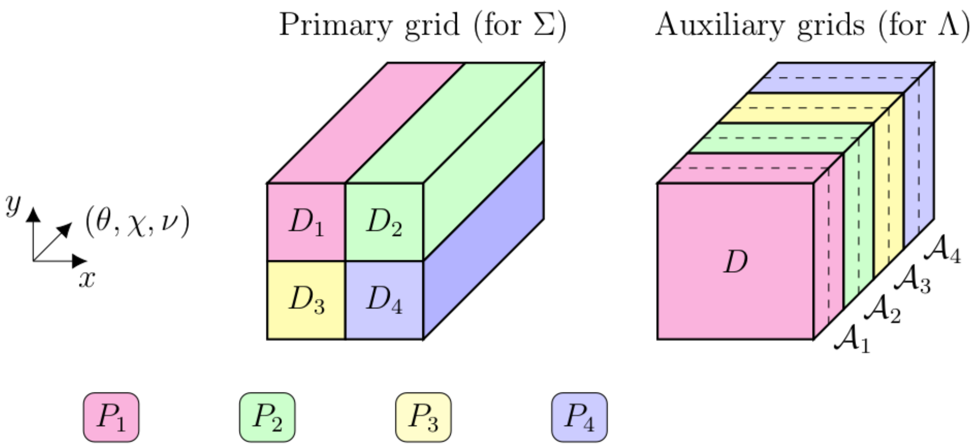
Physics-based preconditioning: $P = Id - \Lambda\Sigma^{\mathrm{CRD}}$

References

- Janett et al. 2021, A&A, 655, 87
- Benedusi et al. 2021, A&A, 655, 88
- Benedusi et al. 2022, A&A, 664, 197

Parallel implementation

Primary – auxiliary grid approach



(Benedusi et al. 2022, JCP, 479, 112013)

Primary grid:
space-distributed

All-to-all communication between grids

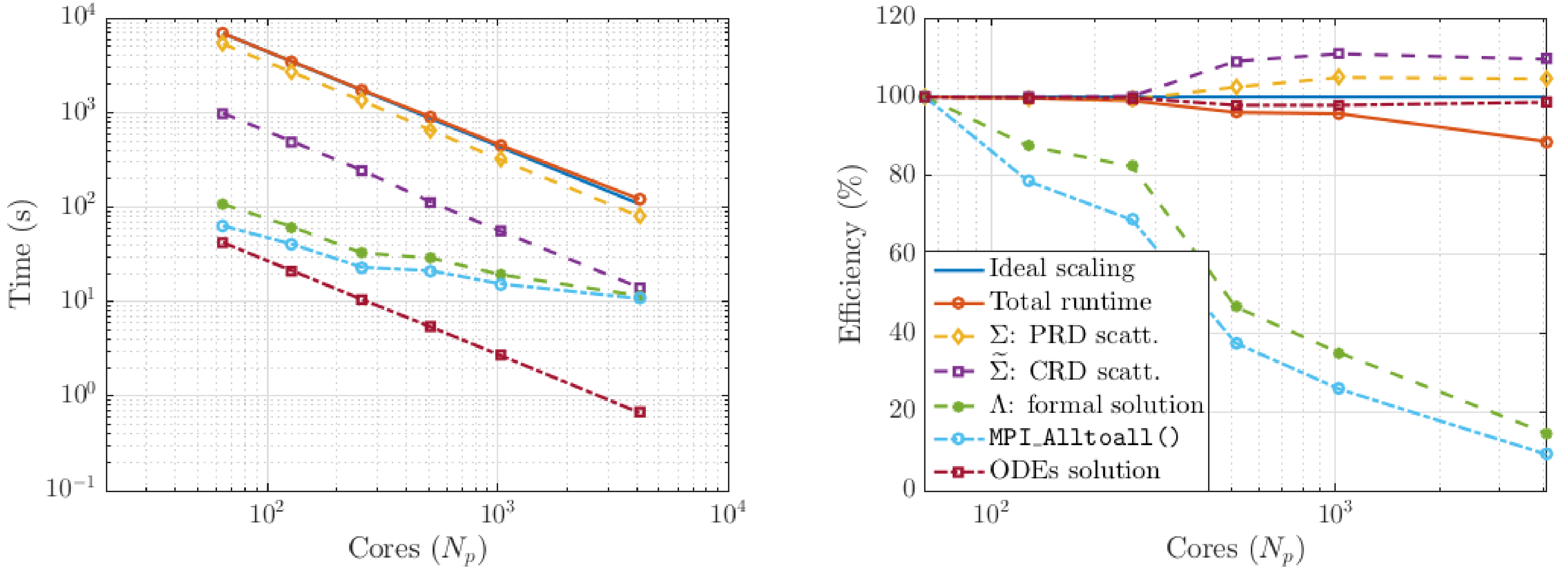
Auxiliary grid:
ray-distributed

$\boldsymbol{\epsilon}^{\mathrm{sc}} = \Sigma \mathbf{I}$ Parallel calculation at different spatial points

$\mathbf{I} = \Lambda \boldsymbol{\epsilon}$ Parallel calculation along different “rays” $(\boldsymbol{\Omega}_l, \nu_m)$

Scaling experiments

Strong scaling experiment



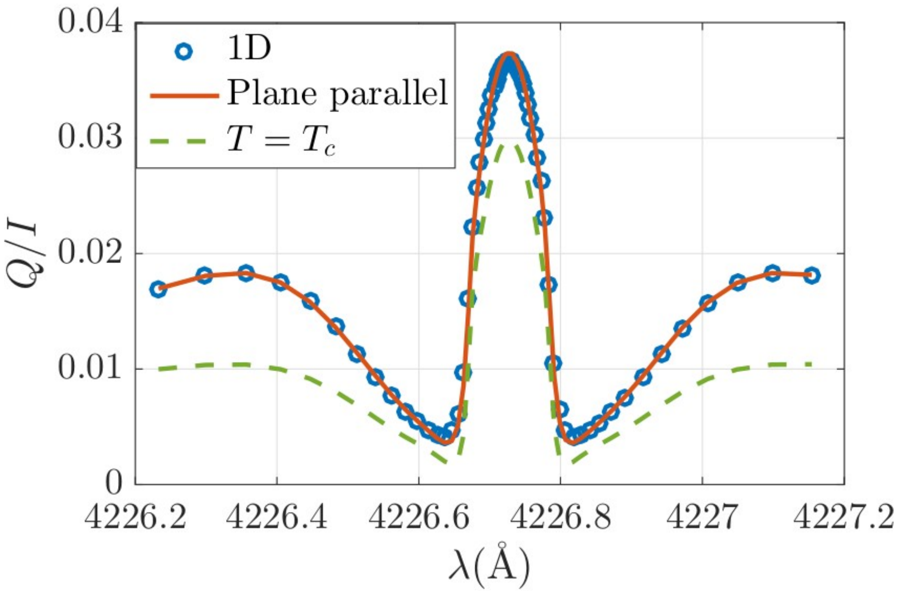
$N_x = 8$, $N_Y = 8$, $N_Z = 64$, $N_\Omega = 64$, $N_\nu = 64$

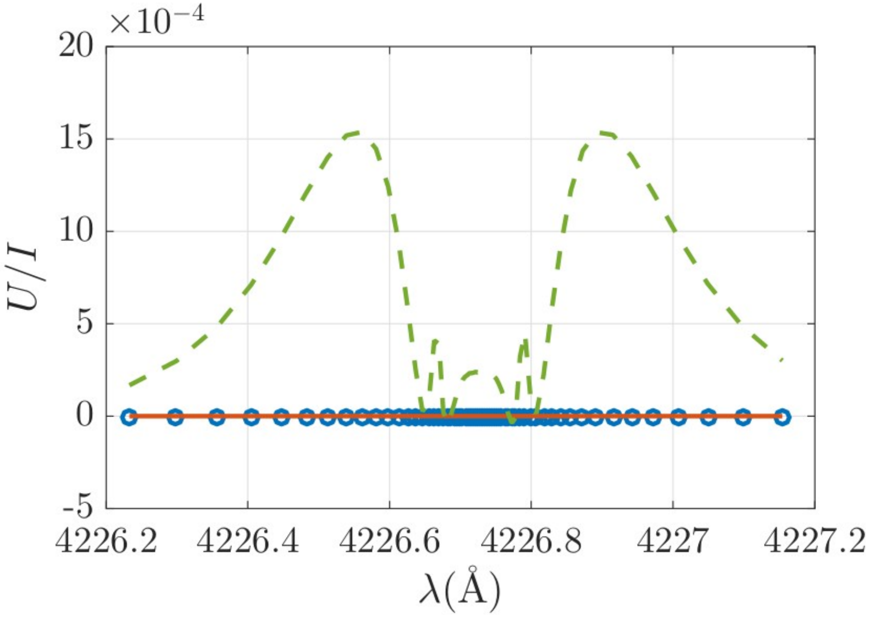
4 Preconditioned GMRES iterations to converge

(Benedusi et al. 2023, JCP, 479, 112013)

Results

$N_x = 8$, $N_Y = 8$, $N_Z = 64$, $N_\Omega = 64$, $N_\nu = 64$ LOS: μ=0.1, χ=π/4

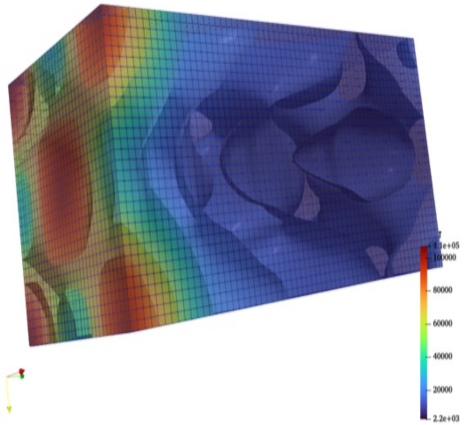




(Benedusi et al. 2023, JCP, 479, 112013)

FAL-C (1D)
FAL-C (3D)
FAL-C (3D) + sinusoidal temperature variation

4 Preconditioned GMRES iterations to converge
Run time: 122s (4096 cores)



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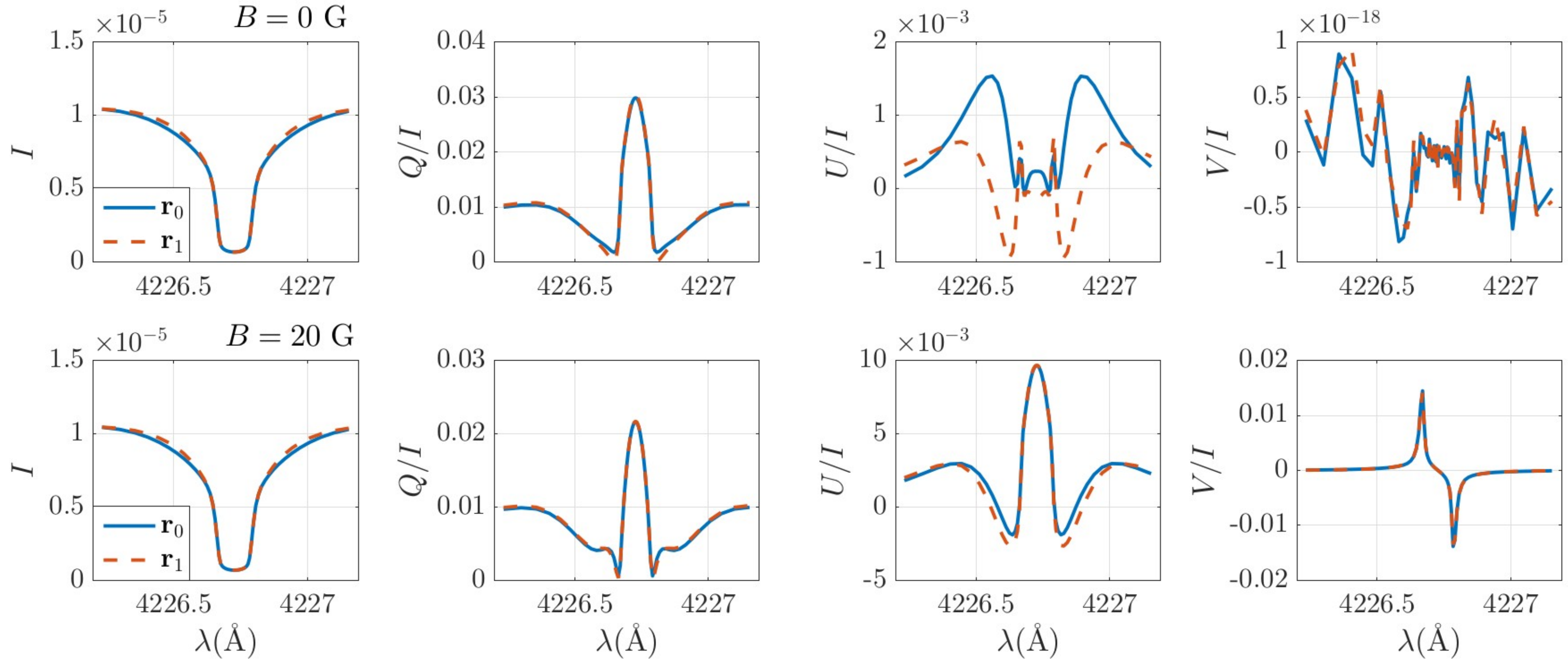

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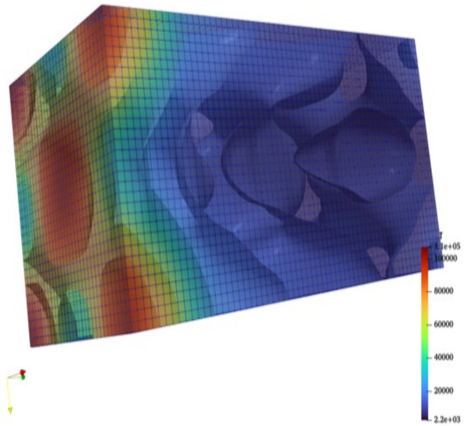

FAL-C (3D) + sinusoidal temperature variation + magnetic field

4 Preconditioned GMRES iterations to converge

Run time: 122s (4096 cores)

Ongoing and future work

Work in progress

- **3D code testing and applications**
- **Generalization to two-term model atom** (Mg II h & k, H I Ly-α, Na I D; **Janett et al. in prep.**)
- Investigation on the impact of bulk velocities **(Guerreiro et al. submitted)**
- Assessment of CRD approximation for R_{III} **(Riva et al. submitted)**
- Investigation of new preconditioners **(Janett et al. in prep.)**
- 1D modeling of other spectral lines **(Riva et al. in prep.)**

Future

- **Generalization of solution strategy to nonlinear problem**
- New strategies for scattering integral calculation (GPUs, machine learning)

References:

- Janett et al. 2021, A&A, 655, A13
- Janett et al. 2021, A&A, 655, A87
- Benedusi et al. 2021, A&A, 655, A88
- Benedusi et al. 2022, A&A, 664, A197
- Benedusi et al. 2023, JCP, 479, 112013

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