

SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten

<https://webspacescience.uu.nl/~rutte101>

thin: cloud modeling corona chromosphere Rydberg per ALMA?

thick: UV line flip VAL3C temperature VAL3C spectrum Kurucz stars

photospheric lines: inversions bright points reversed granulation Na I D1 MGs
limb emission lines

continua from VAL3C: Avrett models versus 3D MHD VAL3C continua
VALII budget hydrogen budget all

lines from ALC7: model optical spectrum ultraviolet depletion hydrogen
strong lines plot formats pops plot BSJ plot profile plot Mg I 4571
Fe I 6302 Mg I b₂ Na I D₁ Ba II 4554 Ca II 8542 Å Ca II K Mg II k
Ly α H α H β He I 584 He I 10830 canonical H α Na I D₁-Mg I b₂
Ly α -H α H α -Ca II 8542 Å Ca II K-Mg II k versus FCHHT-B ALC7-FALC
FALC-FALP ALC7-FALP

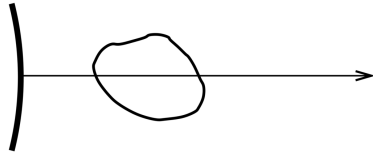
detour lines: pumping suction

Oslo-simulated dynamic atmosphere: 1D RADYN 3D Bifrost Bifrost line synthesis

LA-conjectured PSBE atmosphere: non-E H α aureole boosting H α extinction
CE-SB EBs spicules-II contrail ALMA non-E chromosphere?

IRIS diagnostics: overview diagnostics

CLOUD MODELING



review: Tziotziou 2007ASPC..368..217T

Formal solution for line of sight (LOS) through irradiated cloud

$$I_\nu = I_\nu(0) e^{-\tau_\nu^c} + \int_0^{\tau_\nu^c} S_\nu(t_\nu) e^{-(\tau_\nu - t_\nu)} dt_\nu$$

Homogeneous cloud, Gaussian broadening, parameters $I_0(\Delta\lambda)$, S , τ_0 , LOS v

$$I(\Delta\lambda) = I_0(\Delta\lambda) e^{-\tau(\Delta\lambda)} + S (1 - e^{-\tau(\Delta\lambda)}) \quad \tau(\Delta\lambda) = \tau_0 e^{-\left(\frac{\Delta\lambda - \lambda_0 v/c}{\Delta\lambda_D}\right)^2}$$

$$C(\Delta\lambda) \equiv \frac{I(\Delta\lambda) - I_0(\Delta\lambda)}{I_0(\Delta\lambda)} = \left(\frac{S}{I_0(\Delta\lambda)} - 1\right) (1 - e^{-\tau(\Delta\lambda)})$$

Refinements: Voigt, τ -dependent S , wavelength-dependent S (for PRD with $S \approx S^l$)

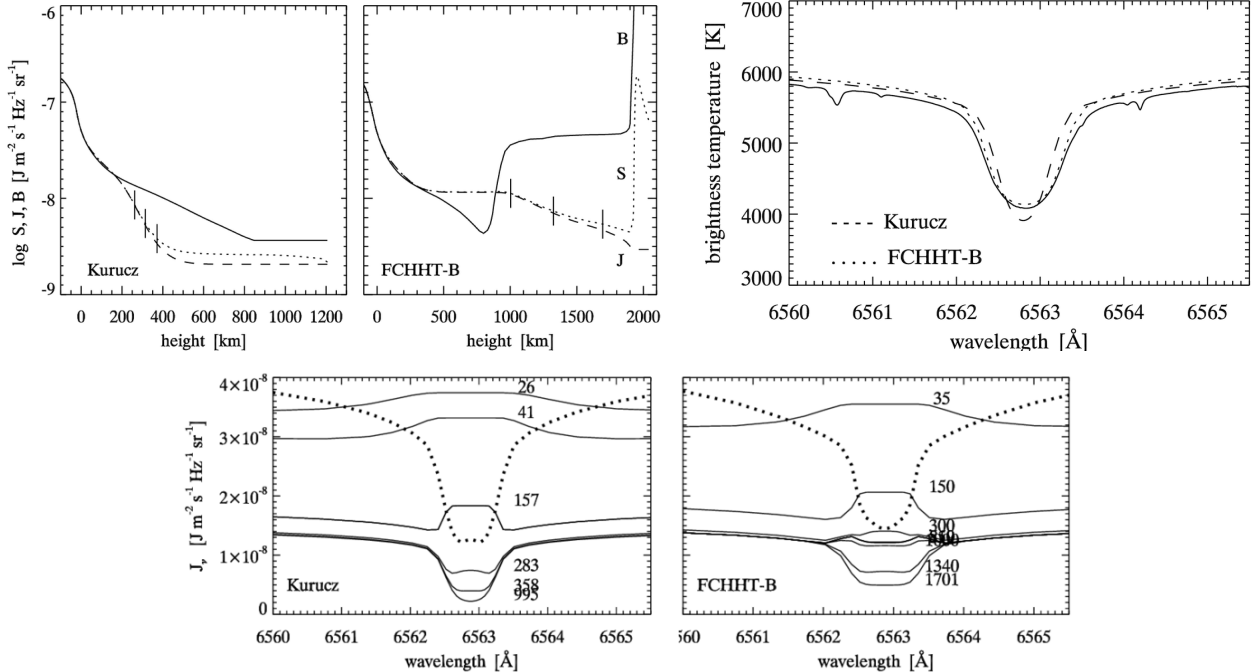
Interpretation: $S \Rightarrow (T, \rho)$

- Beckers 1968SoPh...3..367B: Giovanelli NLTE hydrogen ionization tables
- Molowny-Horas et al. 1999A&A...345..618M: "inversion" from many model profiles

Problems: impinging profile, sideways irradiation, multi-thread

H α CLOUD MODELING

Rutten & Uitenbroek 2012A&A...540A..86R



H α -H α formation: the Kurucz and FCHHT-B models both reproduce observed H α

cloud modeling: $I_\nu = I_\nu(0) e^{-\tau_\nu^c} + \int_0^{\tau_\nu^c} S_\nu(t_\nu) e^{-(\tau_\nu - t_\nu)} dt_\nu$

new recipe: for the impinging profile $I_\nu(0)$ take the outward I_ν profile in a RE model at the depth $\tau_{\nu 0}$ which equals the cloud thickness $\tau_{\nu 0}^c$ (dotted profiles)

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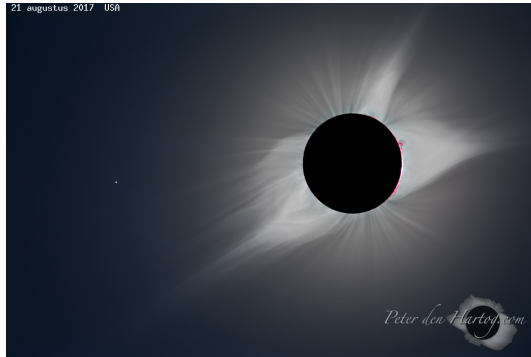
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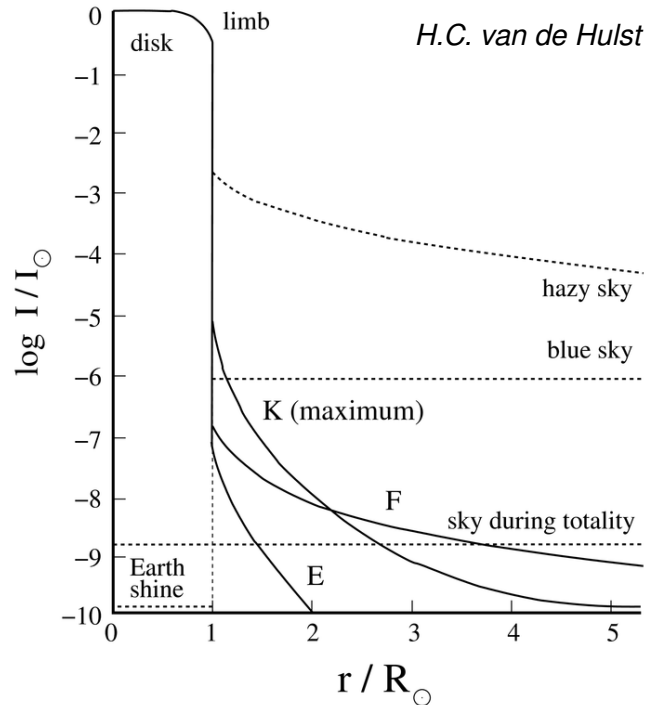
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SOLAR ECLIPSE VISIBILITY

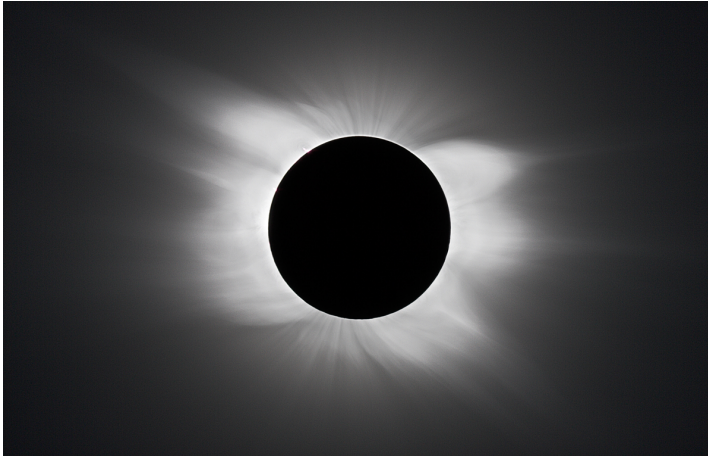


P. den Hartog



- dusty sky has 0.1 – 0.01% of the solar brightness ($10^{-3} - 10^{-4}$), brighter closer to Sun
- “coronal” blue sky (Rayleigh scattering) is one millionth (10^{-6}), even distribution across sky
- during totality the sky brightness is only one billionth (10^{-9}), less than the coronal brightness
- “K” = continuum component, “F” = Fraunhofer component, “E” = emission-line component
- earthshine (10^{-10}): new-moon brightness from full-earth-with-spot irradiation

CORONAL WHITE LIGHT

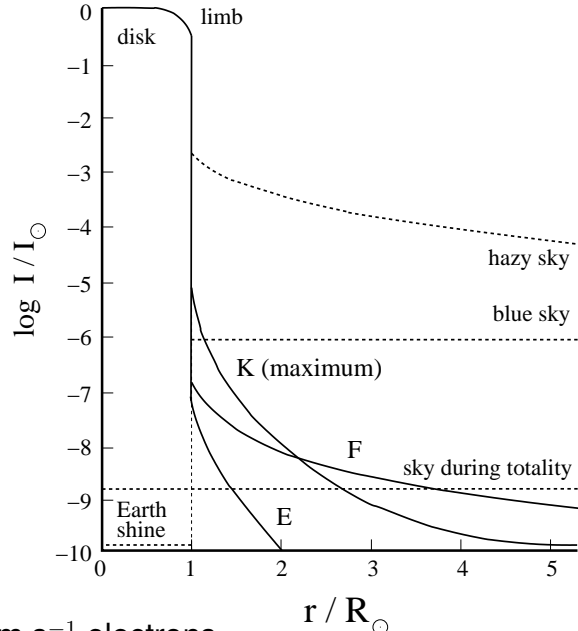


- Walter Grotrian (Potsdam, 1931)
 - white \Rightarrow Thomson scattering of photospheric photons by free electrons
 - weak \Rightarrow low electron density (electron cross-section only 10^{-25} cm²)
 - absence of photospheric Fraunhofer lines \Rightarrow washed out by large Dopplershifts
 - required electron speeds 4000 km/s [\Rightarrow if motions thermal: 1 million degrees !?]
- linear polarisation from right-angle scattering
- fine structure maps variations in electron density dictated by magnetic fields
- the F component further out results from photon scattering by slower-moving interplanetary dust particles; its spectrum shows the photospheric Fraunhofer lines

Appreciate that during totality you are illuminated by normal photospheric light — but only a 10^{-7} fraction bounced around the moon, without Fraunhofer lines, and polarized too!

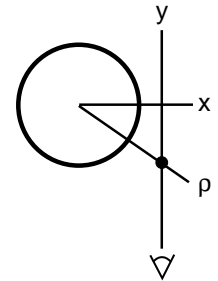
WHITE LIGHT CORONA

M. Stix "The Sun", Section 9.1.3



Grotrian (1931): Thomson scattering 8000 km s^{-1} electrons

$$\rho^2 = x^2 + y^2 \quad I(x) = 2 \int_0^\infty j(\rho) dy = 2 \int_x^\infty \frac{\rho j(\rho)}{\sqrt{\rho^2 - x^2}} d\rho$$



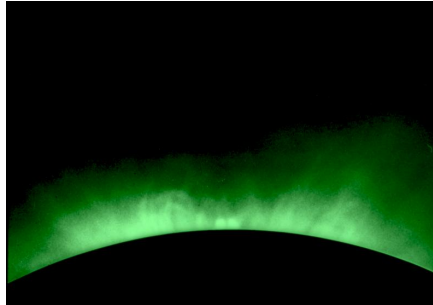
N_e from inverse Abel transform = isotropically scattered irradiation

$$j(\rho) = -\frac{1}{\pi} \int_\rho^\infty \frac{dI/dx}{\sqrt{x^2 - \rho^2}} dx = \sigma_T N_e \frac{1}{4\pi} \int I_\odot(\theta) d\Omega$$

“CORONIUM” LINES

M. Stix “The Sun”, Section 9.1.3

<http://laserstars.org/spectra/Coronium.html>



Grottrian (1939), Edlén (1942): forbidden lines high ionization stages (Stix Table 9.2 p. 398)

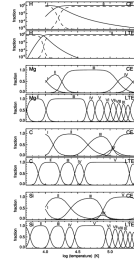
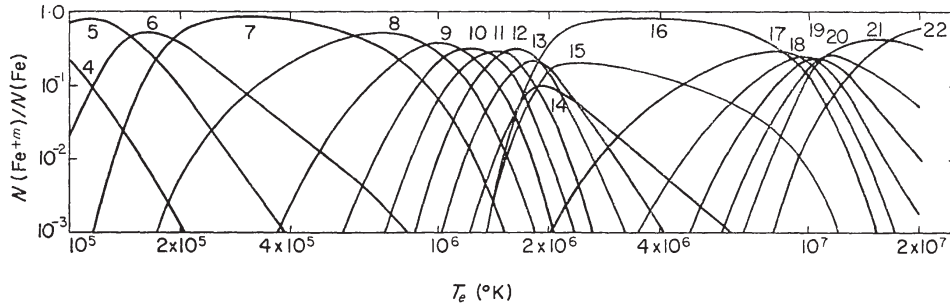
name	wavelength	identification	$\Delta\lambda_D$	\bar{v}	A_{ul}	previous ion	χ_{ion}
green line	530.29 nm	[Fe XIV]	0.051 nm	29 km/s	60 s ⁻¹	Fe XIII	355 eV
yellow line	569.45	[Ca XV]	0.087	46	95	Ca XIV	820
red line	637.45	[Fe XI]	0.049	23	69	Fe X	235

Coronal sky at Dome C



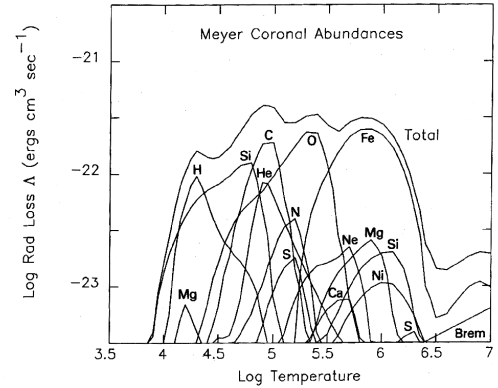
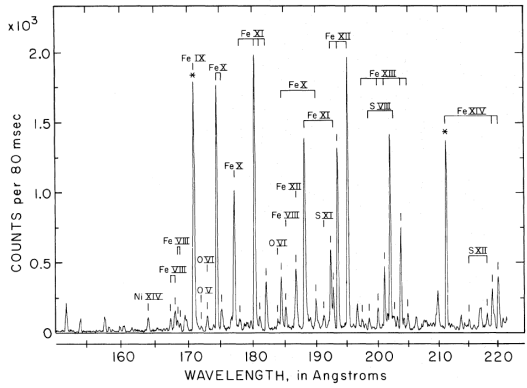
EUV CORONA

bf equilibria: collisional ionization = radiative recombination \Rightarrow only $f(T)$, not $f(N_e)$



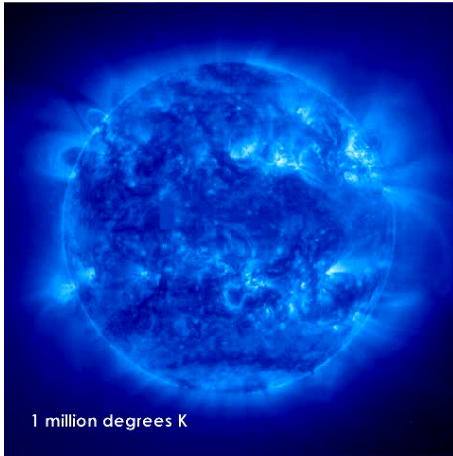
bb equilibria: collisional excitation = spontaneous deexcitation $\Rightarrow f(T, N_e)$

$$n_l C_{lu} = n_l N_e \int_{v_0}^{\infty} \sigma_{lu} f(v) v dv \approx n_u A_{ul} \quad \sum h\nu \propto \int A_{\text{elem}} N_{\text{H}} N_e dz \approx \int N_e^2 \left(\frac{dT}{dz} \right)^{-1} dT \equiv \text{EM}$$

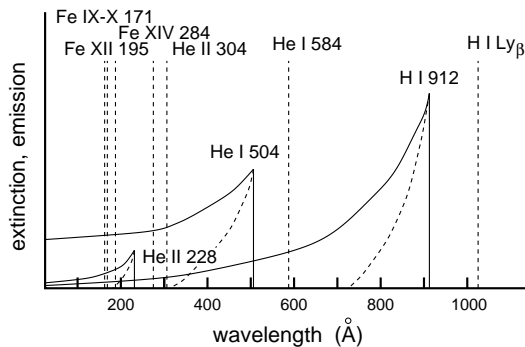


BRIGHT AND DARK IN EUV IMAGES

Rutten 1999ASPC..184..181R



- *iron lines*
 - Fe IX/X 171 Å: about 1.0 MK
 - Fe XII 195 (AIA 193) Å: about 1.5 MK
 - Fe XIV 284 Å: about 2 MK
- *bright*
 - collision up, radiation down
 - thermal photon creation, NLTE equilibrium
 - one line: selected loops = special trees in forest



- *dark*
 - lack of emissivity (“volume blocking”??) or bound-free scattering
 - scattering: radiation up, re-radiation at bound-free threshold = black in narrow passband
 - scattering agents: H I, He I, He II

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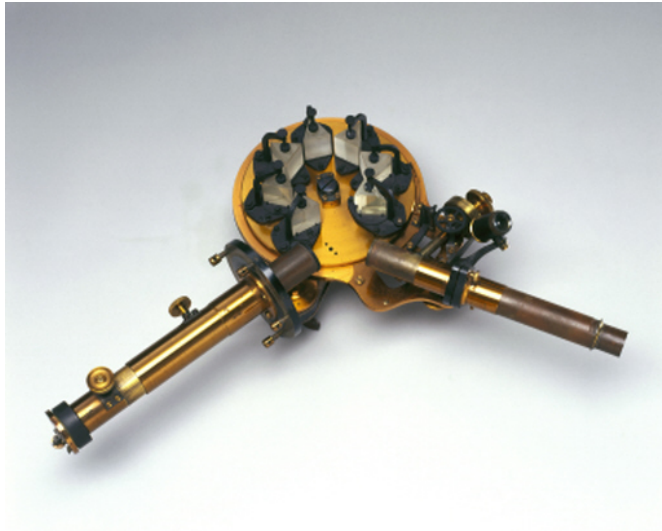
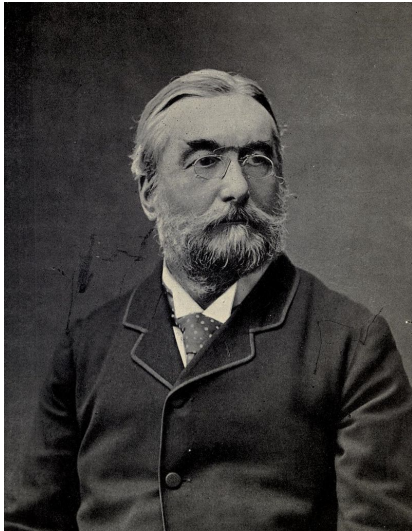
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NORMAN LOCKYER

wikipedia



Sir Joseph Norman Lockyer, FRS (17 May 1836 – 16 August 1920), known simply as Norman Lockyer, was an English scientist and astronomer. Along with the French scientist Pierre Janssen he is credited with discovering the gas helium.

In 1885 he became the world's first professor of astronomical physics at the Royal College of Science, South Kensington, now part of Imperial College. At the college, the Solar Physics Observatory was built for him and here he directed research until 1913.

To facilitate the transmission of ideas between scientific disciplines, Lockyer established the general science journal *Nature* in 1869. He remained its editor until shortly before his death.

CHROMOSPHERE AND HELIUM NAMING

Abstract of Norman Lockyer's paper read Nov. 26, 1868; Procs. Royal Society of London, 17, 131

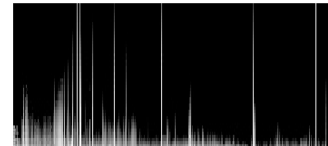
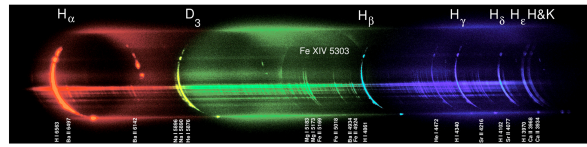
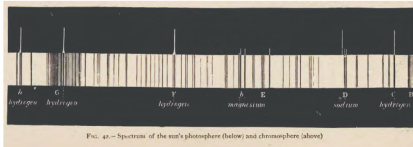
ADS 1868RSPS...17..131L courtesy Kevin Reardon 9 cites (7 RR)

Details are given of the observations made by the new instrument, which was received incomplete on the 16th of October. These observations include the discovery, and exact determination of the lines, of the prominence-spectrum on the 20th of October, and of the fact that the prominences are merely local aggregations of a gaseous medium which entirely envelopes the sun. The term *Chromosphere* is suggested for this envelope, in order to distinguish it from the cool absorbing atmosphere on the one hand, and from the white light-giving photosphere on the other. The possibility of variations in the thickness of this envelope is suggested, and the phenomena presented by the star in Corona are referred to.

Two of the lines correspond with Fraunhofer's C and F; another lies 8° or 9° (of Kirchhoff's scale) from D towards E. There is another bright line, which occasionally makes its appearance near C, but slightly less refrangible than that line. It is remarked that the line near D has no corresponding line ordinarily visible in the solar spectrum. The author has

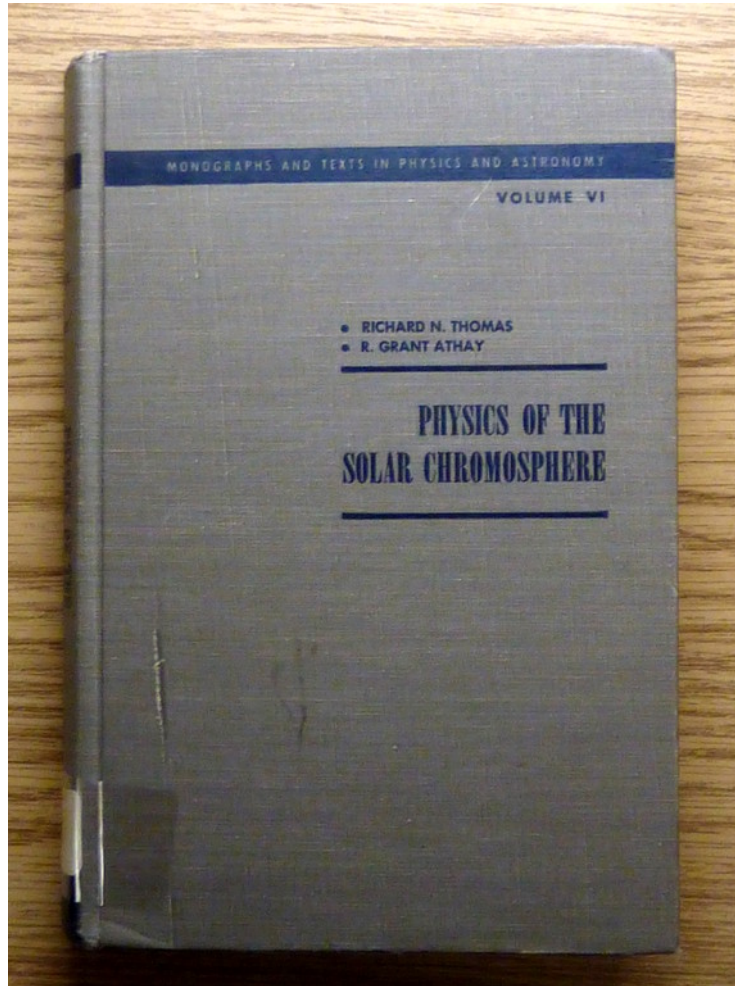
Fraunhofer's "C" is $H\alpha$, "F" is $H\beta$. The non-Fraunhofer line near "D" ($Na I D_1 + Na I D_2$) for which Lockyer proposed a new element "helios" is $He I D_3$. The occasional "less refrangible" (redward) line near $H\alpha$ is $He I 6678 \text{ \AA}$.

SOLAR FLASH SPECTRUM



- *chromosphere naming = definition (Lockyer 1868 outside eclipse)*
 - strong: H I Balmer lines, He I D₃, Ca II H & K
 - weaker: Mg I b, Na I D, Sr II, Ba II
- *chromosphere research = flash spectrometry*
 - Menzel thesis = 1898–1908 Campbell [1930PLicO..17....1M](#) (302 pp, on ADS)
 - Thomas & Athay book = 1952 HAO [1961psc..book....A](#) (422 pp, not on ADS)
 - Dunn et al. = 1962 HAO [1968ApJS...15..275D](#) (275 pp, on ADS; [RR digitized](#))
- *chromosphere = enigma*
 - flash spectrum \neq reversed disk spectrum
 - both hot (He I D₃) and cool (Na I D₁ & D₂) lines
 - spatial extent exceeds radiative-equilibrium scale height

ECLIPSE WISDOM



attention reader

see De Jager's comments on this book
in Z. Astrophysik; v. 55; p. 66 (1962)

(rather damaging!)

Besprechungen

THOMAS, R. N., und R. G. ATHAY: *Physics of the Solar Chromosphere*. X + 422 Seiten. Interscience Publishers, Inc., New York 1961. Geb. \$ 15.50.

Der Titel des Buches verspricht mehr, als der Inhalt gibt. Jeder, der schon einmal durch ein $H\alpha$ -Filter oder durch ein Spektrohelioskop die bezaubernde Struktur der Chromosphärenoberfläche gesehen oder das Profil des Sonnenrandes beobachtet hat, wird — sobald er den Titel „Physik der Chromosphäre“ hört — an eine Erklärung der Dynamik dieser Gasmassen denken. Er wird an Probleme der Schall-, Stoß- und Gravitationswellen und an die Dissipation von deren Energie denken. Vielleicht wird er sich fragen, was die Autoren von der Rolle halten, die Magnetfelder und magnetohydrodynamische Wellen spielen und in welchem Maße von ihnen die verschiedenen Strukturen der ruhigen bzw. gestörten Gebiete dieses merkwürdigen Teiles der Sonne bestimmt werden.

Von allem dem wird er aber in diesem Buche nichts finden: Die betreffenden Probleme werden kaum erwähnt, geschweige denn besprochen.

und so weiter... four pages more

Upshot: the book treats the derivation of a model atmosphere from the spectrograms taken by the 1952 HAO eclipse expedition but ignores the inhomogeneity and dynamics of the chromosphere such as sound, shock, gravity and MHD waves, as well as magnetic fields.

CHROMOSPHERE POTPOURRI

- *line formation theory*

- flash spectrum @ Harvard, Boulder \Rightarrow Mihalas (1970, 1978): [summary](#)
- static 1D “standard” models: [VALIIC](#) [more Avrett](#) [hydrogen exam](#)
- non-E: [detailed balancing](#) [1D Radyn](#) [2D Stagger](#) [3D Bifrost](#)

- *chromosphere diagnostics*

[Na I D₁+Mg I b₂](#) [Ly \$\alpha\$ +H \$\alpha\$](#) [H \$\alpha\$ +Ca II 8542 Å](#) [Ca II H & K+Mg II h & k](#)
[Si IV mm](#) [He I+He II](#)

- *chromospheric & coronal heating ingredients*

- [gravity waves](#)
- [acoustic waves](#)
- [Alfvénic waves](#)
- [reconnection](#)

- *fine structure*

- sketched: [Noyes 1979](#) [Gabriel 1976](#) [Rutten 1998](#) [Wedemeyer 2016](#) [Rutten 2016](#)
- observed and explained: [Ca II grains](#) [dynamic fibrils](#)
- observed but not explained: [straws/spicules-II/RBEs/RREs](#) [long H \$\alpha\$ fibrils](#)
- fibril-field alignment for NLFFF: [yes](#) [partly](#) [only at launch?](#)

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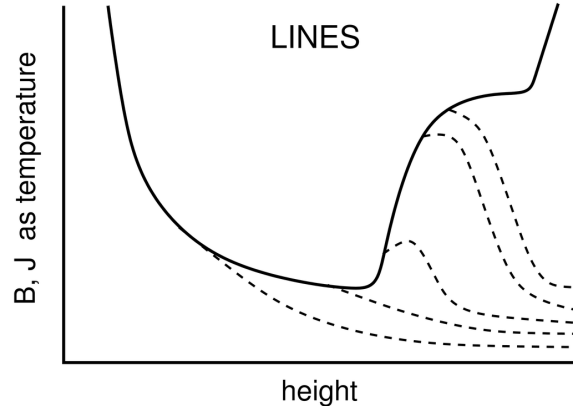
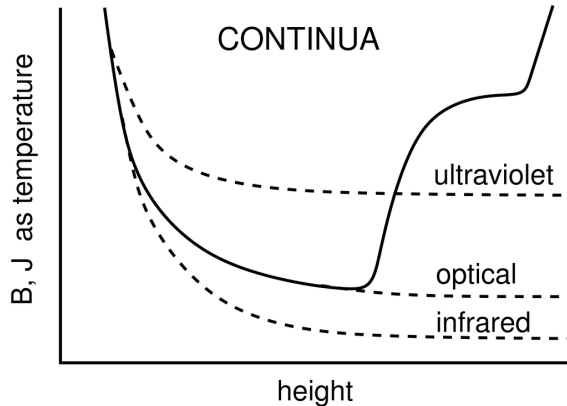
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SUMMARY 1D SCATTERING SOURCE FUNCTIONS



- *continua*

- optical: $J \approx B$ for radiative equilibrium
- ultraviolet: $S \approx J > B \rightarrow$ overionization of minority neutrals
- infrared: $J < B$ but J doesn't matter since H_{ff}^- and H_{ff} have $S = B$

- *lines*

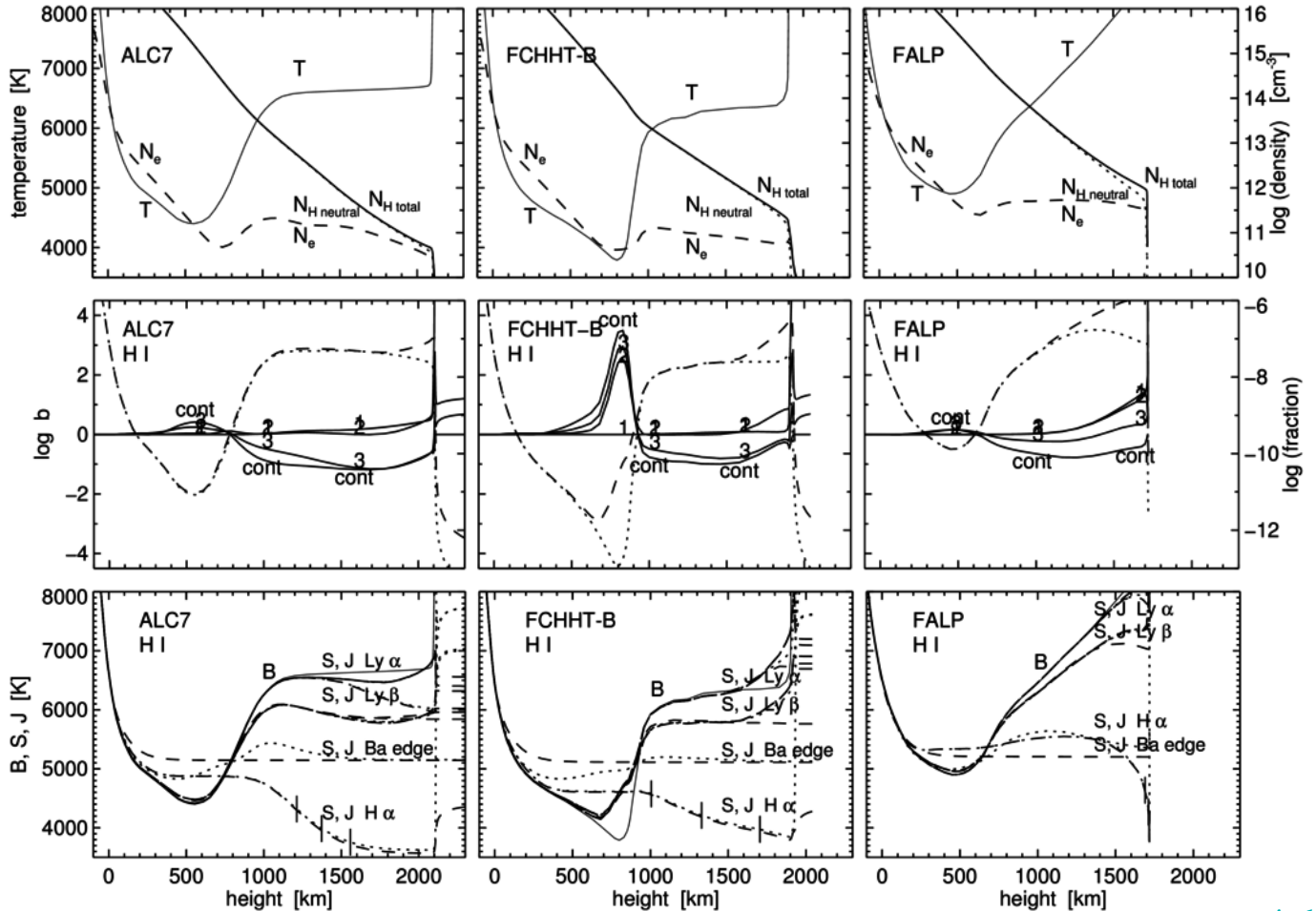
- $dB/d\tau = dB/d(\tau^c + \tau^l)$ much less steep, so closer to isothermal $S \approx \sqrt{\epsilon} B$
- for stronger lines S sees more of the model chromosphere
- PRD lines have frequency-dependent core-to-wing $S \approx J$ curves like these

EXPLAIN EVERYTHING – INCLUDING SIMILARITIES AND DIFFERENCES

ALC7: 2008ApJS..175..229A

FCHHT-B: 2009ApJ...707..482F

FALP: 1993ApJ...406..319F



DYNAMIC FIBRILS

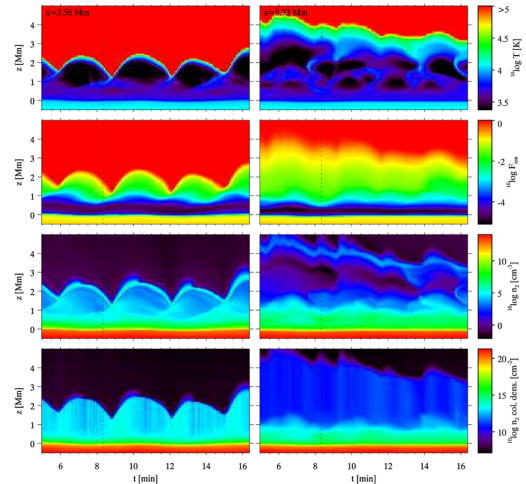
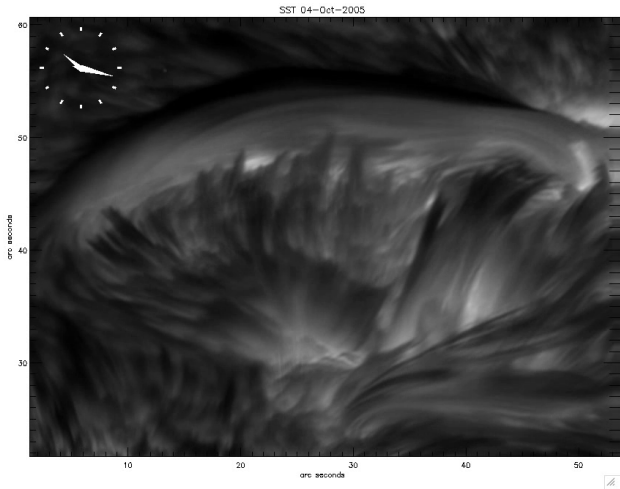
H α : Hansteen et al. 2006ApJ...647L..73H, De Pontieu et al. 2007ApJ...655..624D (plage)

Roupe van der Voort & De la Cruz Rodriguez 2013ApJ...776...56R (sunspots)

Ca II 8542: Langangen et al. 2008ApJ...673.1194L

Ly α : Koza et al. 2009A&A...499..917K

non-E 2D MHD simulation: Leenaarts et al. 2007A&A...473..625L



explanation: p -mode-driven 3–5 minute shock waves along inclined field as slanted wave guide with lowered cutoff frequency; fan pattern = surface network strings

Michalitsanos 1973SoPh...30...47M

Bel & Leroy 1977A&A...55..239B

Suematsu 1990LNP...367..211S

De Pontieu et al. 2004Natur.430..536D

THE FIVE-MINUTE PERIOD OSCILLATION IN MAGNETICALLY ACTIVE REGIONS

A. G. MICHALITSANOS* **

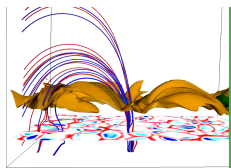
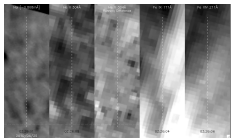
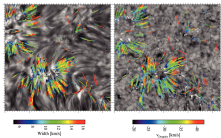
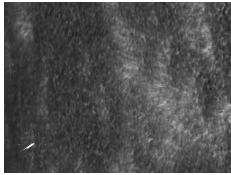
Institute of Astronomy, University of Cambridge, Cambridge, England

If we incline the magnetic field (with respect to g) through 45 degrees in Figure 1d, we note that in Region I, $\omega(k_x)$ is no longer asymptotic to ω_s as k_x tends to zero. Therefore, for an inclined magnetic field, magnetosonic waves may propagate vertically at frequencies $\omega < \omega_s$. If in Equation (3) we set $a=0$ and $k_x=0$, and let $b = -g\gamma/2V_s^2$ we will obtain the critical magnetosonic-gravity frequency ω_c , where

$$\omega_c^2 = \omega_s^2 \left(\frac{1}{2} - \frac{1}{\gamma\beta} \right) + \omega_s^2 \left[\left(\frac{1}{\gamma\beta} - \frac{1}{2} \right)^2 + \frac{2 \cos^2 \theta}{\gamma\beta} \right]^{1/2}, \quad (4)$$

and $\theta = \arccos(B_z/B_0)$. Therefore, at levels where $\beta < 1$, the critical magnetosonic-gravity frequency is less than the critical sonic-gravity frequency ω_s when the field is inclined from the vertical.

STRAWS / SPICULES-II / RBES



- *observations*
 - “straws”, DOT Ca II H
Rutten 2006ASPC..354..276R
 - “spicules-II”, SST Ca II H
De Pontieu et al. 2007Sci...318.1574D
 - on-disk visibility? DOT unpublished
 - “rapid blue excursions”, SST H α
Roupe van der Voort et al. 2009ApJ...705..272R
 - “heating events”, Hinode + SDO H α + EUV
De Pontieu et al. 2011Sci...331...55D
- *simulation: Martínez-Sykora et al. 2011ApJ...736....9M*
 - complex emergence, steep gradients, intense currents
 - spicular Joule heating (green), outflow (blue)
 - nearby coronal loop heating (red)
- *expectations*
 - quiet-sun (also unipolar) coronal heating
 - fast solar wind driving
 - solar wind element segregation

DYNAMIC FIBRILS

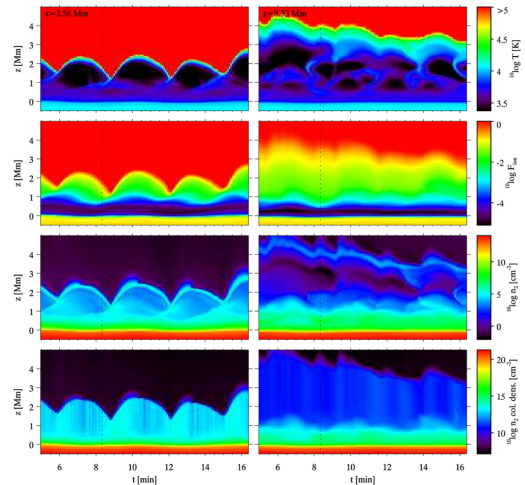
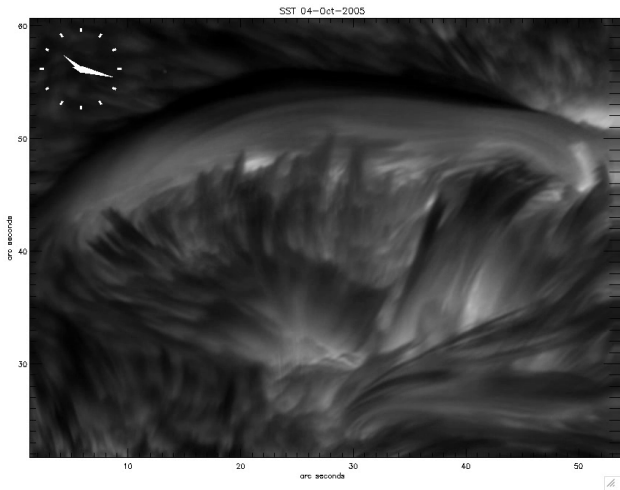
H α : Hansteen et al. 2006ApJ...647L..73H, De Pontieu et al. 2007ApJ...655..624D (plage)

Roupe van der Voort & De la Cruz Rodriguez 2013ApJ...776...56R (sunspots)

Ca II 8542: Langangen et al. 2008ApJ...673.1194L

Ly α : Koza et al. 2009A&A...499..917K

non-E 2D MHD simulation: Leenaarts et al. 2007A&A...473..625L



explanation: p -mode-driven 3–5 minute shock waves along inclined field as slanted wave guide with lowered cutoff frequency; fan pattern = surface network strings

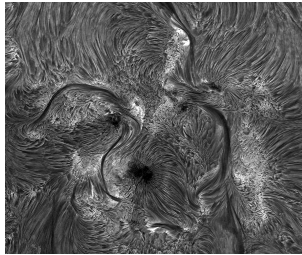
Michalitsanos 1973SoPh...30...47M

Bel & Leroy 1977A&A...55..239B

Suematsu 1990LNP...367..211S

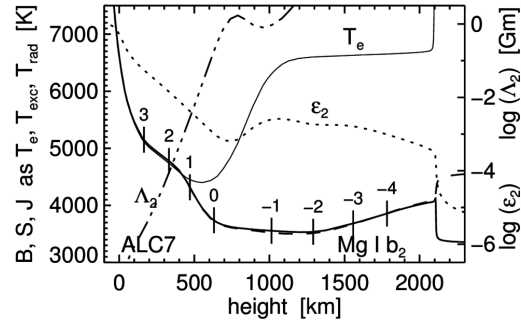
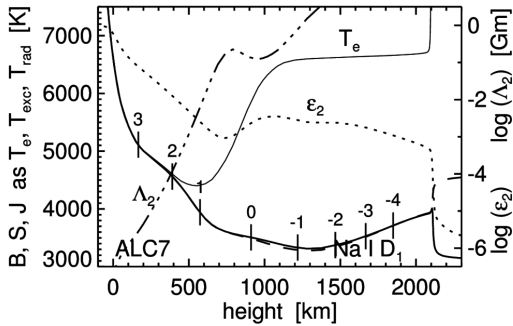
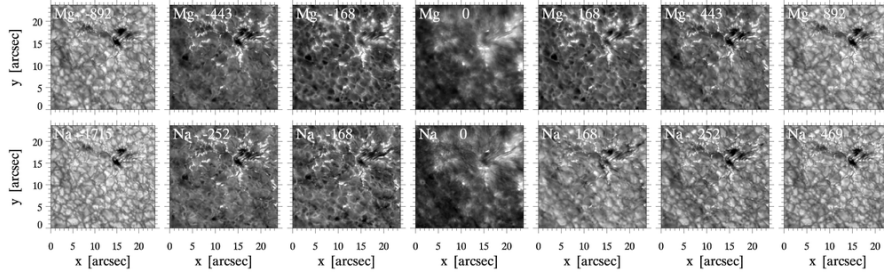
De Pontieu et al. 2004Natur.430..536D

FIBRIL-FIELD ALIGNMENT FOR NLFFF LOWER BOUNDARY



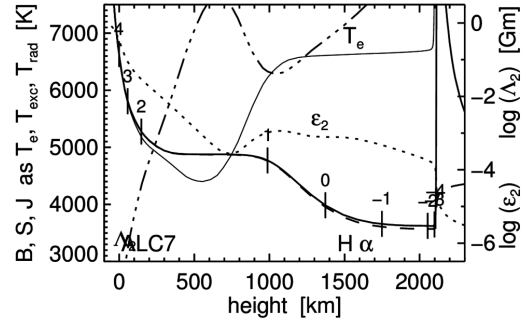
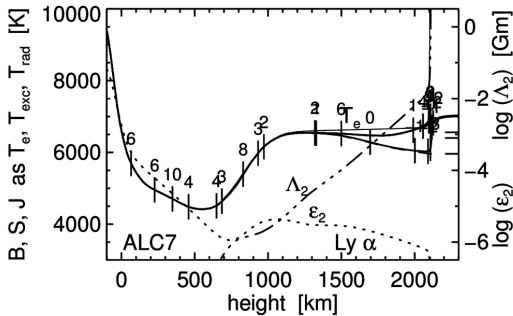
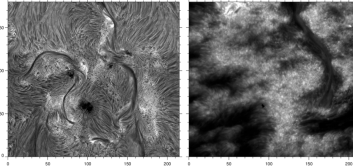
- *NLFFF tests with chromospheric boundary*
 - Na I D₁: Metcalf et al. [1995ApJ...439..474M](#) [2005ApJ...623L..53M](#)
 - H α : Bobra & van Ballegoijen [2008ApJ...672.1209B](#) Wiegelmann et al. [2008SoPh..247..249W](#)
- *good alignment*
 - Aschwanden et al. [2016ApJ...826...61A](#)
- *partial alignment*
 - de la Cruz Rodríguez & Socas-Navarro [2011A&A...527L...8D](#)
 - Leenaarts et al. [2015ApJ...802..136L](#)
 - Martínez-Sykora et al. [2016ApJ...831L...1M](#)
 - Asensio Ramos et al. [2016arXiv161206088A](#)
- non-E alignment only at H ionization in propagating heating events?

Na I D₁ AND Mg I b₂



- similar NLTE formation = heavy two-level scattering
- core intensities do not sense ALC7 chromosphere
- narrow Na I D₁ flanks reverse reversed granulation
- non-E? minority stages: recombination $\propto N_e$ senses Ly α settling and scattering
- SST: Dopplergrams \approx unsigned fluxtube magnetograms (Na I D₁ formation)
non-E enhanced in cooling recombining downflows? (SE = Bifrost snapshot OK)

Ly α and H α

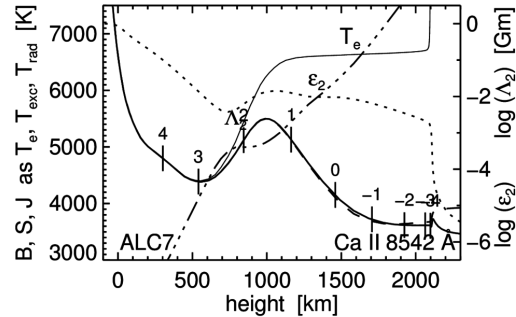
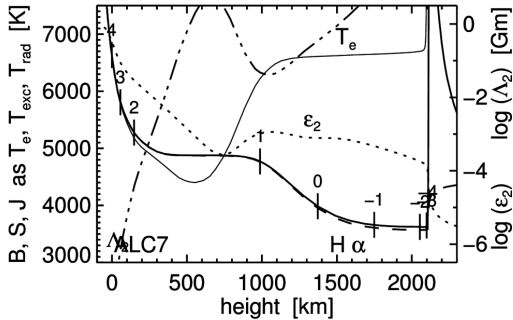
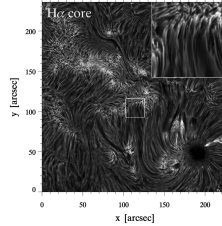


- both: heavy NLTE scatterers with $S \approx J$
- Ly α : boxed-in by enormous extinction \Rightarrow radiative detailed balance: $S = J$
 in shocks (\approx ALC7 chromosphere) collisional thermalization: $b_2 \approx b_1$
 in cool gas surrounding hot structures $b_2 \gg 1$ from Ly α surround scattering
 in post-hot cool gas slow $S \approx J$ thermalization with $b_2 \gg 1$: S^l memory of hot past
- H α : photons created in granulation
 scatter 3D across upper-photosphere opacity gap and through chromosphere
 in shocks etc. Boltzmann extinction $b_2 \approx b_1$
 in post-hot cool gas $b_2 \gg 1$: extinction memory of hot past

Ly α scene: heating events bright down-throat, cooling contrails dark from scattering

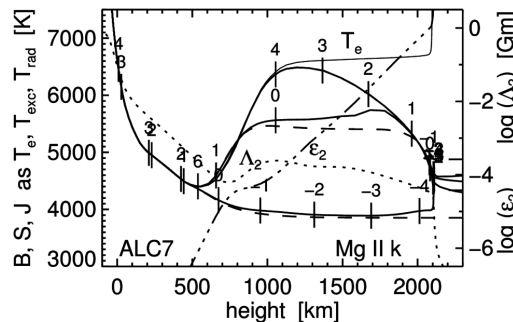
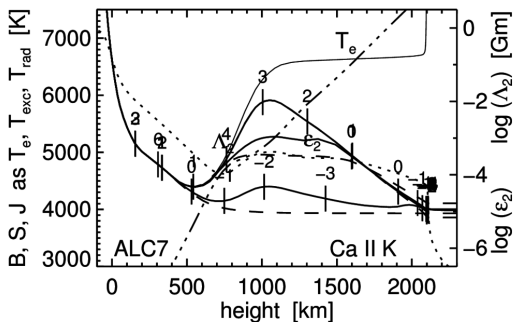
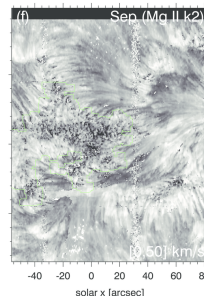
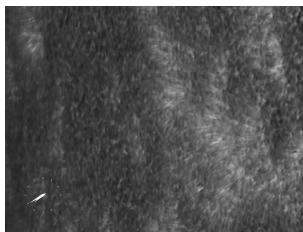
H α scene: RBE/RRE heating events, cooling contrails dark from non-E opacity

H α and Ca II 8542 Å



- both: heavy NLTE scatterers with $S \approx J$ sampled at similar $\tau = 1$ heights
- both: Saha-Boltzmann or larger extinction in shocks and ALC7
- core widths: both decrease away from network = decreasing temperature
- H α fibrils extend further, contradicting [Saha-Boltzmann extinction sensitivities](#)
fibril opacity in Ca II 8542 Å instantaneous, in H α post-hot non-E?

Ca II H & K and Mg II h & k

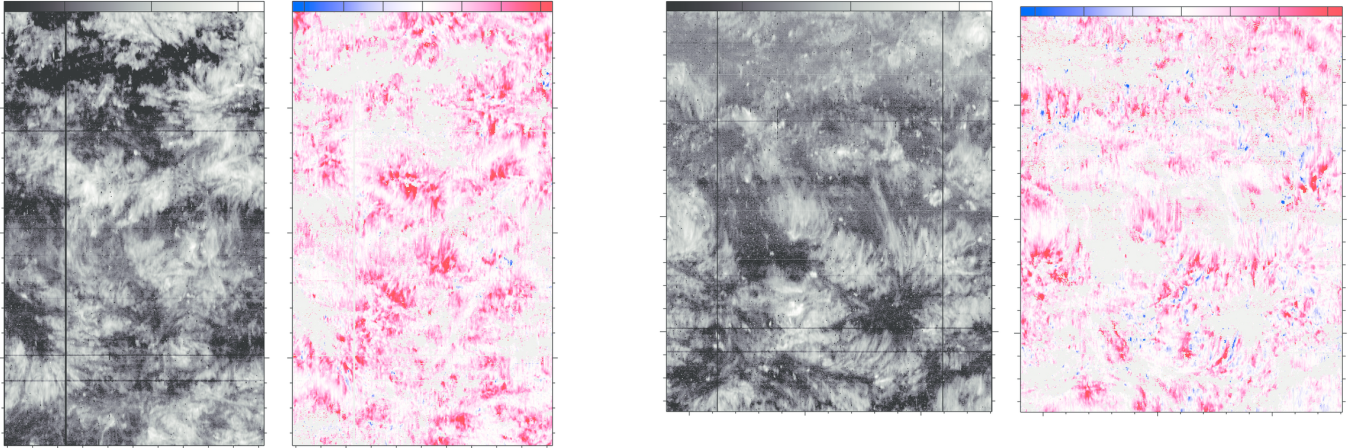


- both: heavy NLTE scatterers with PRD source function splits
- both: near-Saha-Boltzmann extinction everywhere; abundance ratio 18
- both: absence of non-E sensitivities = instantaneous chromosphere
- both: slender fibrils emanating from network, in Ca II H & K better at narrower bandwidth, in Mg II k best in k_2 peak separation

slender fibrils = propagating heating events?

CLOSED AND OPEN QUIET-SUN INTERNETWORK IN Si IV

Peter et al. in preparation



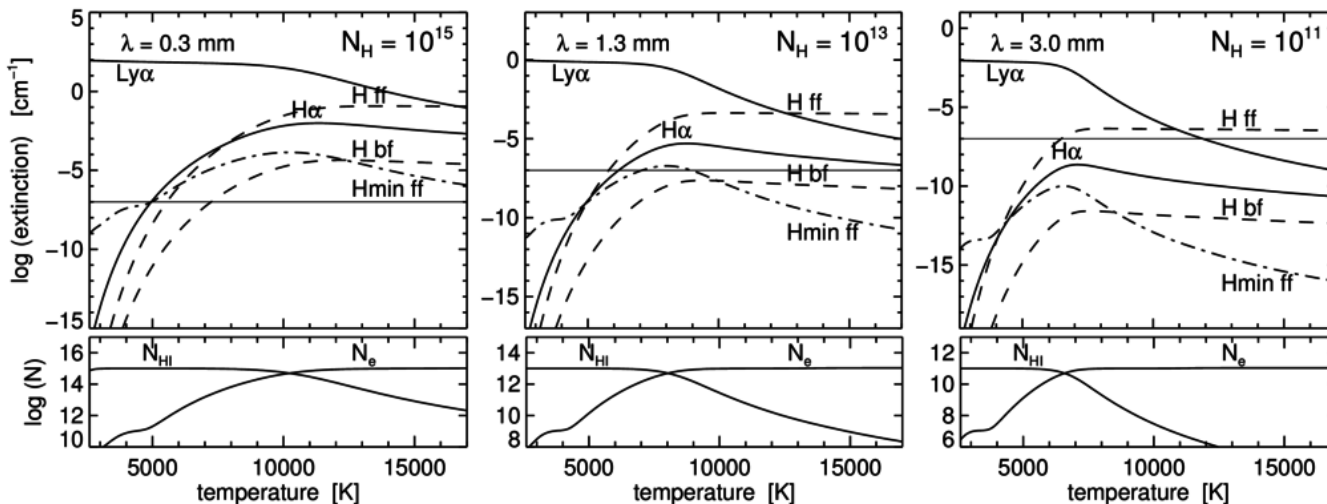
- thin to thickish (ratio < 2) line formation
- Gaussian fits
- widths \approx non-thermal widths

redshifted fibrils away from network \approx recombining $H\alpha$ contrails?

roundish coronal-hole blueshifts in network = down-throat heating events?

SAHA-BOLTZMANN HYDROGEN EXTINCTION AT ALMA WAVELENGTHS

Rutten 2017A&A...598A..89R 2017IAUS..327....1R (tutorial)



- LTE extinction: Ly α H α H I continua H $^-$ ff continuum 8542 other lines
- H α at high T: LTE extinction from $n_2 \approx n_2^{\text{LTE}}$ enforced by enclosed Ly α
- H ionization: $n = 2$ population fixed by (actually non-E) Ly α ; hydrogen top has additional NLTE-SE balancing between Balmer continuum and Balmer lines
- Balmer continuum $T_{\text{rad}} \approx 5250 \text{ K}$: overionization below, underionization above \Rightarrow de-steepening of these LTE H ff Boltzmann increases around 5250 K pivot
- $\alpha_{\nu}^{\text{ff}} \sim \lambda^2 N_e N_{\text{ion}} T^{-3/2}$ (RTSA Eq. 2.79) gives steep H ff increase between ALMA bands
- features with non-E post-hot H α extinction have larger to very much larger H ff extinction

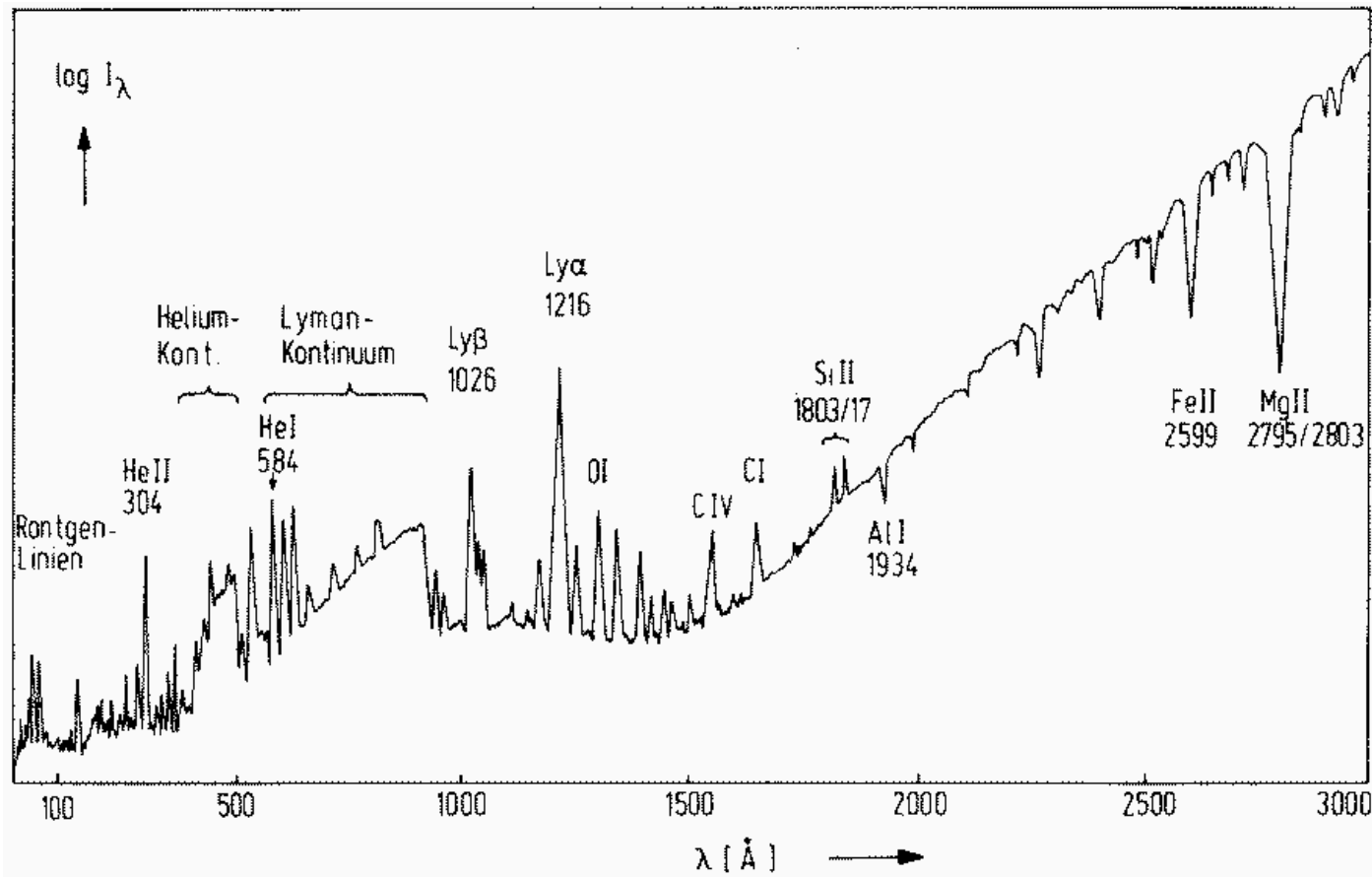
SOLAR RYDBERG LINES WITH ALMA?

Rutten 2017IAUS..327....1R

- “linear thermometer”
 - H^- free-free + H I free-free: $S \equiv B$
 - thick feature: $T_b = T(\tau_\nu = 1)$
 - thin feature: cloud contribution $\Delta T_b = \tau T$
- solar Rydberg lines so far
 - in μm range Mg I stronger than H I
 - prediction H I α lines $n = 4 - 18$
 - H I 19α , 21α observed at limb
- H I Rydberg lines with ALMA?
 - candidate: H I 30α in Band 6 (1.3 mm)
 - much stronger than above predictions from large post-hot non-E extinction?
 - if so, unblendedly present since Mg I etc are not non-E boosted?
 - on disk as $T(\tau_\mu = 1)$ emission at steep $T(\tau)$ gradient
 - at limb as τT extension
 - Zeeman in I and Stokes: super-sensitive chromospheric magnetometer?

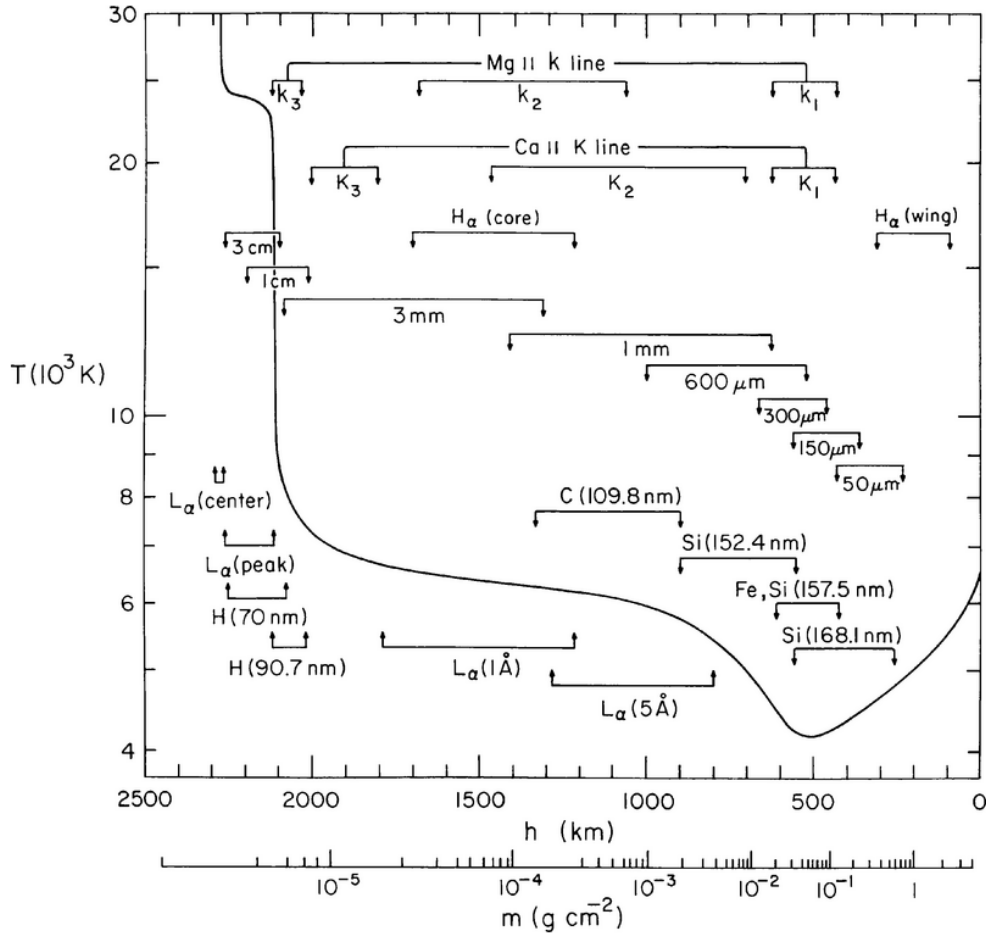
SOLAR ULTRAVIOLET SPECTRUM

Scheffler & Elsässer, courtesy Karin Muglach



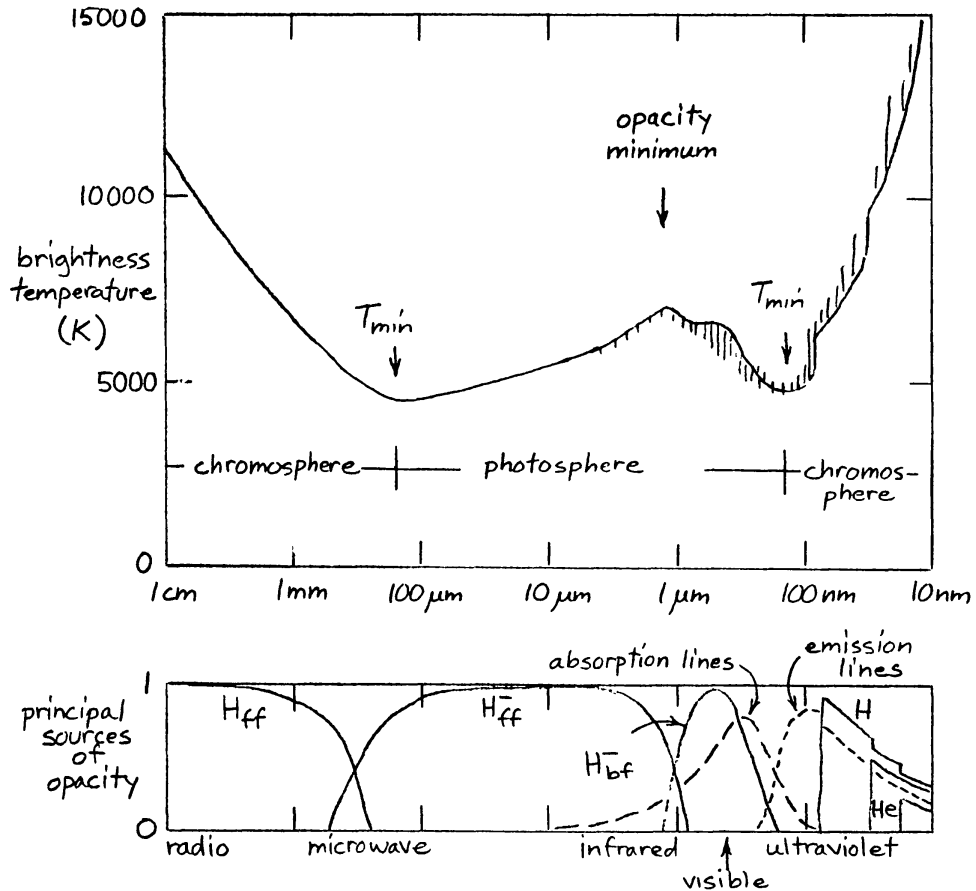
VALIIC MODEL

Vernazza, Avrett, Loeser 1981ApJS...45..635V



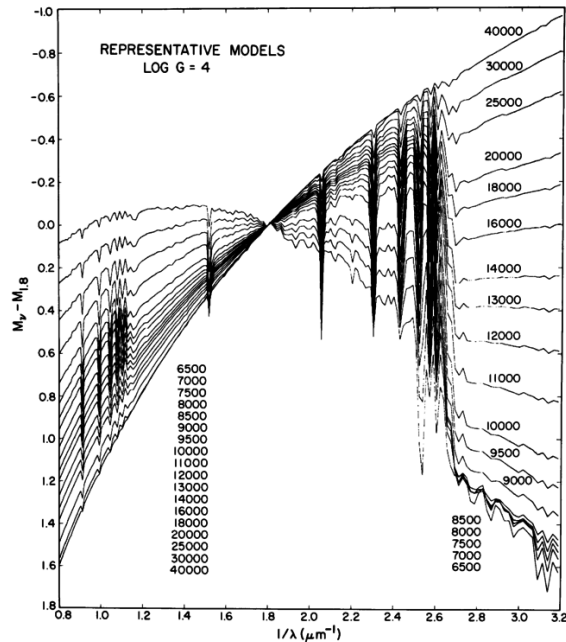
VALIIC SPECTRUM FORMATION

Avrett 1990/AUS..138....3A



KURUCZ STARS

Kurucz ATMOS program = LTE-RE-HE 1979ApJS...40....1K



- color $M_V - M_{1.8}$
- $1/\lambda = 1.8 \mu\text{m}^{-1}$: $\lambda = 555 \text{ nm} = \text{UBV color } V$
- Balmer edge at $1/\lambda = 2.74 \mu\text{m}^{-1}$
- Paschen edge at $1/\lambda = 1.22 \mu\text{m}^{-1}$

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Robert J. Rutten

<https://webspacescience.uu.nl/~rutte101>

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thick: UV line flip VAL3C temperature VAL3C spectrum Kurucz stars

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continua from VAL3C: Avrett models versus 3D MHD VAL3C continua
VALII budget hydrogen budget all

lines from ALC7: model optical spectrum ultraviolet depletion hydrogen
strong lines plot formats pops plot BSJ plot profile plot Mg I 4571
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Ly α H α H β He I 584 He I 10830 canonical H α Na I D₁-Mg I b₂
Ly α -H α H α -Ca II 8542 Å Ca II K-Mg II k versus FCHHT-B ALC7-FALC
FALC-FALP ALC7-FALP

detour lines: pumping suction

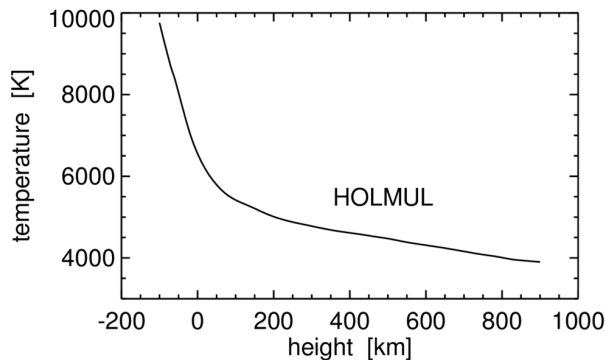
Oslo-simulated dynamic atmosphere: 1D RADYN 3D Bifrost Bifrost line synthesis

LA-conjectured PSBE atmosphere: non-E H α aureole boosting H α extinction
CE-SB EBs spicules-II contrail ALMA non-E chromosphere?

IRIS diagnostics: overview diagnostics

THE MOST SUCCESSFUL INVERSION EVER

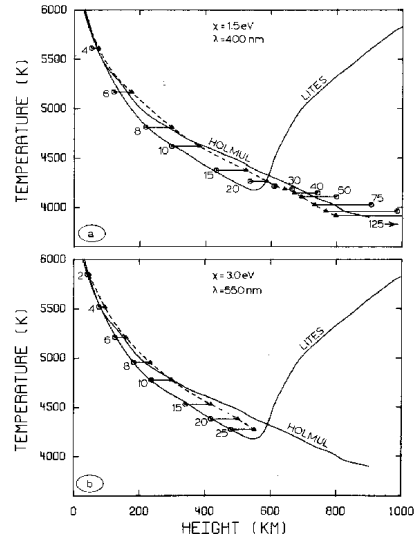
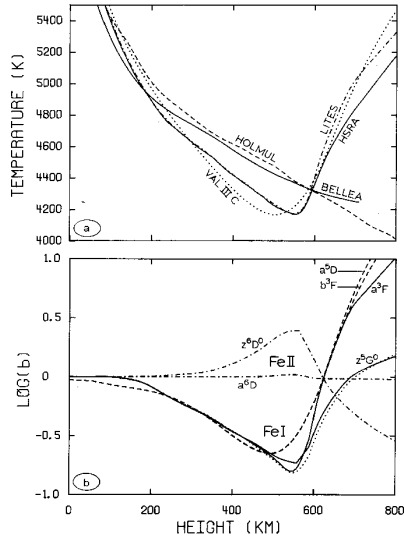
Holweger 1967ZA.....65..365H (243 cites); Holweger & Müller 1974SoPh...39...19H (over 800 cites)



- PhD thesis: empirical LTE fit of the optical continuum and the [depths of 900 lines](#)
- very similar to subsequent “theoretical” radiative-equilibrium models
- HOLMUL = update (fitting Ba II lines) preferred in all pre-Asplund abundance determinations *because* it has no chromosphere – but also no granulation
- “[...] Among the problems that need further study are deviations from LTE. Unfortunately, these are easily arising in the computer if important collisional processes are neglected, or if radiative rates are not realistic. In cool stars, collisional excitation by hydrogen atoms is generally neglected [...] However, in the Sun, hydrogen atoms outnumber the free electrons by a factor of 10000. The UV radiation field is complicated by a vast number of absorption lines ...”

NLTE MASKING

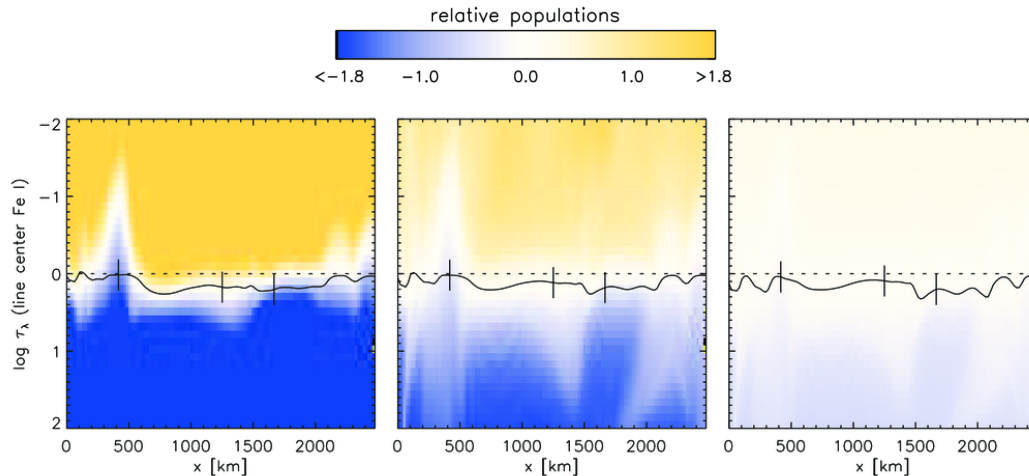
Rutten & Kostik 1982A&A...115..104R



- VALIIC \approx LITES steeper decline than HOLMUL \approx BELLEA
- ultraviolet bf scattering causes Fe I underopacities
- strong-line bb scattering causes Fe I source function deficits
- ultraviolet bb pumping causes Fe II source function excesses
- empirical LTE line depth fitting á la Holweger:
 - opacity-deficient Fe I cores suggest too small height
 - scattering Fe I cores suggest too low temperature
 - pumped Fe II cores suggest too high temperature

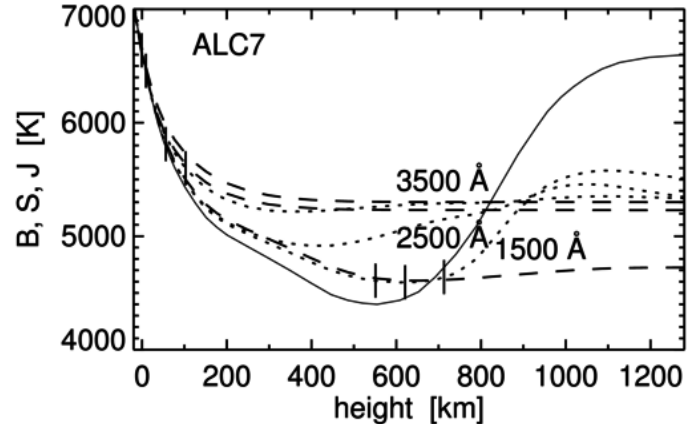
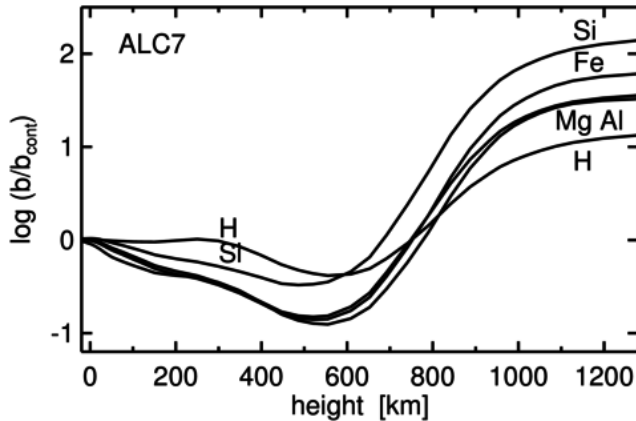
MILNE-EDDINGTON APPROXIMATION IN A MURaM SIMULATION

Vitas et al. 2009A&A...499..301V



- representative weak Fe I line with excitation energy 0, 3, and 6 eV; transition probability scaled to obtain the same emergent line strength
- dotted curve: line-center $\tau = 1$ (normalization)
solid curve: continuum $\tau = 1$. Its modulation represents line-core Doppler brightening. The line vanishes from ionization within a magnetic concentration at $x = 400$ km
- first panel: increasing Fe ionization and corresponding H^- increase at larger depth cause very steep gradients in normalized populations $\sim \eta \equiv \alpha^l / \alpha^c$
- other panels: increasing compensation from Boltzmann excitation factor
- upshot: Milne-Eddington approximation better at higher excitation

ULTRAVIOLET DEPLETION IN THE ALC7 ATMOSPHERE



minority atoms: photospheric extinction depletion by ultraviolet bound-free scattering

- ultraviolet bound-free edges produce scattering continua
- $J > B$ from:
 - $T(h)$ gradient defined by radiative equilibrium for the optical
 - $B(h)$ steeper in the ultraviolet due to Wien nonlinearity
 - Λ operator gives $J > S$ for steep $S(\tau)$
 - deep escape from small H I bf extinction
- b_1/b_{cont} for electron donors Mg I, Fe I, Si I and Al I imply b_1 population depletion across photosphere because $b_{\text{cont}} \approx 1$
- their photospheric lines have increasing extinction deficits compared to LTE
- b_2/b_{cont} for H I shows similar behavior for the top of the hydrogen atom starting at $n=2$

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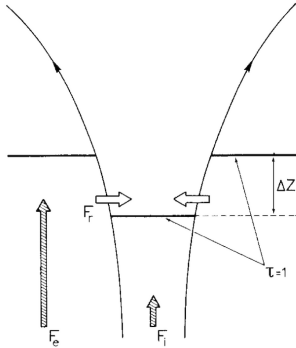
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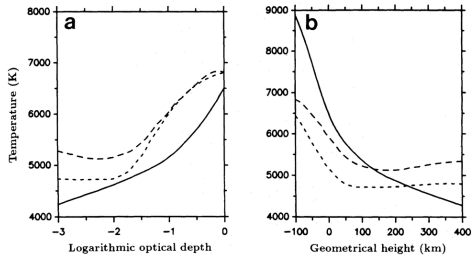
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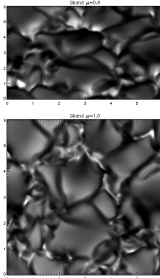
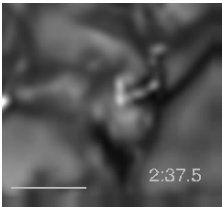
FLUX TUBES



- 1970s: *Utrecht fluxtube paradigm*
 - magnetostatic equilibrium: flaring
 - evacuation: Wilson depression
 - thin tube: hot walls bright, brighter limbwards

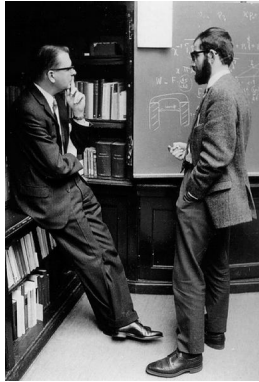


- 1980s: *Zürich unsharp 1.5D models*
 - McMath-Pierce FTS Fe I & Fe II Stokes V
 - assume magnetostatic geometry
 - spatially-averaged LTE Stokes profile fitting
 - flatter-than-RE temperature gradient



- 1990s+: *sharp observations and simulations*
 - enhanced contrast in G band, strong-line wings
 - rapid morphology change, much vorticity
 - near-limb faculae: see-through into granules

1970s magnetostatic fluxtubes



Kees Zwaan & Hans Rosenberg

PRESSURE EQUILIBRIUM AND ENERGY BALANCE OF SMALL PHOTOSPHERIC FLUXTUBES

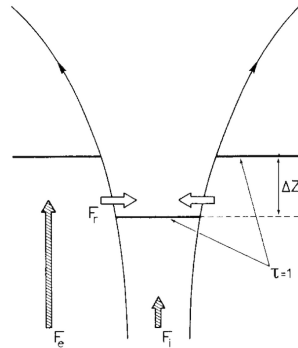
H. C. SPRUIT

The Astronomical Institute of the University of Utrecht, The Netherlands

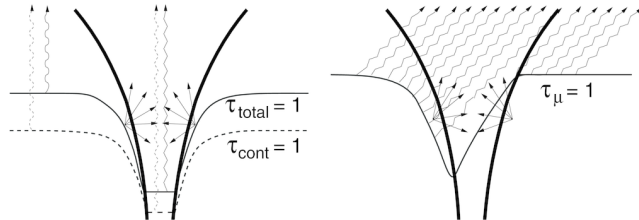
(Received 12 July, 1976)

Abstract. Field configurations and temperature distributions of axially symmetric fluxtubes are determined on the basis of pressure equilibrium and energy balance of the tubes. The description concentrates on layers below ≈ 600 km above the photosphere; a magnetostatic field, and energy transport by a diffusion process are assumed. It is assumed also that the magnetic field of the tubes prevents convective flow across the field lines, so that only radiative energy exchange between the tube and the convection zone is present. A set of model tubes is presented ranging in size from facular points (150 km) to small pores (1000 km), for different values of the field amplitude and the asymptotic energy flux F_e flowing along the tube from the deeper layers. Radial influx of heat into the tube at the photospheric level influences the temperature in the tube strongly for all these models. For a pore-like tube $F_e = 0.25$ (similar to the flux from a spot umbra) seems appropriate if F_e in units of the normal photospheric flux. If in the smallest fluxtubes F_e is also 0.25, a comparison of the intensity contrast with observations of facular points indicates that the radius of tubes corresponding to facular points is 50–100 km. In the continuum the structure looks like a depression in the photosphere (similar to the Wilson depression of spots). The magnitude of this depression is ≈ 200 km for pores of 1000 km diameter and ≈ 100 km for facular points. The walls of the hole created by the depression contribute considerably to the contrast of structures observed near the solar limb. It is shown how this contribution may explain the centre to limb behaviour of facular contrast as seen in the continuum, and why the continuum CLV differs so strongly from that in line cores. Over the first 400 km above the photosphere the tube expands by a factor of ≈ 2 for all the tubes calculated.

Spruit 1976SoPh...50..269S

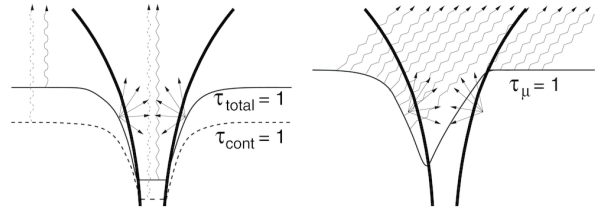


Zwaan 1978SoPh...60..213Z



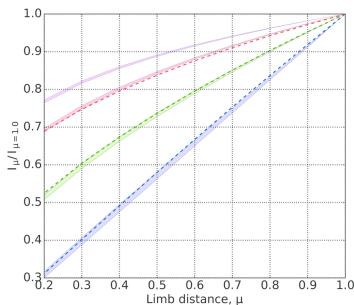
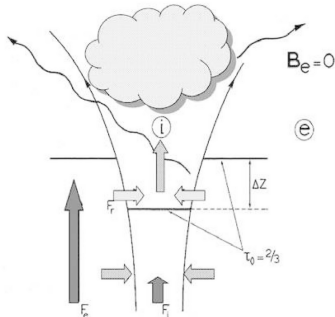
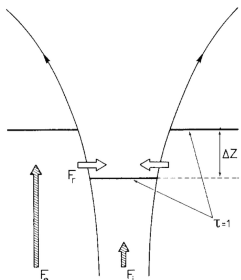
Rutten 1999ASPC..184..181

MAGNETIC BRIGHT POINTS



- *high-resolution observation*
 - Berger et al. 2004A&A...428..613B: G-band bright points as ribbons and flowers
- *high-resolution simulation*
 - Keller et al. 2004ApJ...607L..59K: continuum faculae simulation
 - Carlsson et al. 2004ApJ...610L.137C: G-band faculae simulation
- *bright points in $H\alpha$*
 - DOT $H\alpha$ movie 2004-10-06
 - Leenaarts et al. 2006A&A...449.1209L: bright points in $H\alpha$
 - Leenaarts et al. 2006A&A...452L..15L: comparison of bright-point diagnostics
- *less bright points in “normal” lines*
 - Vitas et al. 2009A&A...499..301V: only Mn I lines are not mucked up by granulation

MODELING NETWORK / PLAGE MAGNETISM FOR SPECTRAL IRRADIANCE



- *golden age of fluxtube modeling = hole in surface*
 - Zwaan – Spruit: **idealized** magnetostatic fluxtubes
 - Stenflo – Solanki – Keller: unresolved FTS polarimetry
 - Steiner – Keller – **Carlsson**: realistic MHD simulations
- *bright-point enhancements = hole deepening*
 - CH G-band, CN 3883 band: dissociation
 - Fe I line gaps: ionization
 - Balmer line wings: small collision broadening
 - Mn I line cores: large hyperfine broadening
- *dark age of 1D irradiance modeling = down the rabbit hole*
 - “chromospheric cloud” \Rightarrow “photosphere heating”
 - **FALP** > **FALC fudge** \Rightarrow SATIRE (ADS N39 H13)
 - **1600 Å – 1700 Å** [SST/CHROMIS Ca II K wing scans]
- *coming age of simulation irradiance modeling \Rightarrow of age \sim 1D \Rightarrow 3D abundances (“pre/post Asplund”)*
 - **first step: MURaM with LTE**
 - to do: 3D(t) MHD with NLTE, line haze, H NSE?

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FALC-FALP ALC7-FALP

detour lines: pumping suction

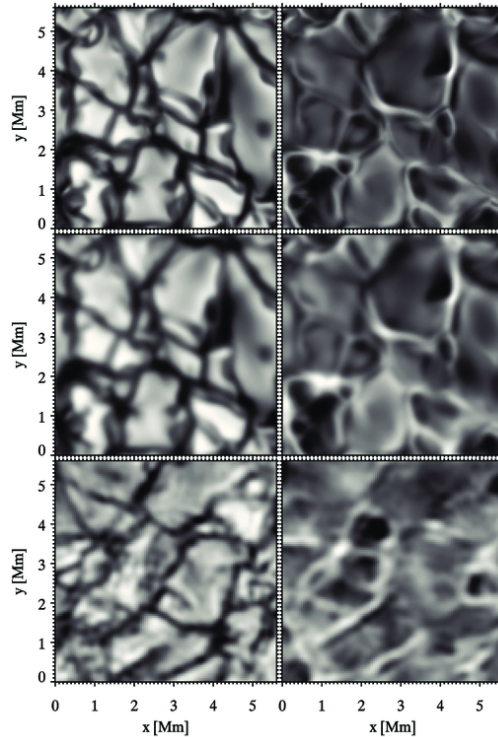
Oslo-simulated dynamic atmosphere: 1D RADYN 3D Bifrost Bifrost line synthesis

LA-conjectured PSBE atmosphere: non-E H α aureole boosting H α extinction
CE-SB EBs spicules-II contrail ALMA non-E chromosphere?

IRIS diagnostics: overview diagnostics

REVERSED GRANULATION OBSERVATION & SIMULATION

Leenaarts & Wedemeyer-Böhm 2005A&A...431..687L

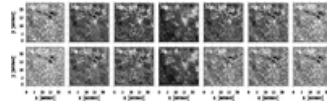


- observation similar to simulation so phenomenon “explained”
- no magnetism since pure hydro simulation (CO⁵BOLD)
- internal gravity waves?

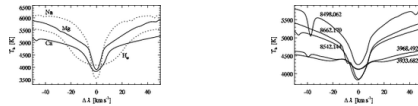
OBSERVATION & SIMULATION OF Na I D₁, Mg Ib₂, Ca II 8542 Å

Rutten et al. 2011A&A...531A..17R

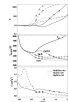
- SST images blue wing - core - red wing



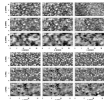
- atlas profiles



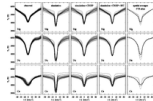
- FALC formation



- Dopplergram comparisons



- profile comparisons



- upshot
- simulation \approx observation but computed Ca II 8542 Å is much too narrow
 - difference in showing reversed granulation is set by reversed intensity–Dopplershift correlation sampled differently by different inner-wing steepness
 - Na I D₁ Dopplergrams are upper-photosphere kilogauss magnetograms

SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten

<https://webspacescience.uu.nl/~rutte101>

thin: cloud modeling corona chromosphere Rydberg per ALMA?

thick: UV line flip VAL3C temperature VAL3C spectrum Kurucz stars

photospheric lines: inversions bright points reversed granulation Na I D1 MGs
limb emission lines

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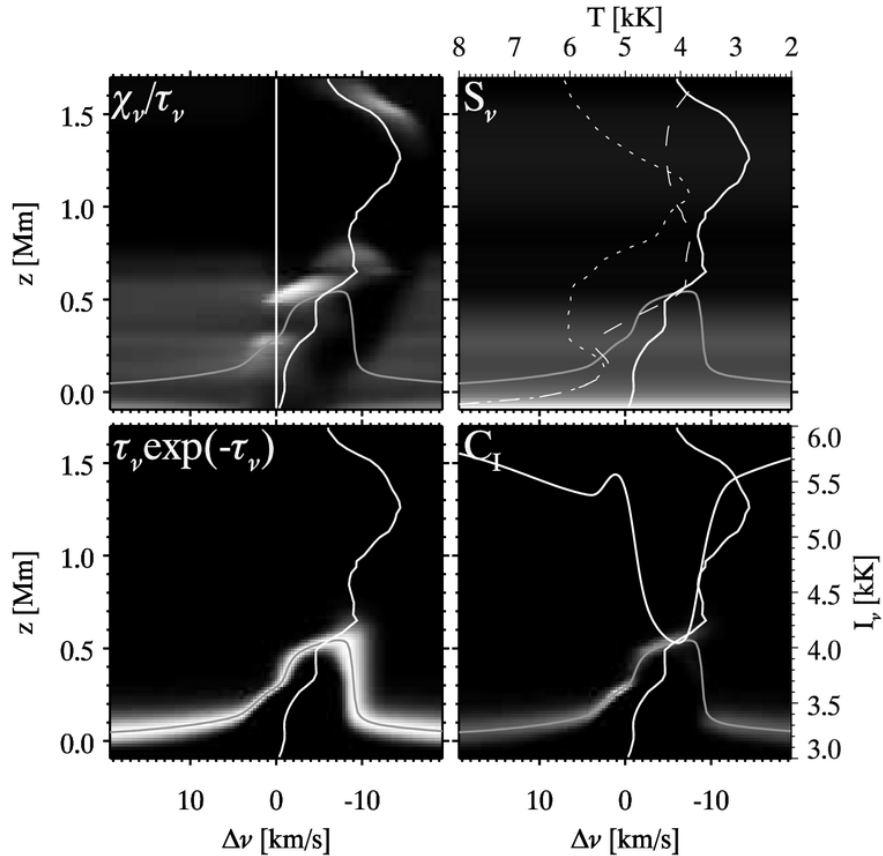
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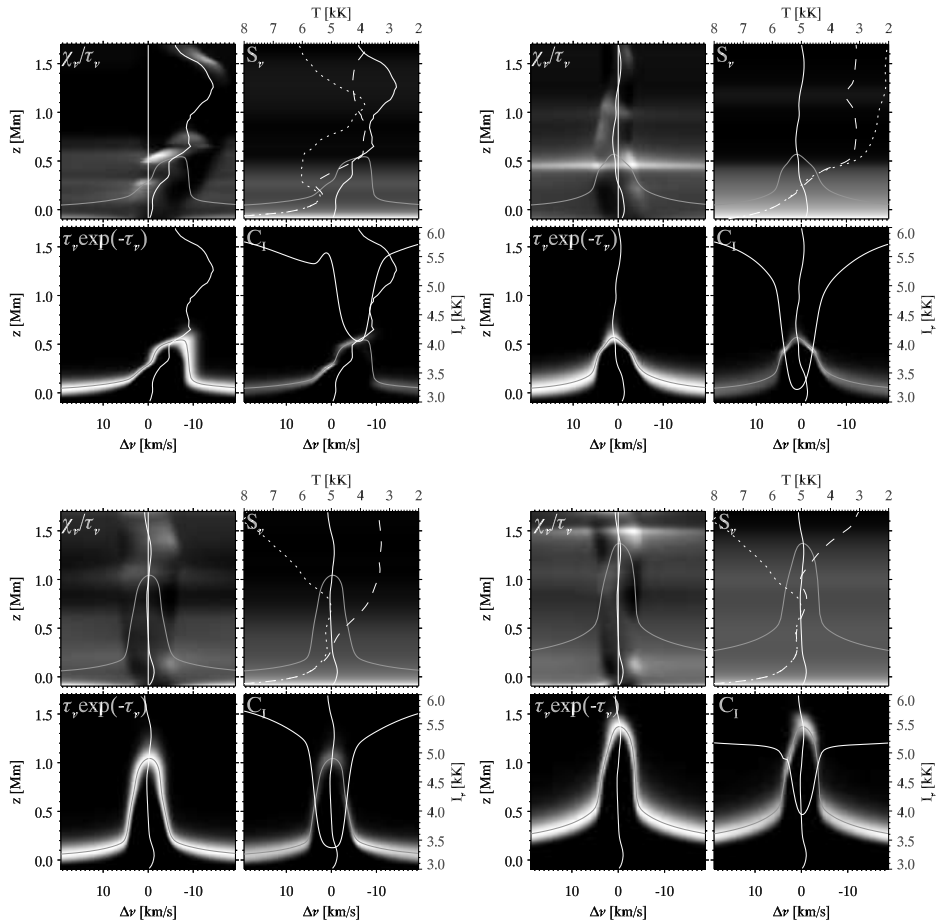
Na I D₁ IN A MAGNETIC CONCENTRATION

Leenaarts et al. 2010ApJ...709.1362L



FORMATION BREAKDOWNS Na I D₁ & Ca II 8542 Å

Leenaarts et al. 2010ApJ...709.1362L



Rutten et al. 2011A&A...531A..17R

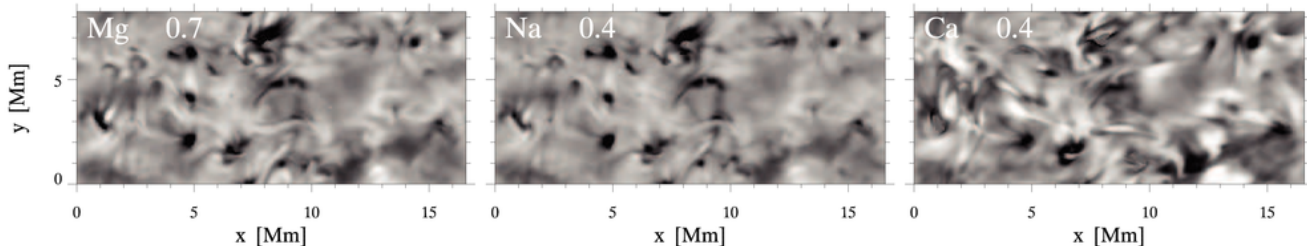
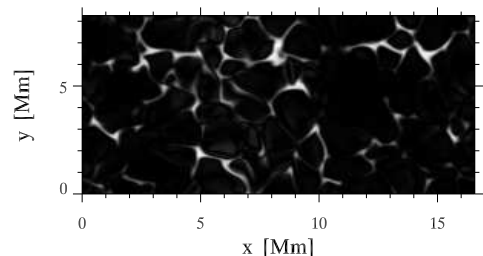
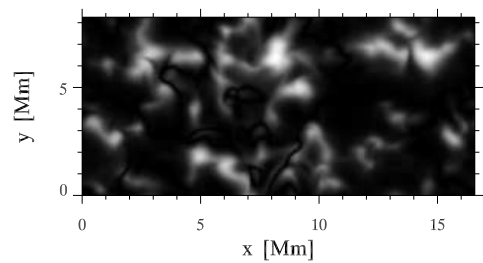


Fig. 16. Dopplergrams from the simulation as in the bottom row of Figure 7 but closer to line center and with only CRISP spectral smearing, no spatial PSF smearing.

$|B_z|$ at $h = 0$ km



$|B_z|$ at $h = 500$ km



A corollary is that searches for global g -modes and so-called “chromosphere seismology” using full-disk resonance-cell sampling of the Na line as with GOLF-NG (e.g., [Turck-Chièze et al. 2006](#); [Salabert et al. 2009](#)) will suffer noise from reversed granulation just as classical helioseismology suffers noise from granulation. Magnetic concentrations contribute much noise (literally) by their shocks. GOLF-NG’s 15 passbands, spread over $\Delta\lambda = \pm 9 \text{ km s}^{-1}$, have $FWHM = 30 \text{ m\AA}$, half CRISP’s passband in this line and clearly narrow enough. Interpretation of such multi-passband oscillation sampling that relies on one-dimensional height-of-formation interpretation, for example to diagnose upward propagation from inward phase difference, is likely to fail since the clapotospheric signals are better described as clouds of varying opacity at varying height of which the varying Dopplershifts act as shutters obscuring the inner line wings.

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IRIS diagnostics: overview diagnostics

LIMB EMISSION LINES

- *tabulations*
 - Menzel, thesis 1930, Pubs. Lick Obs., Campbell eclipse spectra, ADS antiquities
 - Dunn et al. 1968ApJS...15..275D HAO eclipse spectra [comprehensive plot](#)
 - Pierce 1968ApJS...17....1P extreme limb spectra [plate with Mg I 4571 Å](#)
 - Rutten & Stencel 1980A&AS...39..415R limb emission lines in Ca II H & K wings
 - Rutten + XX: limb emission lines in [Mg II h & k wings](#)
- *rare earths*
 - Canfield 1971A&A...10...54C [excerpt](#) 1971A&A...10...64C [excerpt](#)
 - interlocking $\Rightarrow \eta > \varepsilon \Rightarrow S > B$ with much spatial smoothing
 - higher emission for larger quasi-continuous extinction (Ce II in H & K wings)
- *pumped ion lines*
 - Fe II 3969.4 Å between Ca II H and H ϵ : Cram et al. 1980ApJ...241..374C [excerpt](#)
 - subordinate lines sharing upper levels with strong UV lines
 - large sensitivity to deep temperature variations
- *strong lines with PRD wings*
 - Ba II 4554 Å: Rutten 1978SoPh...56..237R [excerpt](#) 1979ApJ...231..277R [excerpt](#)
 - others: Fe II, Ti II, ...
- *LTE lines*
 - Mg I 4571 Å Rutten 1977SoPh...51....3R [excerpt](#)

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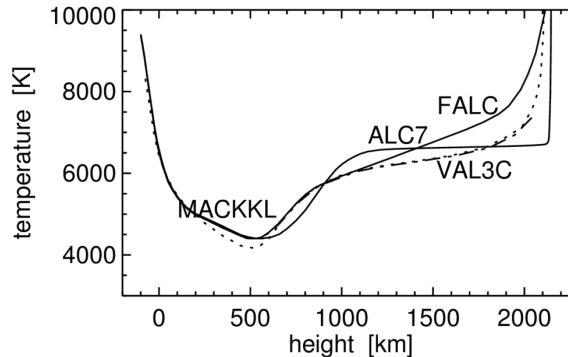
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IRIS diagnostics: overview diagnostics

AVRETT SOLAR-ANALOG STARS

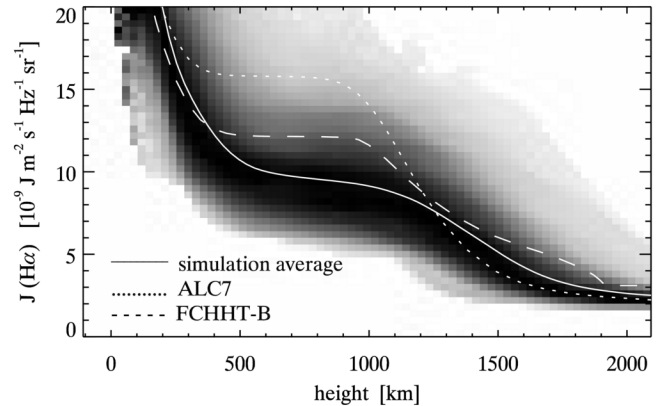
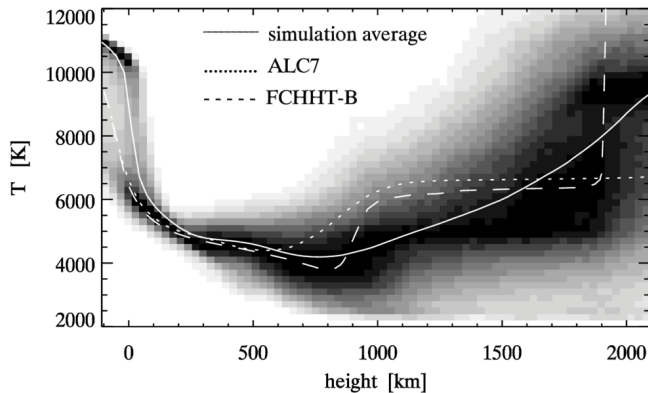


- VAL3C = Vernazza, Avrett, Loeser 1981ApJS...45..635V: best-fit to UV continua
- MACKKL = Maltby et al. 1986ApJ...306..284M: less steep upper photosphere
- FALC = Fontenla, Avrett, Loeser 1993ApJ...406..319F: ambipolar diffusion
- ALC7 = Avrett & Loeser 2008ApJS..175..229A: UV-line fit; update 2015ApJ...811...87A

[...] *The results may be interpreted as holding for a computationally existing star called VALIII [...]. This star is remarkably like the Sun in its temporally and spatially averaged continuous spectral distribution, but in contrast to the Sun it does obey hydrostatic equilibrium and static plane-parallel geometry, and it contains only those atoms, ions and electrons that were specified in the Pandora code, fortunately with just the corresponding cross-sections. Its modeling is exact! The advantage of studying the star VALIII rather than the star Sol is that the physics of VALIII radiation is fully understandable. Also, it keeps adhering to these course notes ad infinitum while solar physics evolves to more complexity.*

Rutten “Radiative Transfer in Stellar Atmospheres”

OSLO SIMULATION VERSUS 1D STANDARD MODELS

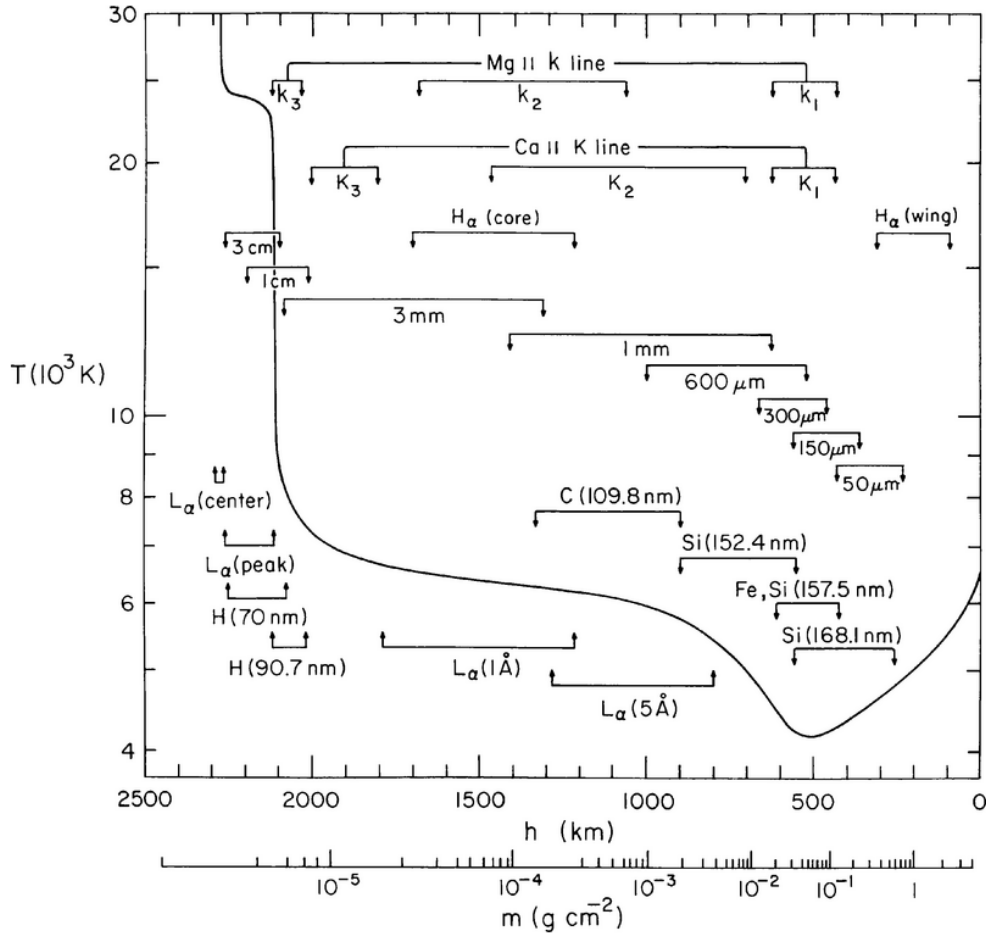


- simulation = state-of-the-art: 3D(t), \vec{B} , non-HE, SE populations but NE for H
Leenaarts, Carlsson & Rouppe van der Voort [2012ApJ...749..136L](#)
- ALC7 = UV fit: 1D static, no \vec{B} , HE + microturbulence, SE populations
Avrett & Loeser [2008ApJS..175..229A](#)
- FCHHT-B = UV fit: 1D static, no \vec{B} , HE + imposed acceleration, SE populations
Fontenla, Curdt, Haberreiter, Harder & Tian [2009ApJ...707..482F](#)

The T and $J_\nu(\text{H}\alpha)$ behavior seems arguably similar. However, the conceptual differences between plane-parallel static hydrostatic-equilibrium modeling and the 3D(t) MHD simulation are enormous (cf. Newtonian gravitation versus general relativity). The $T(h)$ stratifications in the simulation vary tremendously, with shocks propagating upwards and sideways and the increase to coronal temperature dancing up and down over a large height range.

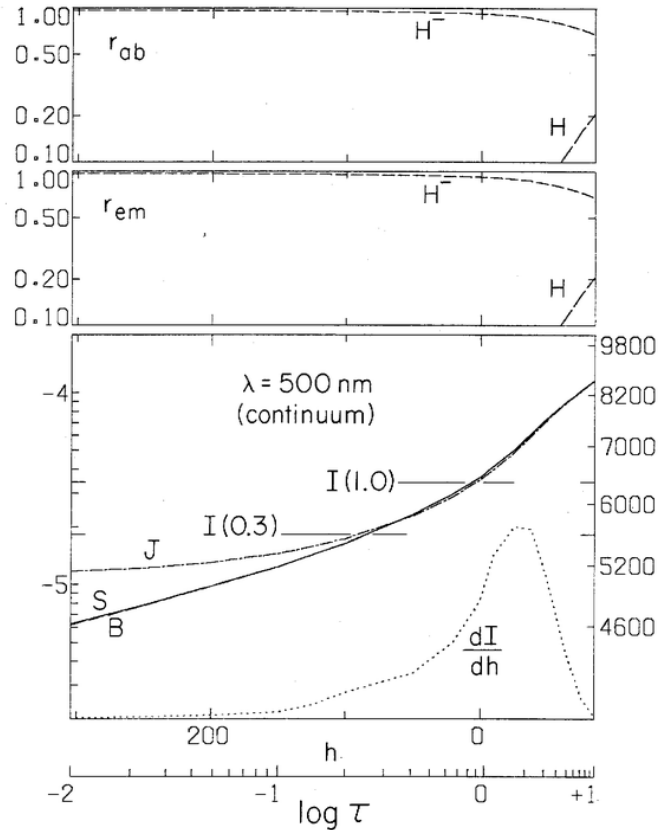
VALIIC MODEL

Vernazza, Avrett, Loeser 1981ApJS...45..635V

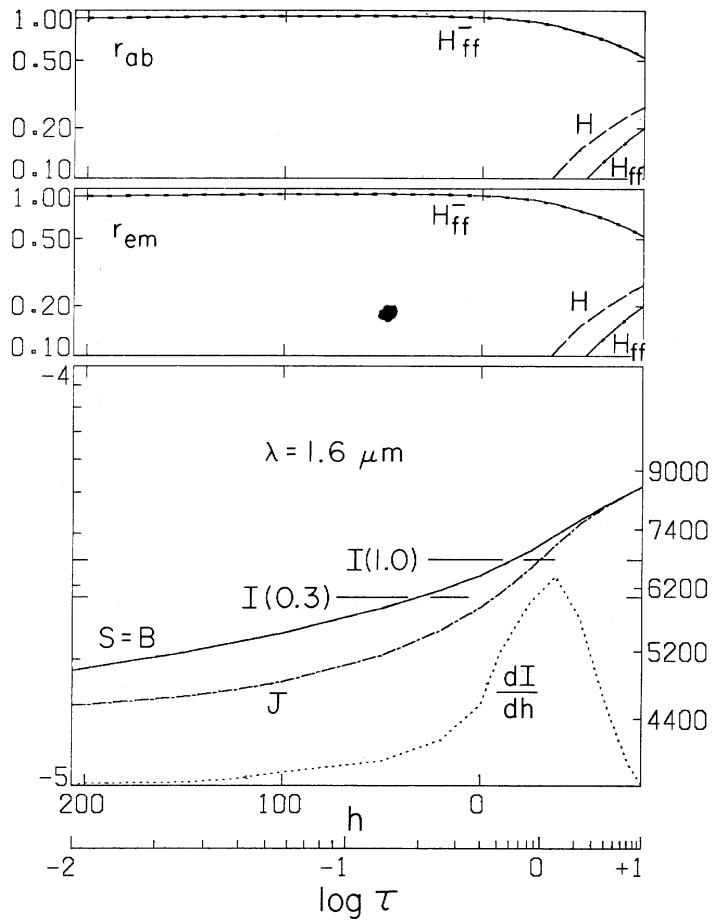
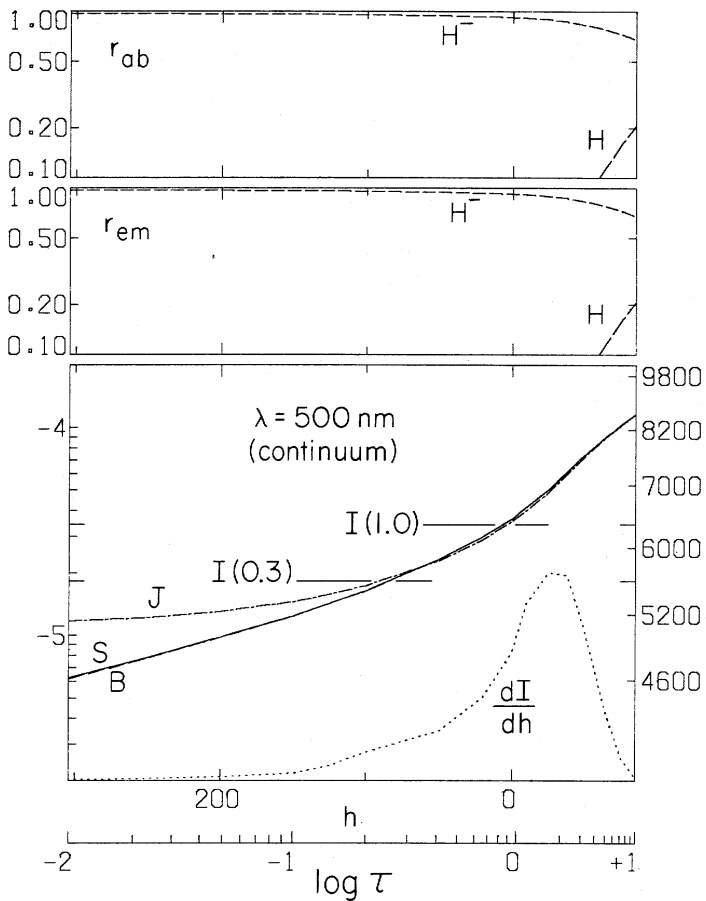


VALIIC 500 nm FORMATION

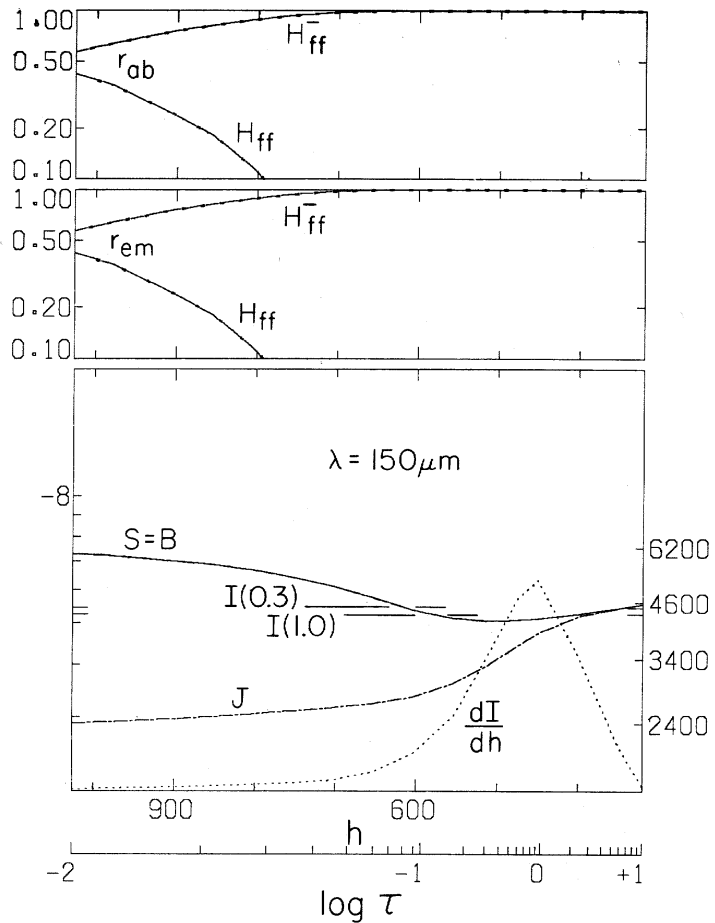
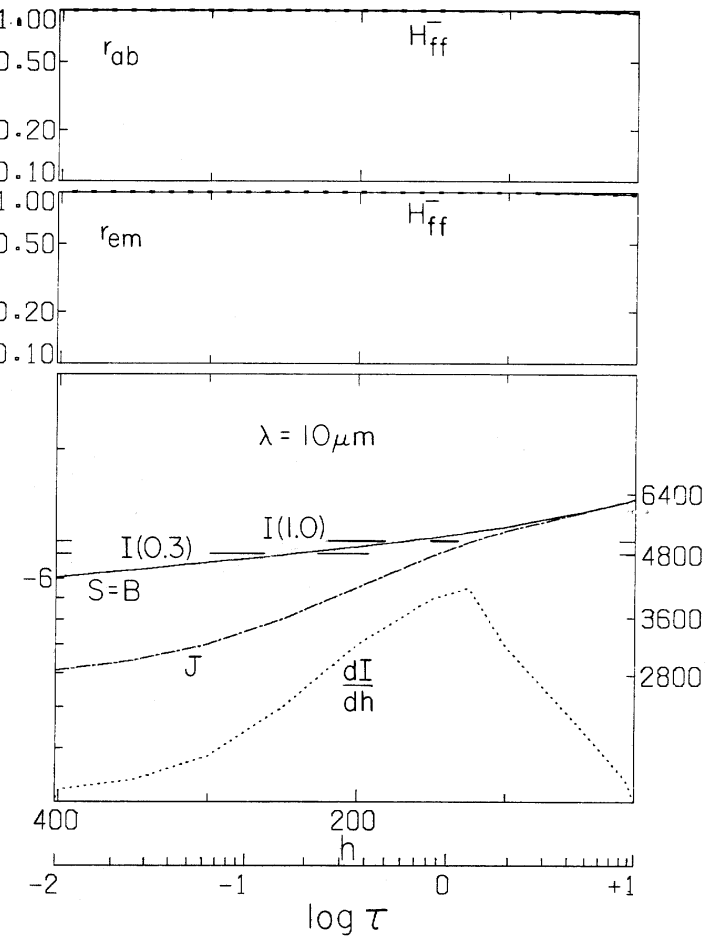
$$I_\nu(0,1) = \int_0^\infty S_\nu e^{-\tau_\nu} d\tau_\nu = \int_0^\infty j_\nu e^{-\tau_\nu} dh \quad \frac{dI_\nu}{dh} = j_\nu e^{-\tau_\nu}$$



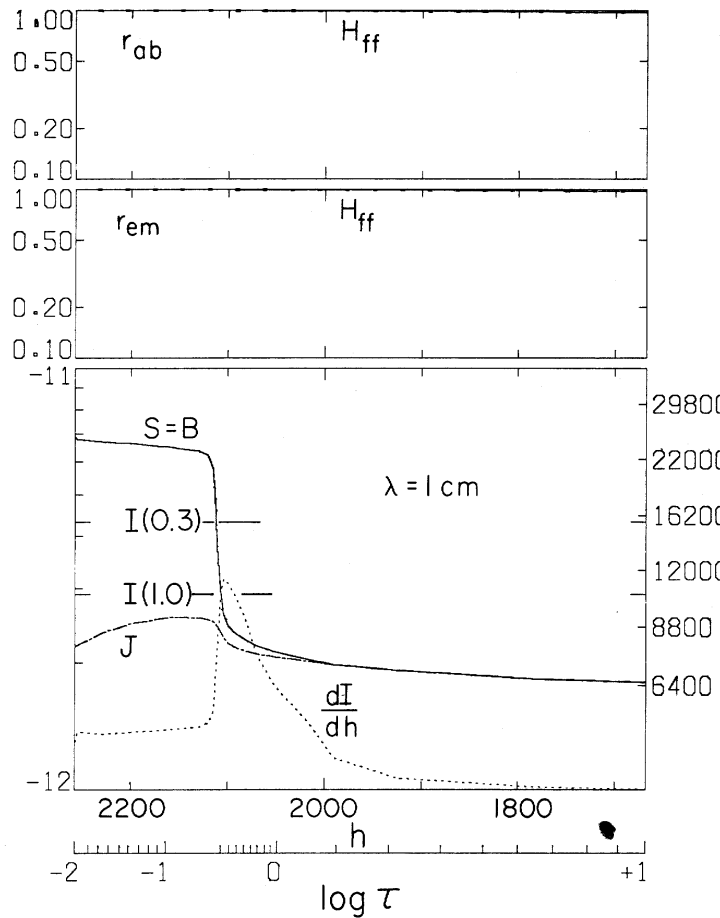
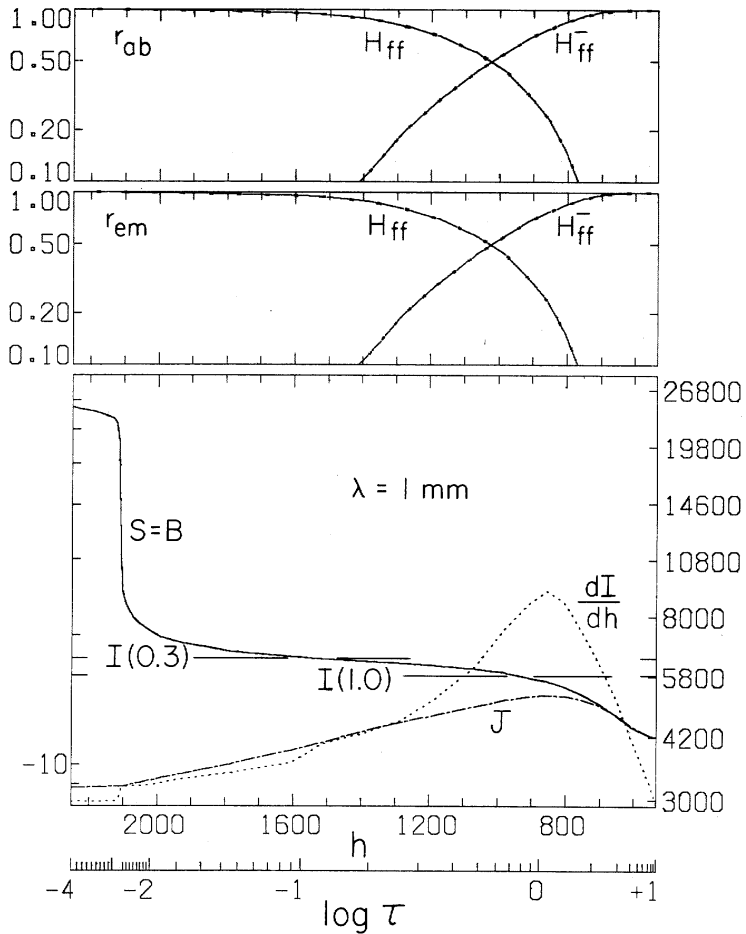
VAL3C CONTINUUM FORMATION



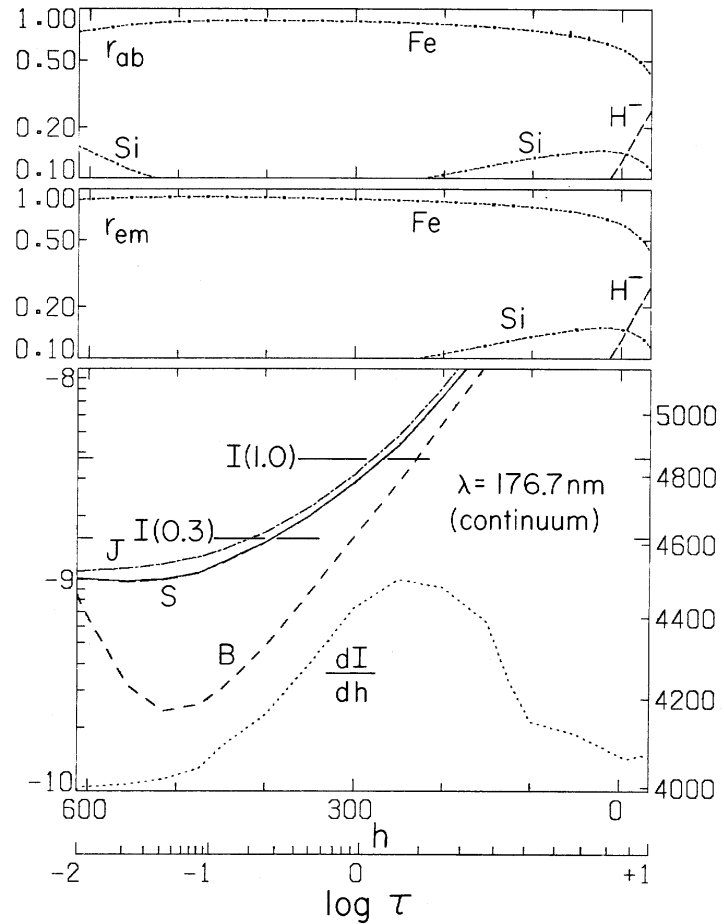
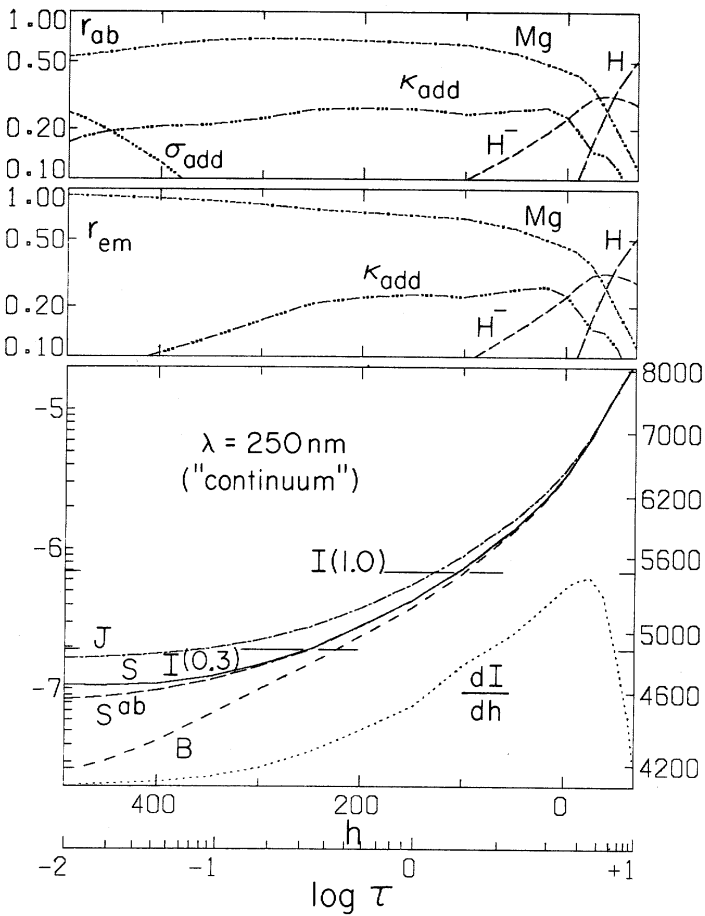
VAL3 CONTINUUM FORMATION



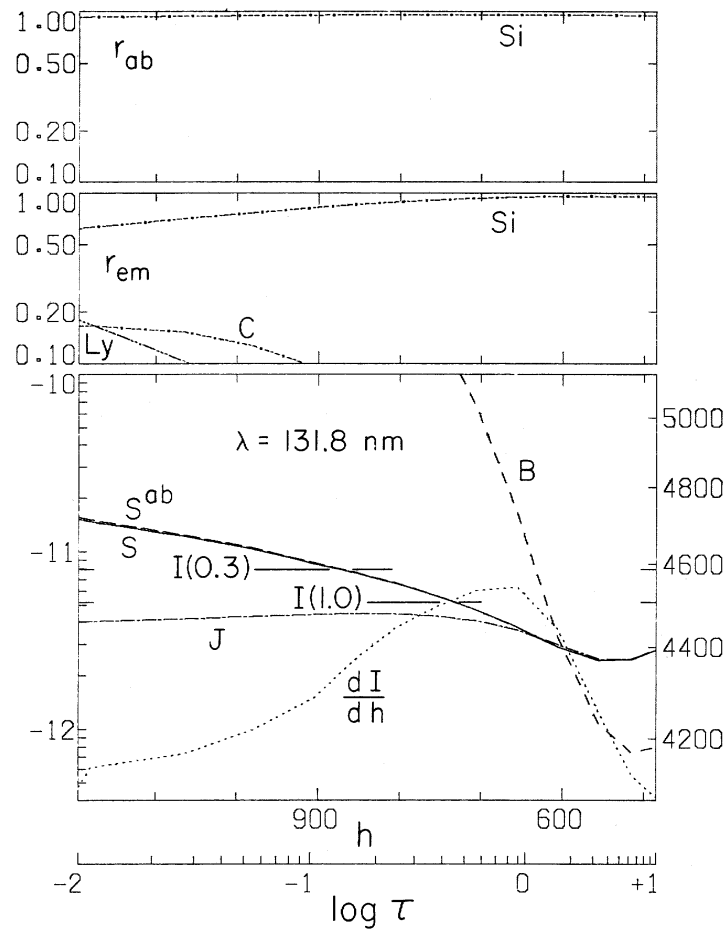
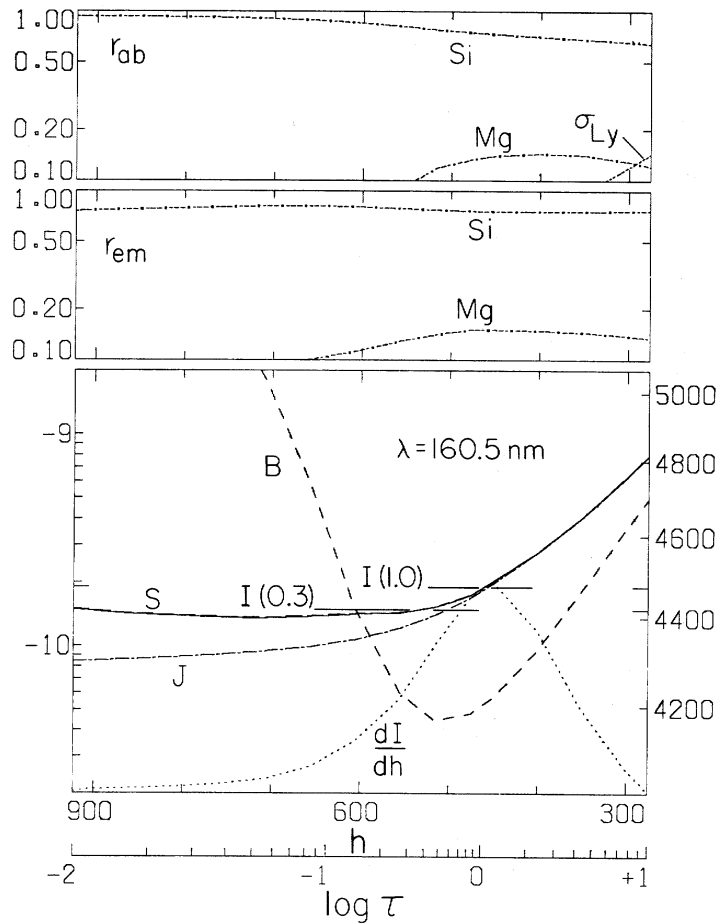
VAL3 CONTINUUM FORMATION



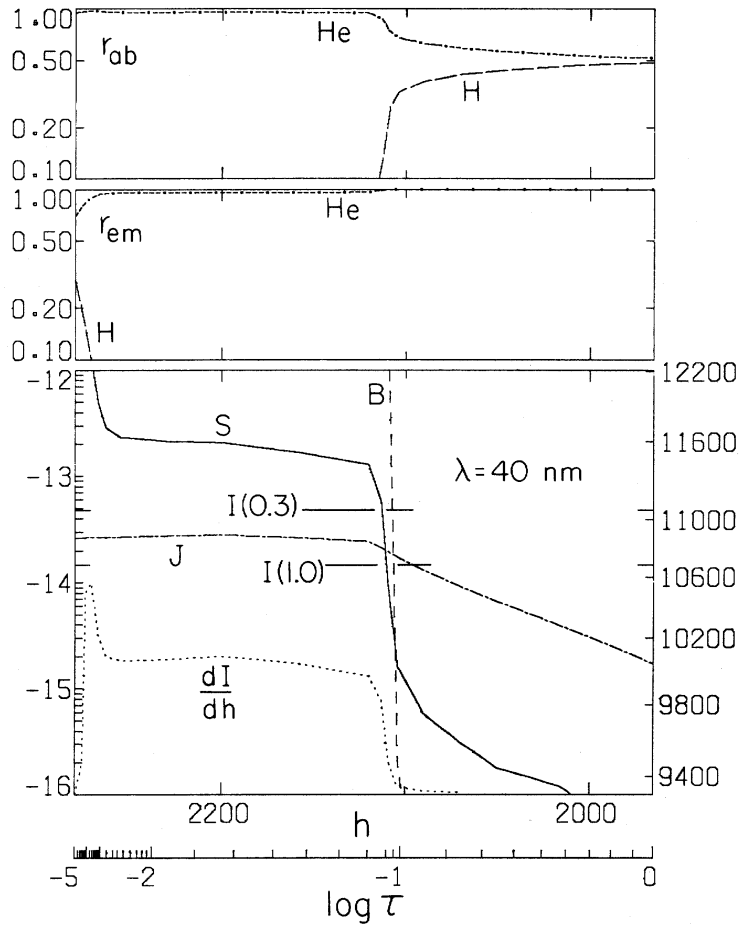
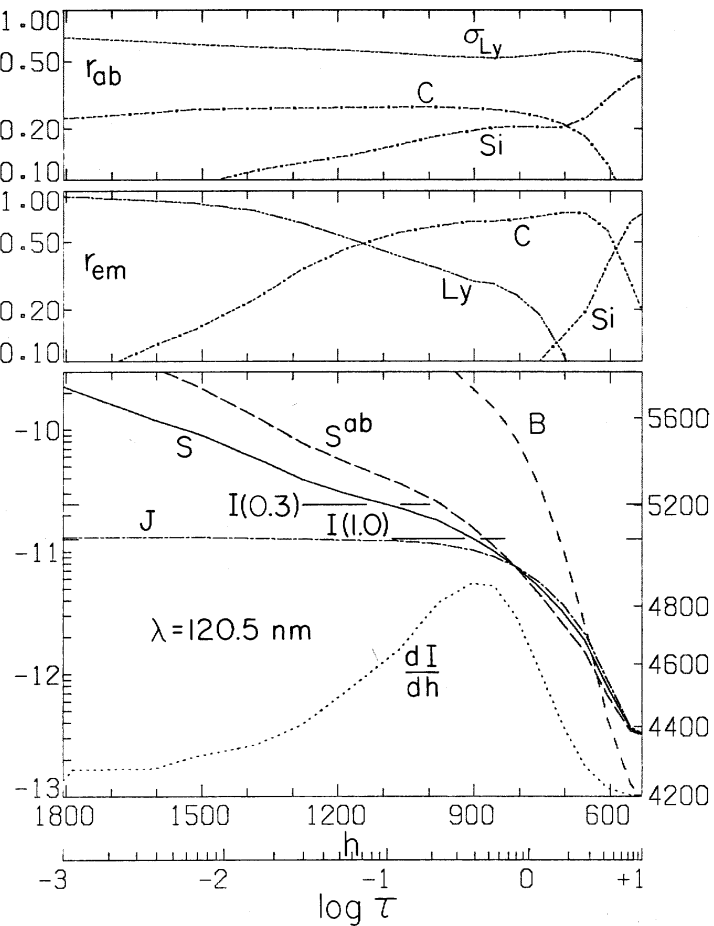
VAL3C CONTINUUM FORMATION



VAL3C CONTINUUM FORMATION

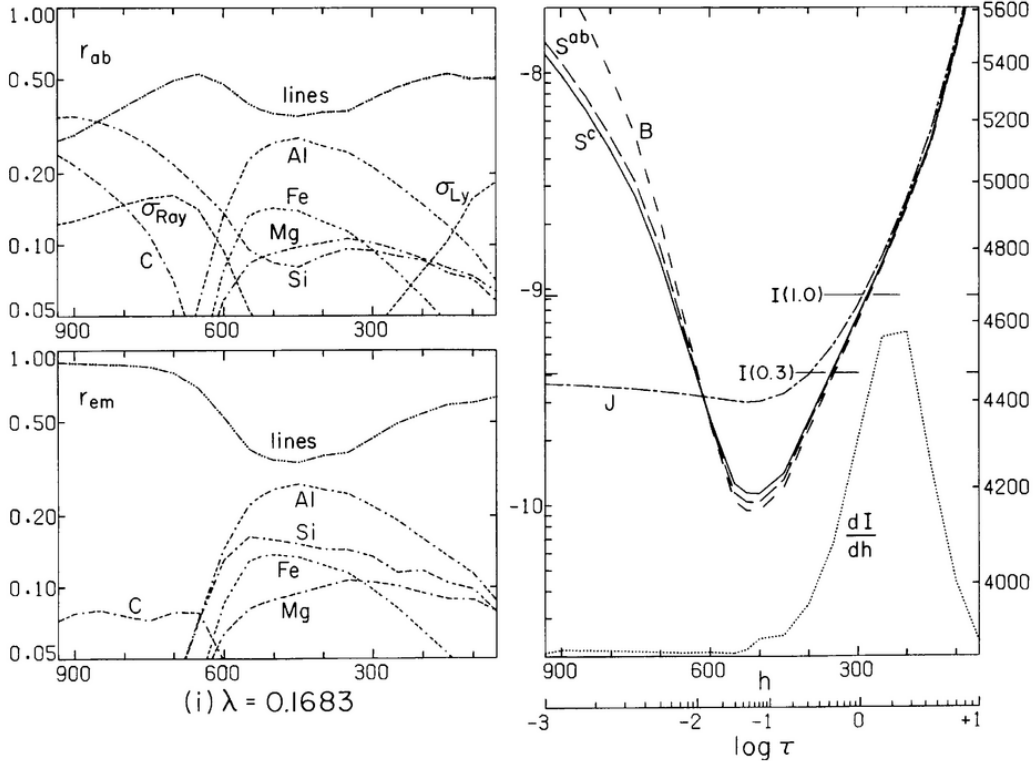


VAL3C CONTINUUM FORMATION



TEMPERATURE MINIMUM IN VALII

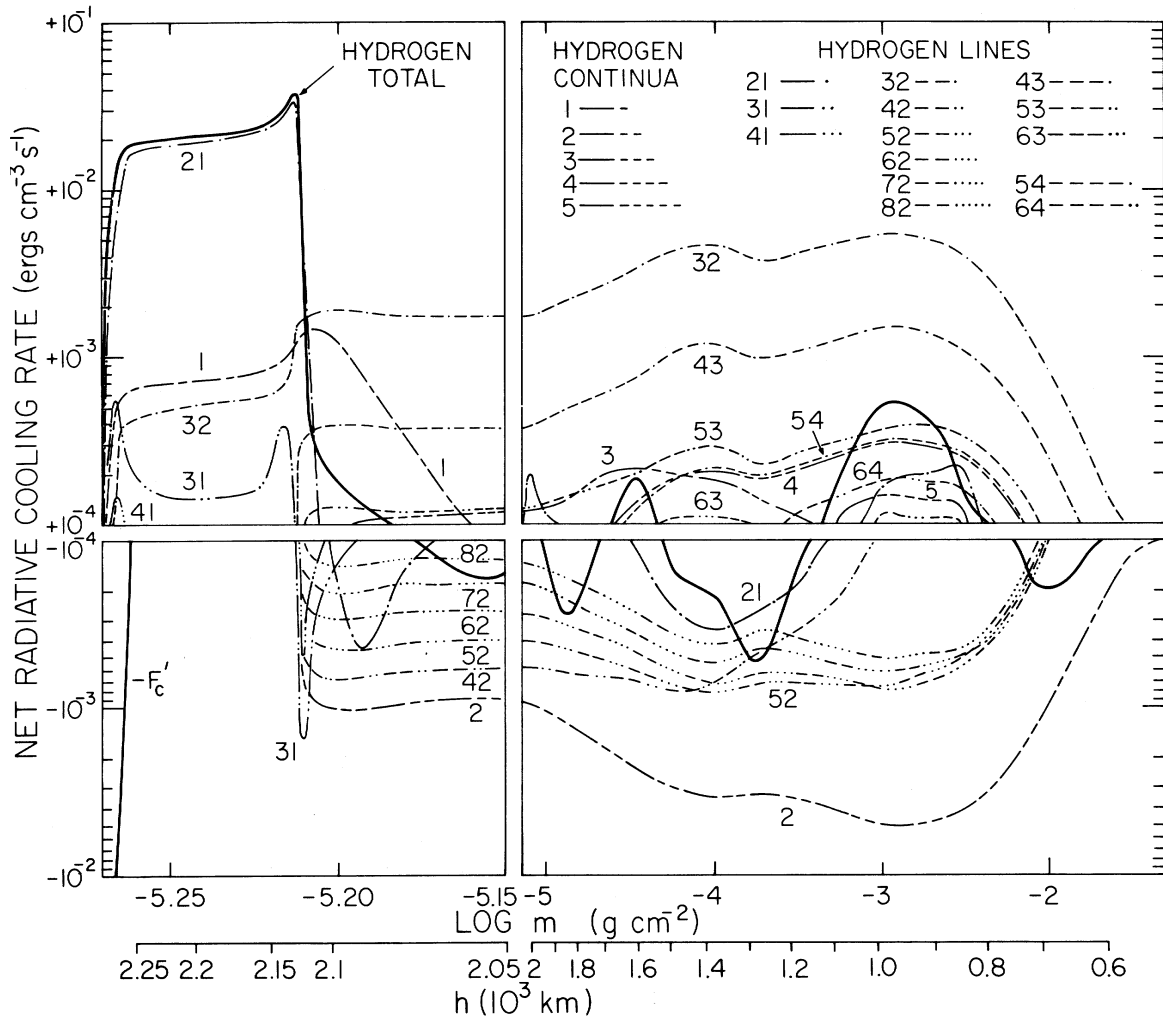
Vernazza, Avrett & Loeser 1976ApJS...30....1V (VALII)



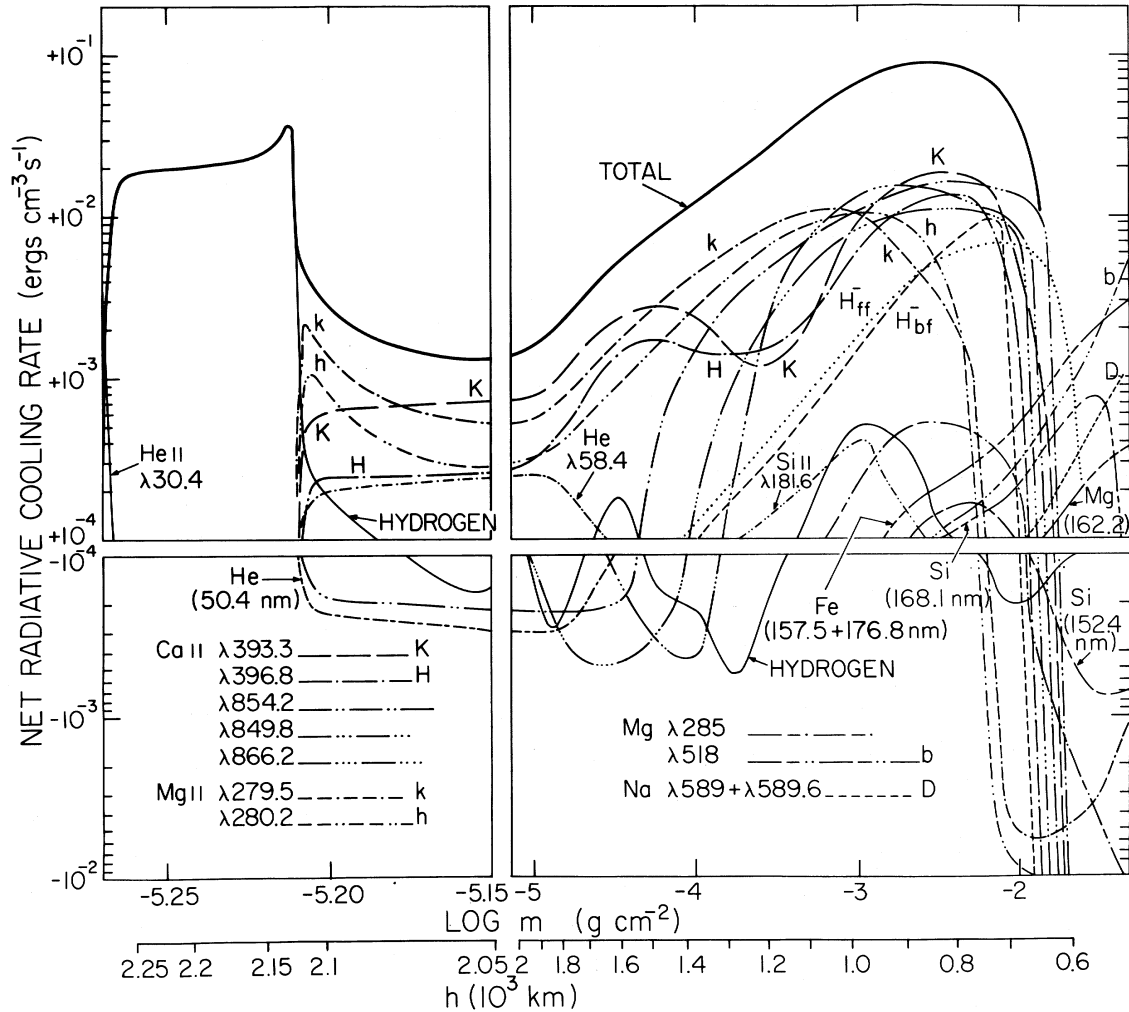
(i) $\lambda = 0.1683$

- oops: bf edges of electron-donor metals wrongly in LTE
- oops: too few line-haze lines and wrongly in LTE

VAL3C RADIATION BUDGET



VAL3C RADIATION BUDGET



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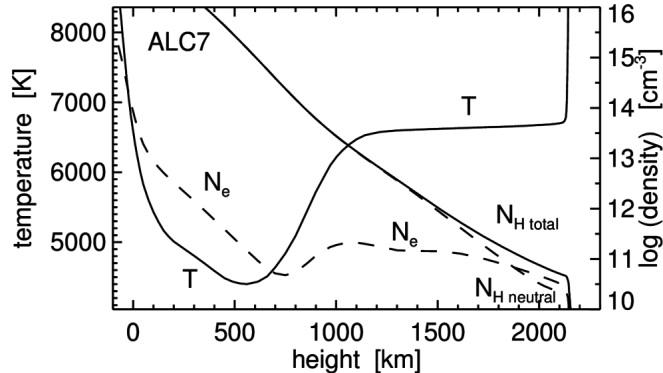
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ALC7 ATMOSPHERE

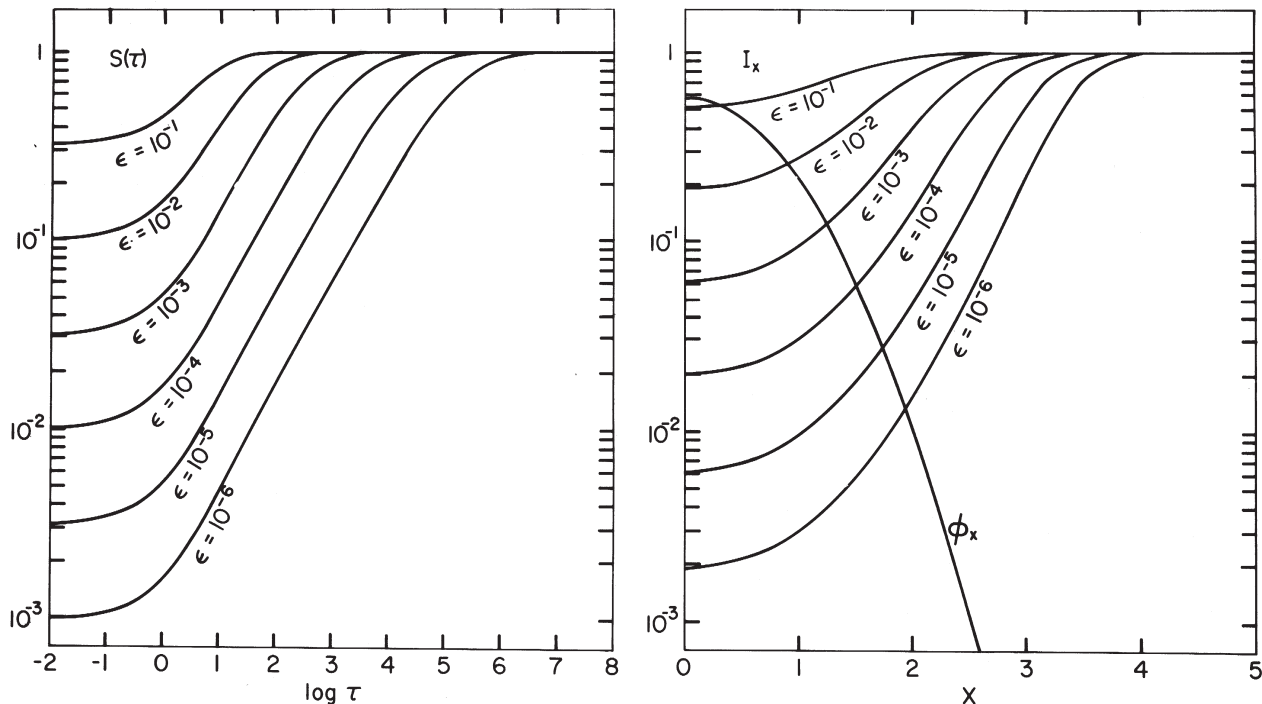
Avrett & Loeser 2008ApJS..175..229A



- unrealistic plane-parallel static computational star with solar-like average spectrum
 - exemplary in obeying all equations in my RT courses: understandable line formation
- best-fit temperature: near-RE in photosphere, shock-dominated in chromosphere
 - slope in upper photosphere depends on NLTE ultraviolet line haze
- total hydrogen density: exponential decay
 - turbulent pressure added to gain scale height and chromospheric extent
- low electron density in photosphere and temperature minimum
 - from ionization of donor-elements Si, Fe, Mg, Al with 10^{-4} relative abundance
- increasing hydrogen ionization across chromosphere
 - electron density reaches proton density at its top
- near-isothermal near-constant- N_e chromosphere
 - mimics Avrett's (1965) [isothermal constant- \$\epsilon\$ two-level-atom scattering atmosphere](#)

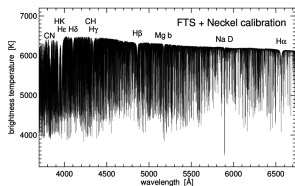
CRD RESONANT SCATTERING IN AN ISOTHERMAL ATMOSPHERE

RTSA figure 4.12; from Avrett 1965SAOSR.174..101A

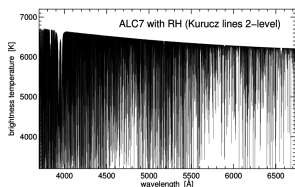


- left: S/B in a plane-parallel isothermal atmosphere with constant ϵ for complete redistribution. The curves illustrate the $\sqrt{\epsilon}$ law and thermalization at $\Lambda \approx 1/\epsilon$.
- right: corresponding emergent line profiles and Gaussian extinction profile shape ϕ (only the righthand halves; $x = \Delta\lambda/\Delta\lambda_D$)

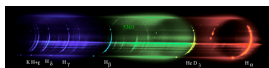
SOLAR OPTICAL VERSUS ALC7 OPTICAL – ON DISK AND OFF LIMB



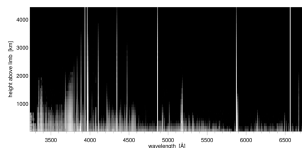
- *observed disk-center spectrum*
 - Na I D lines darkest from scattering
 - H I Balmer lines widest from linear Stark + Holtsmark
 - Ca II H & K strongest from Saha-Boltzmann (“Cecilia Payne”)



- *ALC7 disk-center spectrum per RH*
 - 1D-SE without granules, waves, shocks, fibrils, magnetism
 - chromospheric extent from imposed turbulent pressure
 - good reproduction, also ultraviolet (RH: not H, not Kurucz)



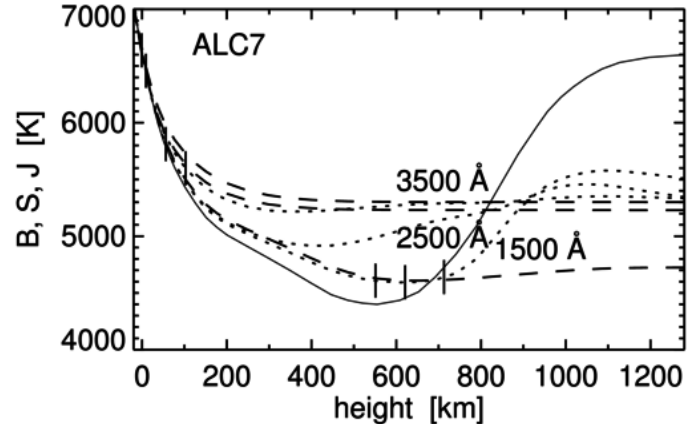
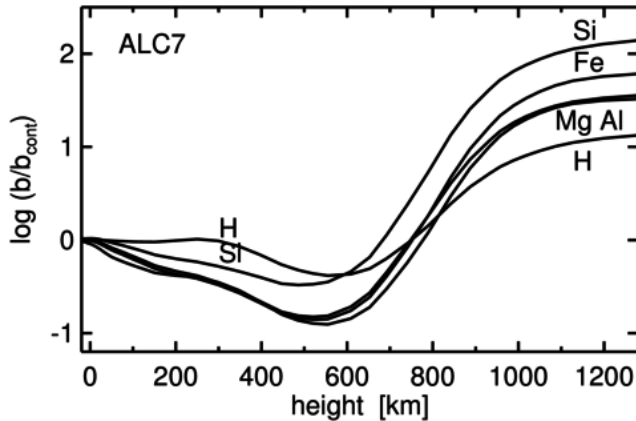
- *observed flash spectrum*
 - H I Balmer, Ca II H & K, He I ≡ Lockyer’s “chromosphere”
 - Janssen/Lockyer discovery of He I D₃
 - made up of spicules



- *ALC7 flash spectrum per RH*
 - too small extent
 - cannot explain H I Balmer, let be He I D₃
 - no spicules



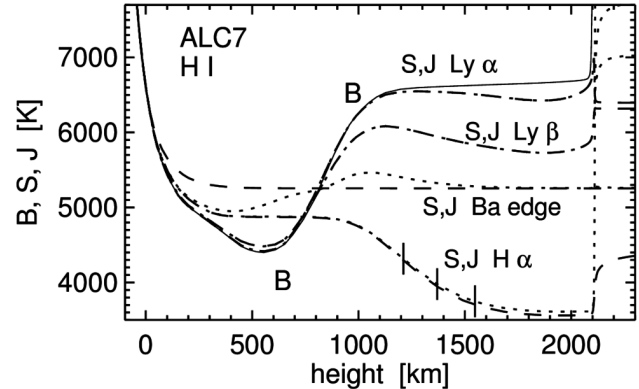
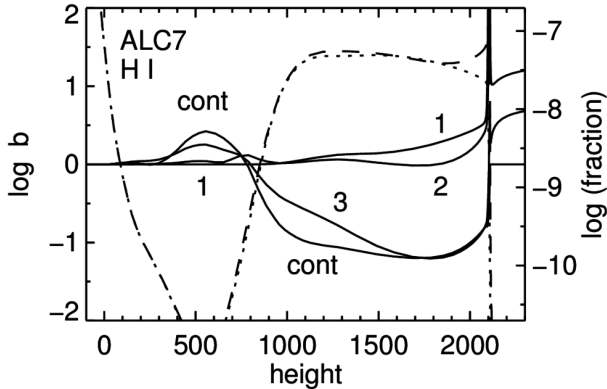
ULTRAVIOLET DEPLETION IN THE ALC7 ATMOSPHERE



minority atoms: photospheric extinction depletion by ultraviolet bound-free scattering

- ultraviolet bound-free edges produce scattering continua
- $J > B$ from:
 - $T(h)$ gradient defined by radiative equilibrium for the optical
 - $B(h)$ steeper in the ultraviolet due to Wien nonlinearity
 - Λ operator gives $J > S$ for steep $S(\tau)$
 - deep escape from small H I bf extinction
- b_1/b_{cont} for electron donors Mg I, Fe I, Si I and Al I imply b_1 population depletion across photosphere because $b_{\text{cont}} \approx 1$
- their photospheric lines have increasing extinction deficits compared to LTE
- b_2/b_{cont} for H I shows similar behavior for the top of the hydrogen atom starting at $n=2$

HYDROGEN LINES IN THE ALC7 ATMOSPHERE



$H\alpha$: chromosphere is back-scattering attenuator for radiation from deep photosphere; outward S decline as in [isothermal constant- \$\epsilon\$ two-level-atom atmosphere](#)

$Ly\alpha$: tremendous scattering with $S_{Ly\alpha} \approx J_{Ly\alpha}$ but local thermalization with $J_{Ly\alpha} \approx B_{Ly\alpha}$ from short photon mean free paths (S dotted, J dashed; dot-dashed = identity)

$Ly\beta$: scattering as $Ly\alpha$, shares photon losses in $H\alpha$ ($H\alpha$ ticks $\tau = 3, 1, 0.3$)
(same $S/B \approx b_3/b_1$ since $b_2 \approx b_1$ but offsets differ in temperature representation)

$n = 1$: Saha-Boltzmann $b_1 \approx 1$ population because hydrogen is neutral
(except in transition region at right)

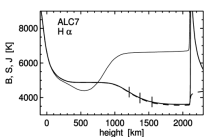
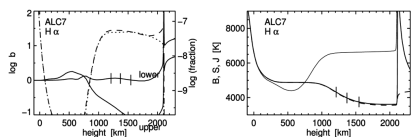
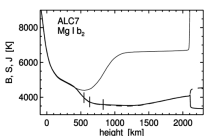
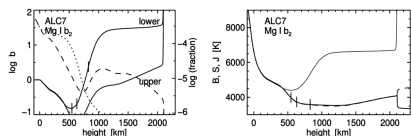
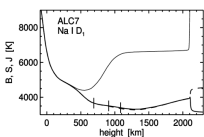
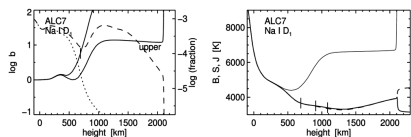
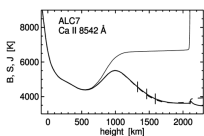
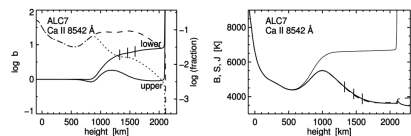
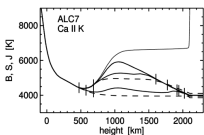
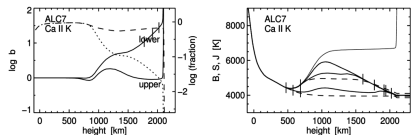
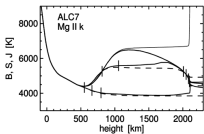
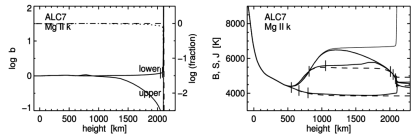
$n = 2$: Saha-Boltzmann $b_2 \approx 1$ population from $Ly\alpha$ thermalization
(dotted fraction curve = $n_2^{LTE}/N_{Htot} \approx$ dashed curve = actual n_2/N_{Htot})

ionization: b_{cont}/b_2 defined by SE balancing of $B(T_{rad}^{Bacont})/B(T_e)$ ionization driving and cascade recombination with high- n line photon losses. The H I top ($n \geq 2$) represents a 3.4 eV alkali atom with ground-state population set by $Ly\alpha$.

STRONG LINES IN ALC7

Avrett & Loeser 2008ApJS..175..229A

Rutten 2016A&A...590A.124R



• Mg II k

- extinction LTE, source function 2-level scattering
- high peaks, low PRD dips, low wings

• Ca II K

- lower abundance and ionization, underionization
- small peaks and PRD dips

• Ca II 8542

- as Ca II K with Boltzmann lowering and sensitivity
- similar source function sampling as H α

• Na I D₁

- photospheric scattering, suction and underionization
- no sensitivity to temperature rise

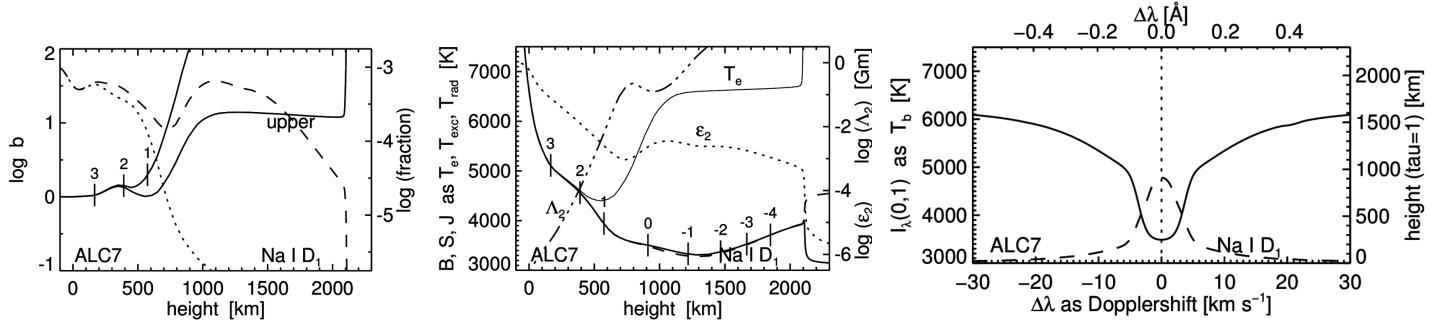
• Mg I b₂

- as Na I D₁ but photospheric overionization
- no sensitivity to temperature rise

• H α

- chromospheric scattering of photospheric photons
- chromospheric extinction LTE from Ly α box-up

LINES FROM THE ALC7 CHROMOSPHERE: PLOT FORMATS (Na I D₁)



$$b_i \equiv n_i/n_i^{\text{LTE}} \quad \alpha^l \approx b_l \alpha^{\text{LTE}} \quad S^l \approx (b_u/b_l)B \quad S^l \approx (1-\epsilon_2)J + \epsilon_2 B \quad \Lambda_2 \approx \sqrt{\pi}/(\alpha_0 \epsilon_2) \quad I(0) \approx S[\tau=1]$$

• first plot: populations

- solid: population departure coefficients. Always unity in the deep photosphere. Divergence with increasing $b_u < b_l$ shows resonance scattering. Steep b_l rise due to radiative overionization of this minority species (Na I). $\log \tau$ ticks on b_l curve are for line center.
- dashed: fractional population n_i/N_{element} in NLTE. Scale at right. Na I is minority species.
- dotted: fractional population n_i/N_{element} per Saha-Boltzmann. Difference with the NLTE curve corresponds to departure of b_l from unity.

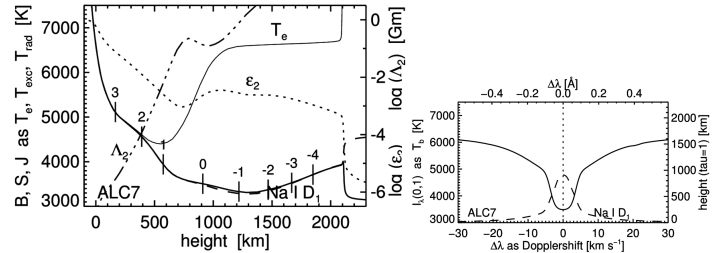
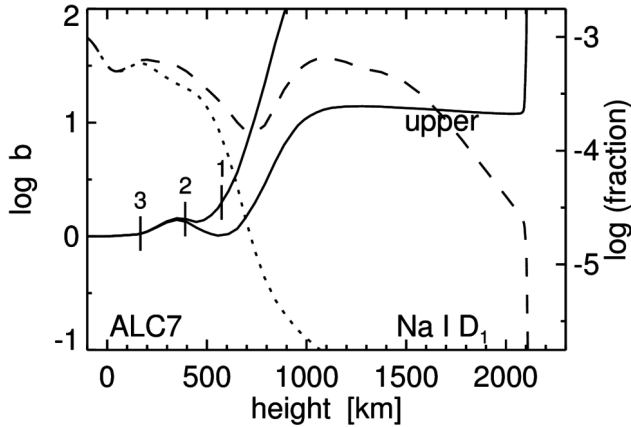
• second plot: line source function

- solid thin, thick, dashed: B, S, J as formal temperatures (for common scale with other lines). $\log \tau$ ticks are for line center.
- dotted: ϵ for the Doppler core in 2-level approximation. Scale to the right.
- dot-dashed: thermalization length in Gm. $\Lambda_2 = -6$ means thermalization of S to B within a homogeneous slab of 1 km. The Λ mark is near core thermalization depth.

• third plot: emergent profile

- solid: emergent profile as brightness temperature
- dashed: $\tau_{\lambda}=1$ height scale at right
- dotted, vertical: wavelength sampling(s) for second plot

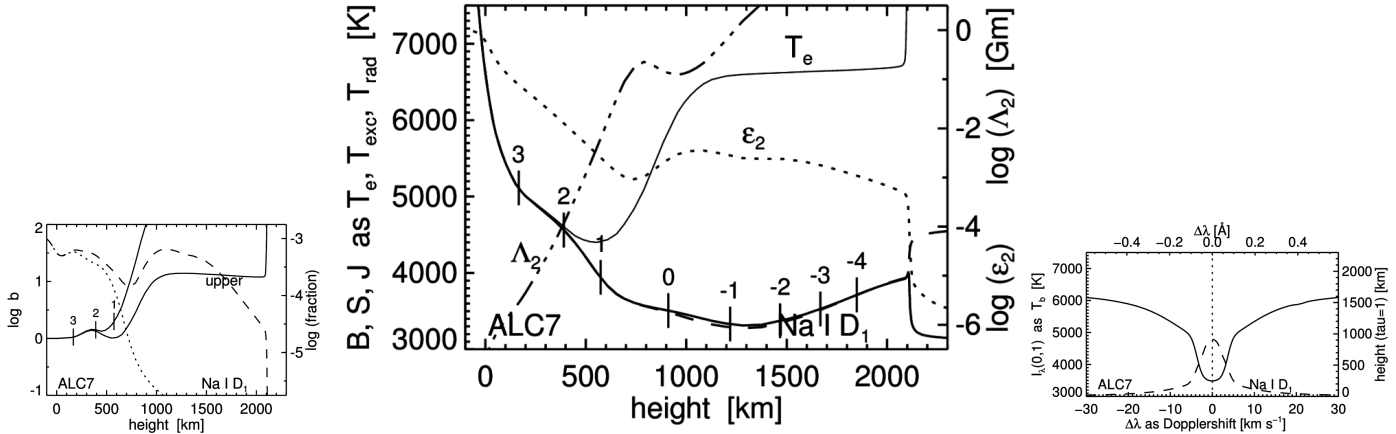
LINES FROM THE ALC7 ATMOSPHERE: POPULATIONS PLOT (Na I D₁)



$$b_i \equiv n_i/n_i^{\text{LTE}} \quad \alpha^l \approx b_l \alpha^{\text{LTE}} \quad S^l \approx (b_u/b_l)B \quad \varepsilon \approx \varepsilon_2 = \alpha^a / (\alpha^s + \alpha^a) \quad S^l \approx (1 - \varepsilon_2) \bar{J} + \varepsilon_2 B$$

- **solid**: population departure coefficients for Na I D₁. Unity in deep photosphere from large collision frequency at high density, with $\varepsilon \approx 1$ ($B S J$ plot). Increasing $b_u < b_l$ divergence = $S^l < B$ divergence ($B S J$ plot) from $\sqrt{\varepsilon}$ -law resonance scattering. Small initial hump in upper photosphere from photon suction (replenishment from ion reservoir) by scattering-out Na I D photons. Steep b_l rise above 700 km from ultraviolet underionization ($1 - c$ edge at 2412 Å, typical for minority neutrals). The $\log \tau$ ticks on the b_l curve are for line center.
- **dotted**: fractional population $n_l^{\text{LTE}}/N_{\text{elem}}$ per Saha-Boltzmann. Scale at right. Na I is a minority species. Initial decrease from increasing ionization at decreasing N_e , slight hump from less ionization at lower temperature, steep decline at increasing T and decreasing N_e (Saha).
- **dashed**: fractional population n_l/N_{elem} in NLTE. Line-center optical depth $\tau_\lambda = - \int (\alpha^l + \alpha^c) dh$ has $\alpha^l \gg \alpha^c$ and $\alpha_\lambda^l \sim n_l = (n_l/N_{\text{elem}}) A_{\text{elem}} N_{\text{Htot}}$. Divergence from LTE curve corresponds to departure of b_l from unity. The steep b_l increase compensates the steep n_l^{LTE} decrease.

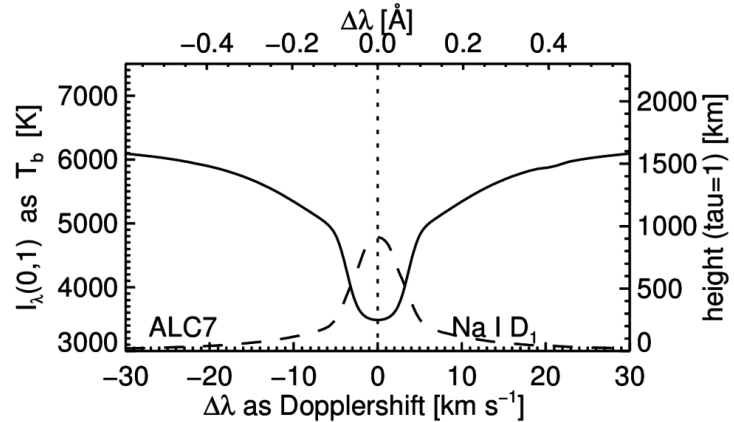
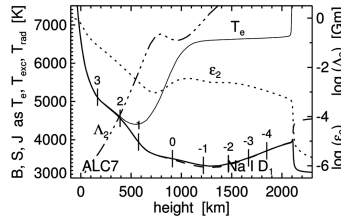
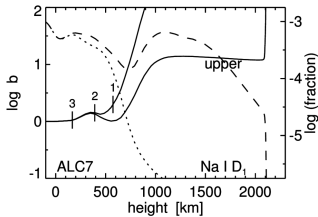
LINES FROM THE ALC7 ATMOSPHERE: B S J PLOT (Na I D₁)



$$S^l \approx (b_u/b_l)B \quad \varepsilon \approx \varepsilon_2 \equiv \alpha^a / (\alpha^s + \alpha^a) \quad S^l \approx (1 - \varepsilon_2) \bar{J} + \varepsilon_2 B \quad \Lambda_2 \approx \sqrt{\pi} / (\alpha_0 \varepsilon_2)$$

- *thin solid*: B_{λ_0} as temperature T_e to remove Planck function variation with wavelength for comparison with other lines. The ALC7 atmosphere has a near-isothermal chromosphere.
- *thick solid*: Na I D₁ S^l as formal excitation temperature T_{exc} . The $B > S$ divergence corresponds to the $b_l > b_u$ divergence in the populations plot, but not equally in their plotted logarithms due to the B and S conversions to formal temperature. The $\log \tau$ ticks are for line center. This scattering line does not sense the ALC7 chromosphere in S^l .
- *dashed*: profile-averaged angle-averaged intensity \bar{J} as formal radiation temperature T_{rad} .
- *dotted*: 2-level photon destruction probability ε_2 for the Doppler core. Scale to the right. Follows N_e , so fairly constant over 1000–2000 km from increasing hydrogen ionization.
- *dot-dashed*: 2-level thermalization length Λ_2 for the Doppler core in gigameter. Scale to the right. Example: $\Lambda_2 = -6$ implies thermalization of S to B at the center of a 2-km thick feature. The curve label is placed near the line-core thermalization height in the mid photosphere.

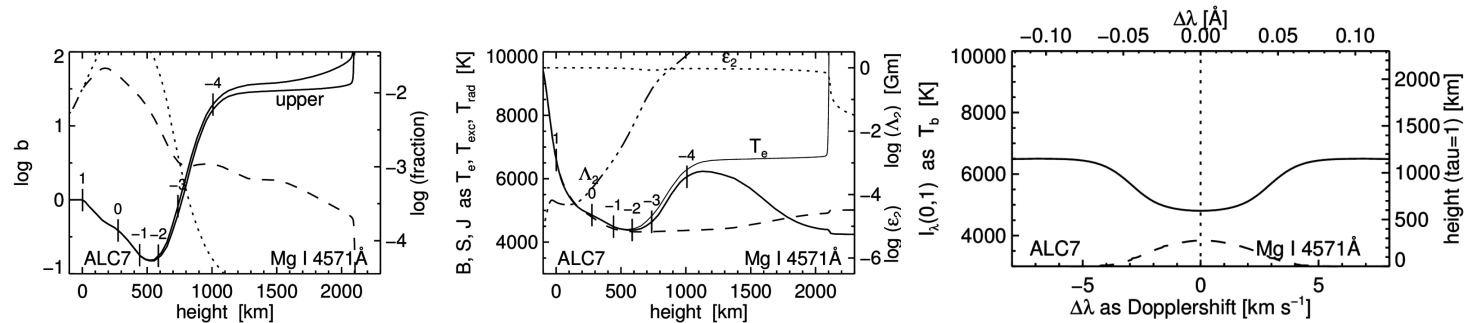
LINES FROM THE ALC7 ATMOSPHERE: PROFILE PLOT (Na I D₁)



$$\alpha_{\lambda}^l \sim b_l (n_l^{\text{LTE}} / N_{\text{elem}}) A_{\text{elem}} N_{\text{Htot}} \varphi(\lambda - \lambda_0) \quad \tau_{\lambda} = - \int (\alpha^l + \alpha^c) dh \quad I_{\lambda}(0) \approx S_{\lambda}^{\text{total}} [\tau_{\lambda} = 1]$$

- **solid**: emergent intensity in the radial direction, represented as formal brightness temperature for comparison with other lines and the Eddington-Barbier estimate (*BSJ* plot, temperature axes match in the coming line-formation displays). Similarly, the bottom scale for wavelength separation from line center is in km s⁻¹ for comparison with other lines. Wavelength separations in Å along the top.
- **dashed**: $\tau_{\lambda} = 1$ height, scale at right.
- **dotted, vertical**: sampling wavelength(s) for *S* and *J* in the *BSJ* plot. Only one for CRD lines (as Na I D₁) with frequency-independent line source functions (and \bar{J} in the *BSJ* plot).
- one might overplot an observed solar disk-center profile, but this is misleading because even a perfect match does not imply that the ALC7 model is correct. ALC7 is an idealized didactic star not like the Sun with an easier-to-understand solar-lookalike spectrum.

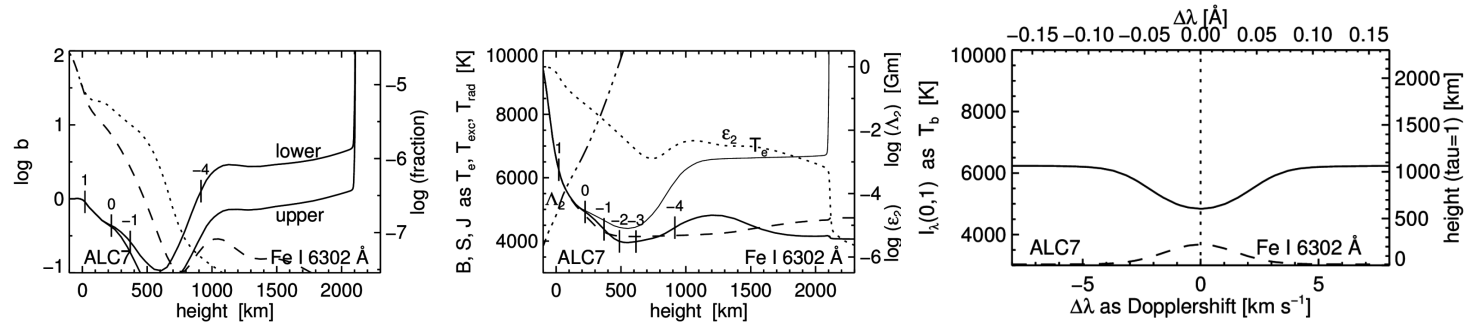
Mg I 4571 Å FROM THE ALC7 ATMOSPHERE



unique photospheric line with LTE source function

- extinction severely out of LTE. Deep b_l dip across the ALC7 photosphere from overionization by deeply escaping bound-free scattering ultraviolet radiation, including edges of Mg I itself at 2512 and 1621 Å. Corresponding steep b_l rise above 700 km from ultraviolet underionization where the temperature increases in excess of the ultraviolet radiation temperature.
- this pattern is common to all lines of minority neutrals with ultraviolet ionization wavelengths, including the electron donors (Mg I, Fe I, Si I, Al I).
- source function unusually close to LTE because this is a “forbidden” intersystem line with small $A_{ul} = 2.7 \cdot 10^2 \text{ s}^{-1}$, dominated by collisions ($\epsilon \approx 1$) with $b_u \approx b_l$, $S^l \approx B$ to large heights.
- yet fairly strong because its lower level is the Mg I ground state
- usefulness: photospheric thermometer but requires ultraviolet NLTE for optical depth

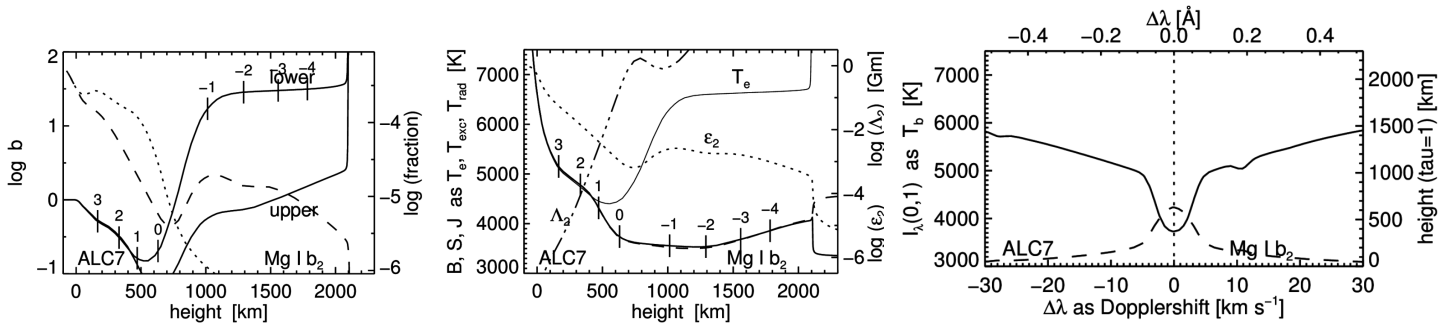
Fe I 6301.5 Å FROM THE ALC7 ATMOSPHERE



standard polarimetry line

- severe extinction NLTE across the photosphere due to ultraviolet bound-free scattering overionization and affecting the tau scaling (b_l curve)
- minor S^l NLTE from resonance scattering in the upper photosphere ($S < B$ split)
- “inversion” codes (numerical best-fit iteration) sometimes include S^l NLTE but usually not extinction NLTE, ignoring that bound-free scattering with $S^{UV} \approx \bar{J}^{UV}$ depends on 3D temperature gradients in deeper layers and makes b_l (hence n^l and α^l) non-local both in space and wavelength
- problem: the enormous density of NLTE lines (“haze”) in the ultraviolet affecting J^{UV}
- usefulness: differential line-pair polarimetry with its twin Fe I 6302.5 Å

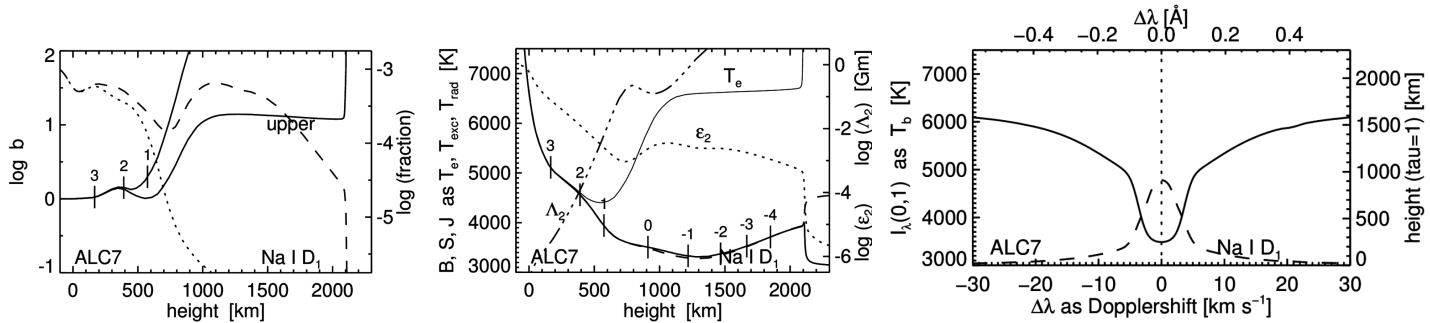
Mg Ib₂ 5173 Å FROM THE ALC7 ATMOSPHERE



diagnostic of upper photosphere

- large NLTE n_l depletion from ultraviolet bound-free scattering across the photosphere
- large NLTE b_l increase from ultraviolet scattering offsets Saha decline in chromosphere
- CRD scattering source function with $\epsilon \approx 10^{-3}$
- similar to Na I D₁
- usefulness: as Na I D₁ but wider core = less asymmetry from reversed granulation

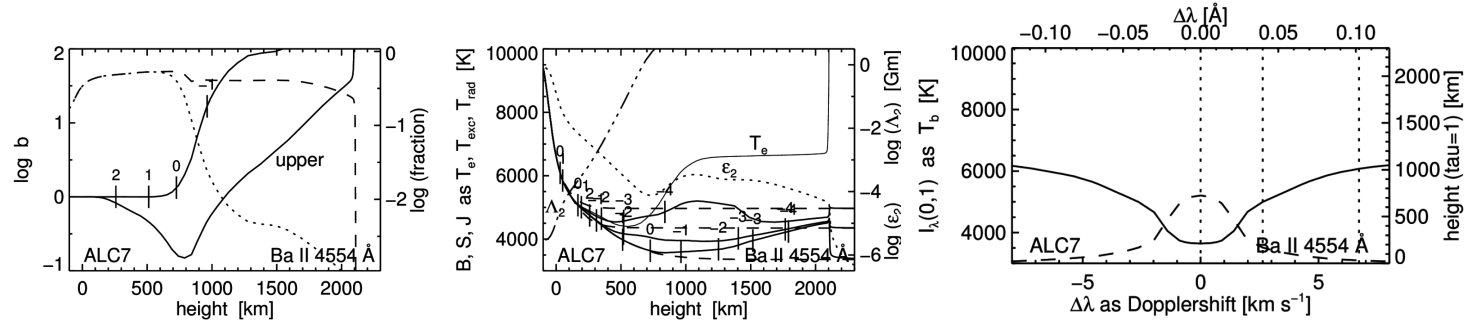
Na I D₁ 5896 Å FROM THE ALC7 ATMOSPHERE



Na I D lines: darkest lines in optical spectrum = textbook example of two-level scattering

- photon suction offsets ultraviolet overionization across the photosphere
- ultraviolet underionization offsets Saha depletion above 700 km
- 2-level CRD scattering with $\epsilon \approx 10^{-3}$ and $S \approx \bar{J} \ll B$ in the ALC7 chromosphere
- thermalization in mid photosphere: core intensity does not sense ALC7 chromosphere, observed photons are created near the thermalization depth (height of Λ_2 label), observed intensity variation preferentially encodes temperature variation there
- last scattering near $\tau = 1$: Doppler and Stokes inner-wing encoding occurs around 500 km
- usefulness: sharp Na I D Dopplergrams indicate deeply-located shocks in fluxtubes

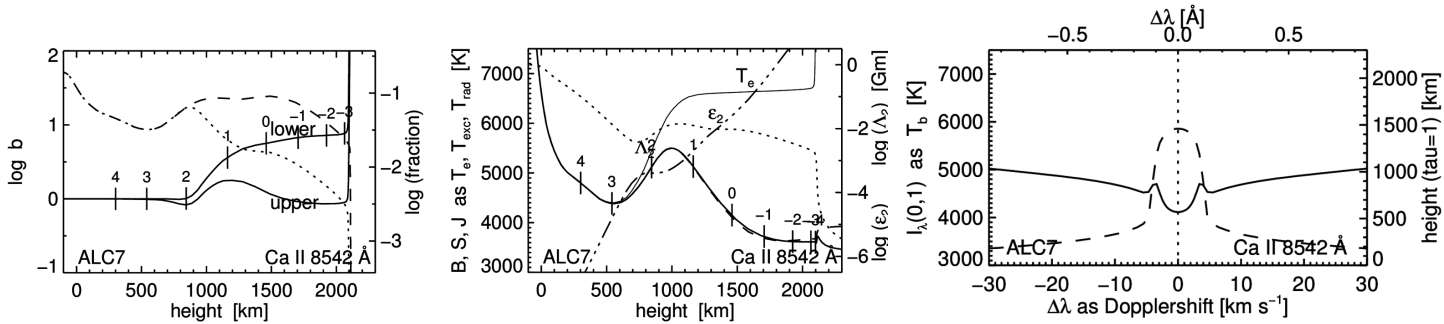
Ba II 4554 Å FROM THE ALC7 ATMOSPHERE



weakest PRD line, best velocity diagnostic, good Hanle diagnostic

- extinction LTE up to line-core formation height thanks to photon losses offsetting overionization (edge at 1240 Å outside Ly α)
- steep b_l increase above 800 km from underionization offsets Saha depletion
- resonance line with Grotrian diagram similar to Ca II K. PRD scattering source function with $\epsilon \approx 10^{-4}$, therefore different monochromatic S_λ and J_λ curves for line center, inner wings, outer wings
- S^l split in upper photosphere produces emission wings at the limb (my 1976 eclipse-expedition PhD thesis)
- usefulness: non-thermal Doppler sensitivity from large mass ($\sqrt{m_{Ba}/m_H} = 11.7$) intricate near-limb Hanle profile from hyperfine structure

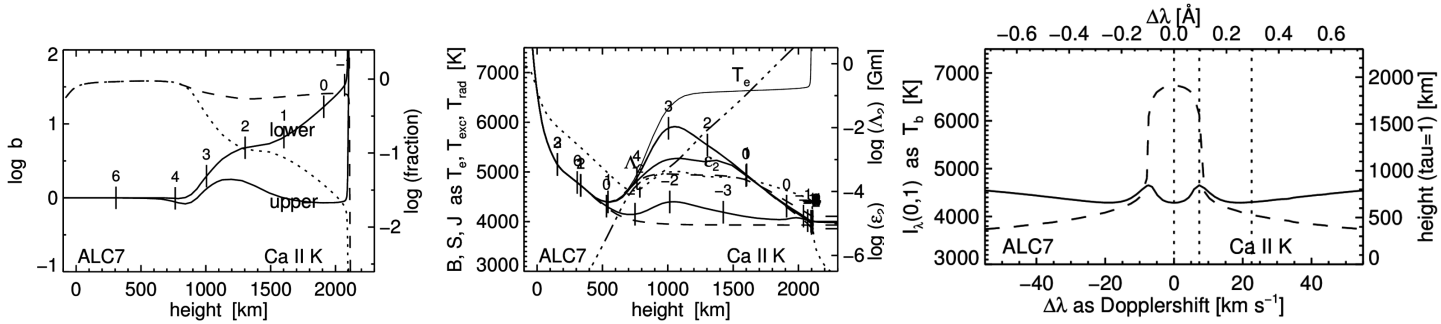
Ca II 8542 Å FROM THE ALC7 ATMOSPHERE



cleanest chromospheric diagnostic in the near infrared

- extinction: b_l boost from its own photon losses compensates Saha depletion
- CRD scattering source function with $\epsilon \approx 10^{-2}$
- core formation spans lower ALC7 chromosphere
- best optical line for chromospheric magnetometry
- usefulness: at longer wavelengths more diffraction but less seeing \Rightarrow prime DKIST line

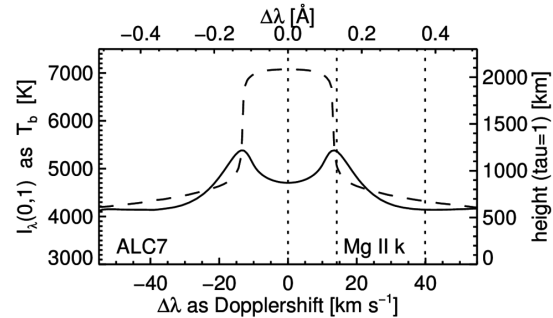
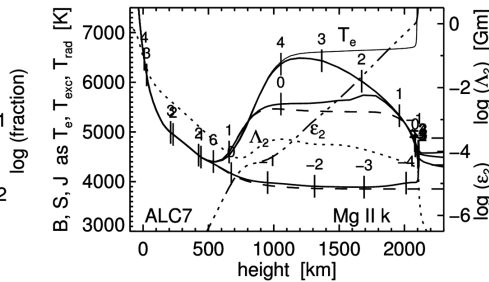
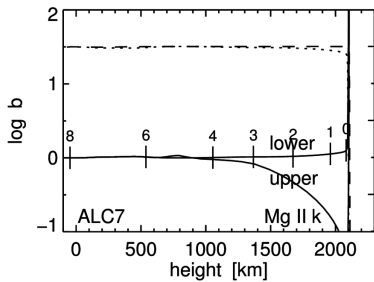
Ca II K 3934 Å FROM THE ALC7 ATMOSPHERE



largest extinction in the optical spectrum

- extinction: successive b_l boosts from photon losses in infrared triplet and H&K compensates Saha depletion
- PRD scattering source function with $\epsilon \approx 10^{-4}$ (split between profile center, peaks, dips)
- core formation spans the ALC7 chromosphere
- narrowness of the Doppler core upsets filter imaging so far
- Sunrise-2/SuFi best so far; high hopes for SST/CHROMIS
- usefulness: best optical chromosphere diagnostic but challenging (bandwidth, S/N)

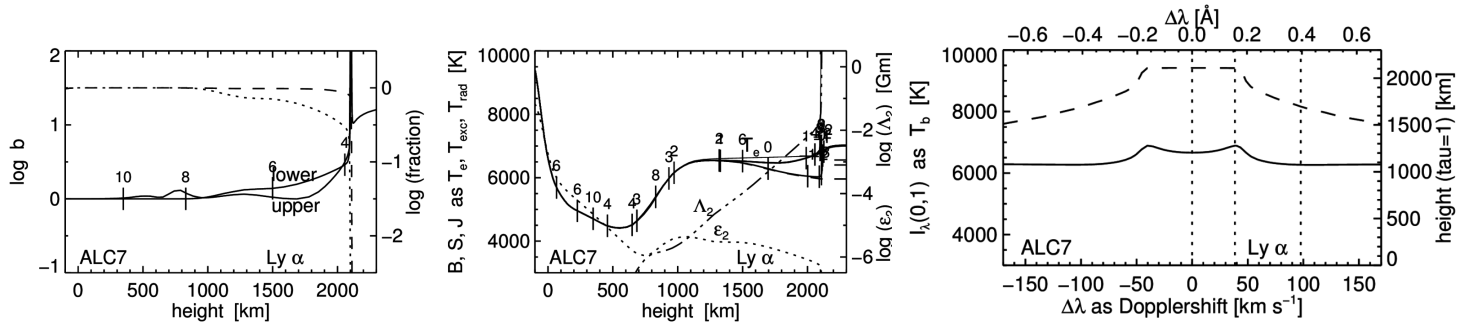
Mg II k 2796 Å IN THE ALC7 CHROMOSPHERE



cleanest PRD line and yet larger extinction than Ca II K

- LTE lower-level population and extinction because all Mg sits in the Mg II ground state
- PRD scattering source function with $\epsilon \approx 10^{-4}$ (split between profile center, peaks, dips)
- textbook scattering decline
- similar to Ca II K but with $18\times$ larger abundance and with much darker wings
- usefulness: key diagnostic but requires space platform
slitless imaging spectrometry very difficult
combine with “triplet” doublet between h & k (recombination indicator)

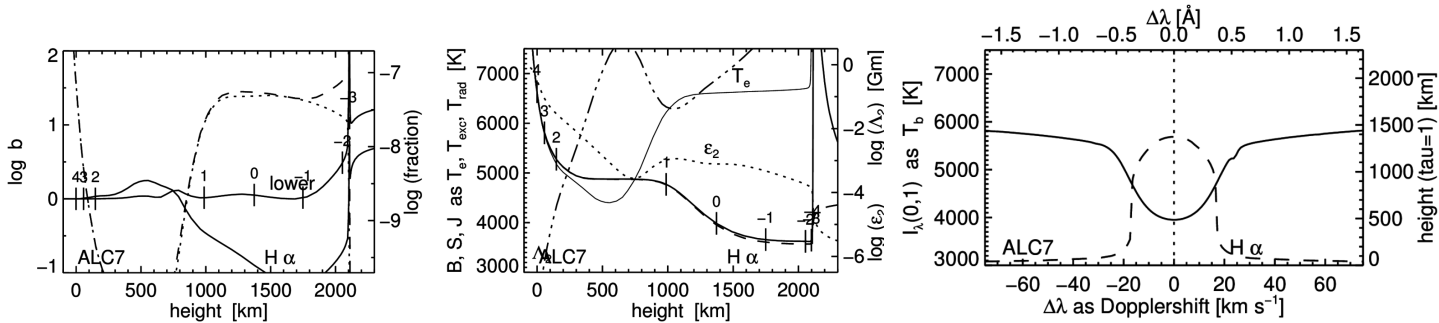
$\text{Ly}\alpha$ 1216 Å IN THE ALC7 CHROMOSPHERE



champion: largest extinction and most scattering of all lines

- lower-level population fraction ≈ 1 : all hydrogen in ground state
- overpopulation of the ground state towards the transition region from photon losses in wings with slight scattering drops $S \approx J < B$
- enormous line-center extinction across the ALC7 chromosphere
- PRD scattering source function with $\epsilon \approx 10^{-6}$ (split between profile center, peaks, dips)
- Λ goes from $\propto 1/\epsilon$ towards $\propto 1/\epsilon^2$ with density from Stark wing development (not shown)
- radiation lock-in from large extinction produces radiative balance $n_u(A_{ul} + B_{ul}\bar{J}) = n_l B_{lu}\bar{J}$
- local thermalization from small Λ produces $\bar{S} \approx B$ throughout ALC7 chromosphere;
 $b_u \approx b_l \approx 1$ implies LTE extinction for H α where it escapes
- usefulness: premier diagnostic but needs space; slitless imaging spectrometry difficult

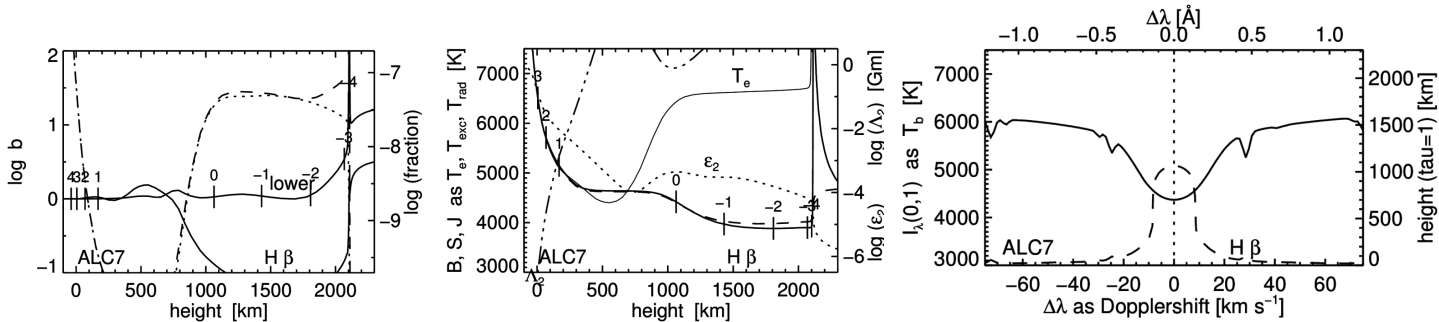
H α 6563 Å FROM THE ALC7 ATMOSPHERE



H α : extraordinary from high excitation energy, huge element abundance, on top of Ly α

- lower-level fractional population varies $10^{-10} - 10^{-7}$ due to 10 eV in Boltzmann
- extinction coefficient near-LTE up to 2000 km by Ly α thermalization
- $S^l \approx$ two-level scattering below transition region (not “photoelectric”) just like Ca II 8542 Å
- upper photosphere transparent: core shows fibrils, wings show granules
- Eddington-Barbier tau = 1 in chromosphere, but photon creation in deep photosphere
- large J across T-min from backscattering: ALC7 chromosphere \approx scattering attenuator
- wide line core from small atomic mass in Doppler broadening $\sim \sqrt{2kT/m_H + v_{micro}^2}$
- extended wings from linear Stark effect in deep photosphere (Holtsmark distribution)
- usefulness: prominences, flares, Ellermans, dynamic fibrils, spicules-II, ... = non-E

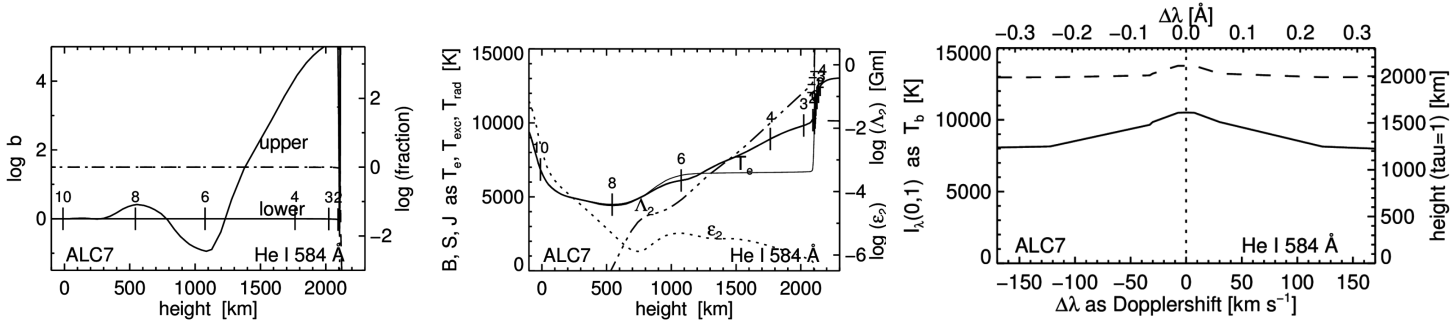
H β 4861 Å FROM THE ALC7 ATMOSPHERE



H β : analogon to H α at $5.4\times$ smaller oscillator strength and in the blue

- same large Boltzmann sensitivity and Ly α lower-level control as H α
- in comparison with H α (blink with previous):
 - same b_l , steeper b_u decay
 - similar scattering
 - less steep S^l decay from shorter wavelength
 - smaller chromosphere thickness from smaller gf
 - narrower core and $\tau=1$ peak
- RH-computed profile has less deep wings then observed atlas profile (not shown) because RH does not use the Holtmark distribution for linear Stark broadening by charged particles (less steep wing drop than Voigt function)
- usefulness: differences against H α

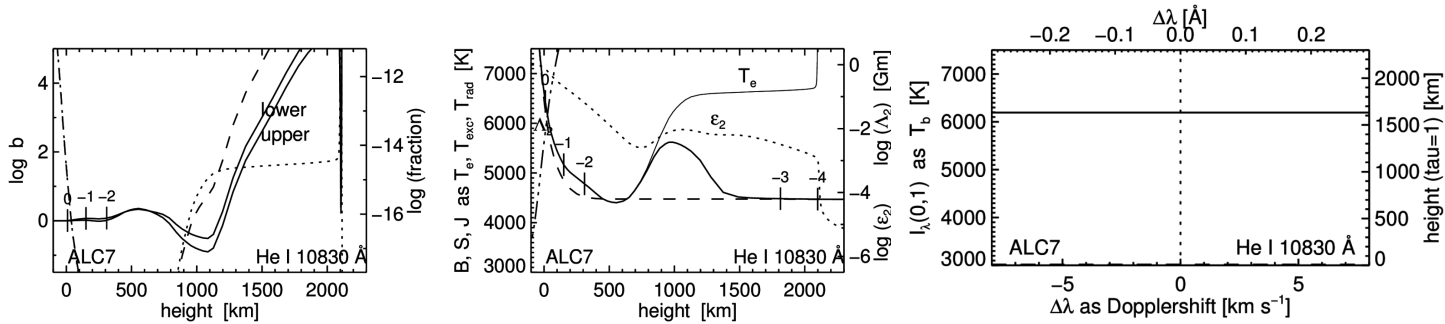
He I 584 Å IN THE ALC7 CHROMOSPHERE



backradiator into chromosphere

- lower-level population fraction ≈ 1 : all helium in He I ground state
- $b_1 = 1$ up to coronal rise
- PRD neglected here but not much difference
- detailed radiative balance $S \approx \bar{J}$
- much radiation from coronal rise down into chromosphere due to fairly large Λ , resulting in b_u increase to very large values
- radiation lock-in to $S \approx B$ only below 1000 km

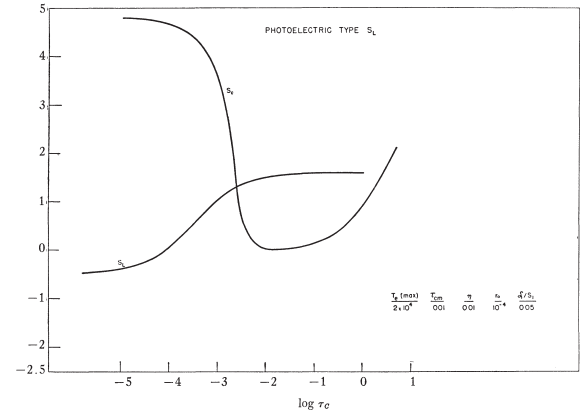
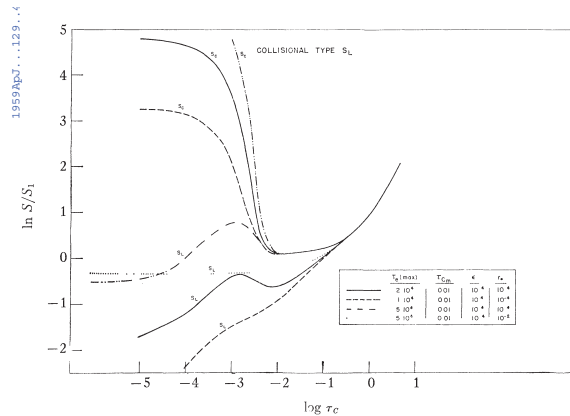
He I 10830 Å IN THE ALC7 CHROMOSPHERE



not of interest in ALC7

- high-excitation line supposedly obtaining visibility from coronal irradiation – not in ALC7
- minute fractional population from large Boltzmann factor
- upper-level b_1 set by He I 584 Å plus collisional coupling $2p^3P - 2p^1P$ with large He I 584 Å down-radiation from transition region into chromosphere
- total source function \approx LTE H^- source function until Thomson scattering takes over
- nothing in the ALC7 spectrum

CANONICAL CHROMOSPHERIC LINE FORMATION



- CRD line source function including detour paths:

$$S_{\nu_0}^l = \frac{\bar{J}_{\nu_0} + \epsilon'_{\nu_0} B_{\nu_0}(T) + \eta'_{\nu_0} B_{\nu_0}(T_d)}{1 + \epsilon'_{\nu_0} + \eta'_{\nu_0}}$$

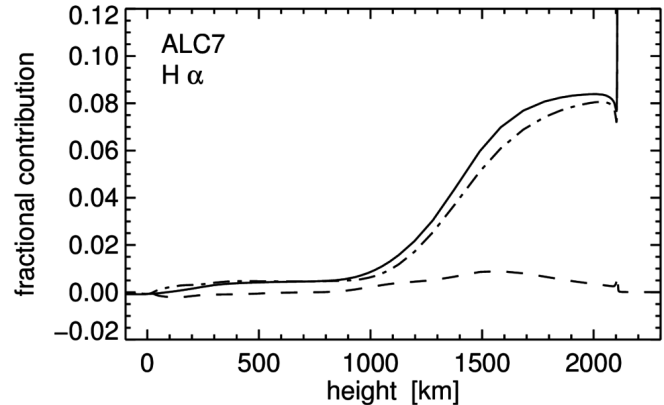
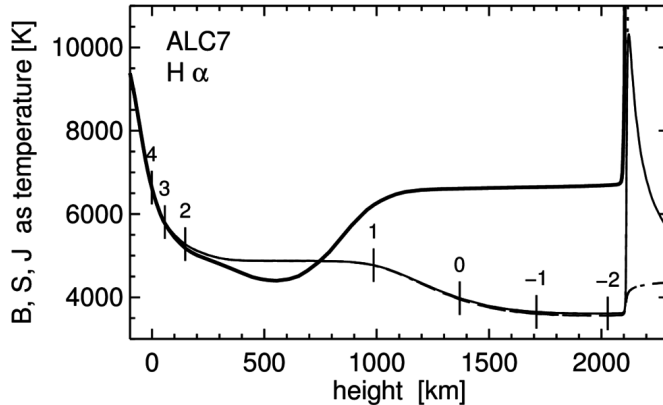
$$= (1 - \epsilon_{\nu_0} - \eta_{\nu_0}) \bar{J}_{\nu_0} + \epsilon_{\nu_0} B_{\nu_0}(T) + \eta_{\nu_0} B_{\nu_0}(T_d)$$

- ϵ = upper-lower collisional destruction fraction of total extinction
- η = detour-path extinction fraction of total extinction
- ϵ', η' = idem as ratio to scattering extinction
- \bar{J} = profile-averaged angle-averaged intensity
- T_d = formal detour excitation temperature: $(g_u D_{ul}) / (g_l D_{lu}) \equiv \exp(h\nu_0 / kT_d)$

- line source function split (Thomas 1957ApJ...125..260T):
 “collision type” (H & K) or “photoelectric type” (H α , Balmer continuum feeding)

H α SOURCE FUNCTION IN THE ALC7 CHROMOSPHERE

after Rutten & Uitenbroek 2012A&A...540A..86R



- $S_{\nu_0}^l = (1 - \varepsilon_{\nu_0} - \eta_{\nu_0}) \bar{J}_{\nu_0} + \varepsilon_{\nu_0} B_{\nu_0}(T) + \eta_{\nu_0} B_{\nu_0}(T_d) = \bar{J}_{\nu_0} + \varepsilon_{\nu_0} [B_{\nu_0}(T) - \bar{J}_{\nu_0}] + \eta_{\nu_0} [B_{\nu_0}(T_d) - \bar{J}_{\nu_0}]$

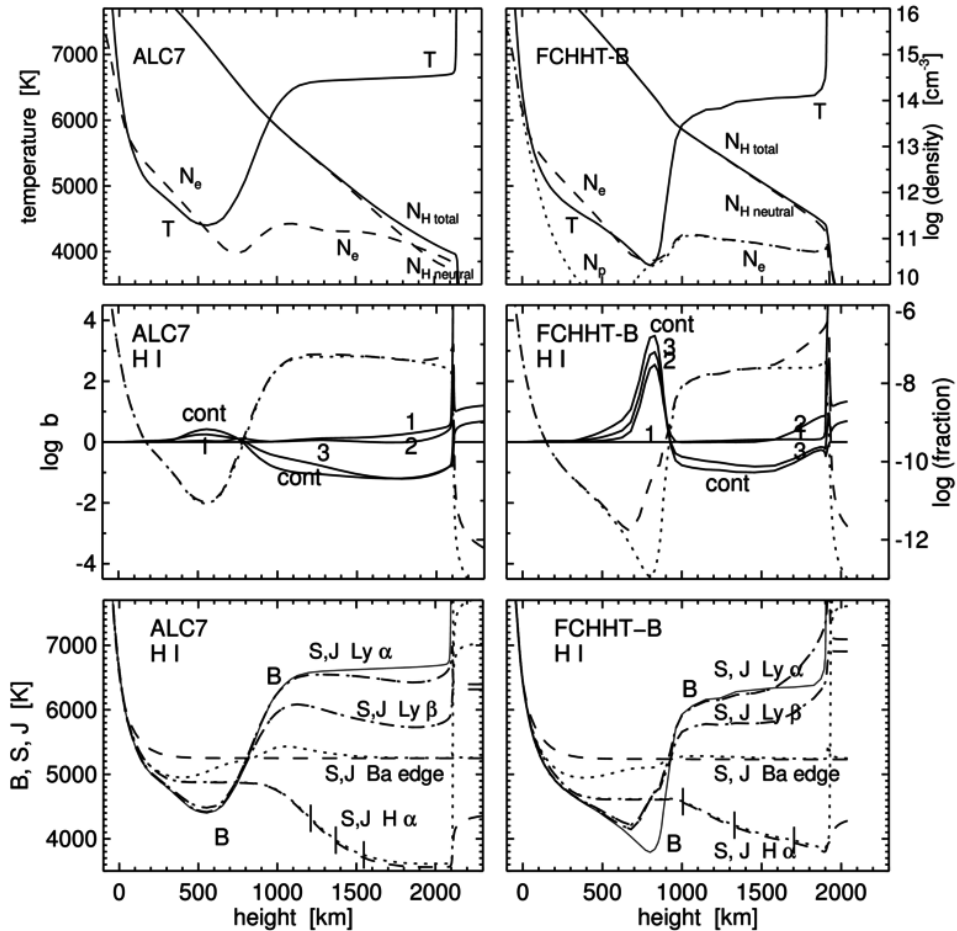
The detour part $\eta_{\nu_0} [B_{\nu_0}(T_d) - \bar{J}_{\nu_0}] / S_{\nu_0}^l$ exceeds the collision part $\varepsilon_{\nu_0} [B_{\nu_0}(T) - \bar{J}_{\nu_0}] / S_{\nu_0}^l$.

However, their sum $[S_{\nu_0}^l - \bar{J}_{\nu_0}] / S_{\nu_0}^l$ (solid) reaches only a few percent so $S_{\nu_0}^l \approx \bar{J}_{\nu_0}$. Across the ALC7 chromosphere H α is a scattering line, not “photoelectrically controlled”.

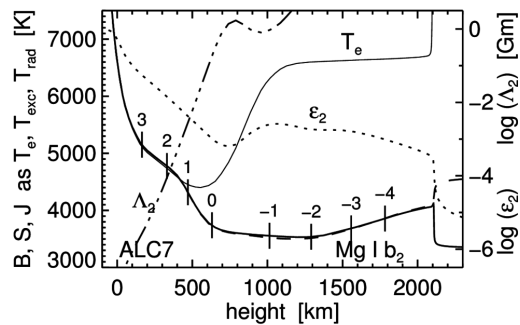
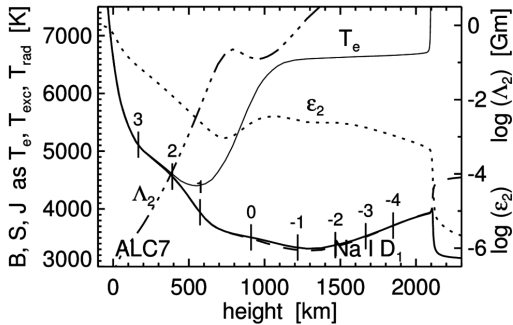
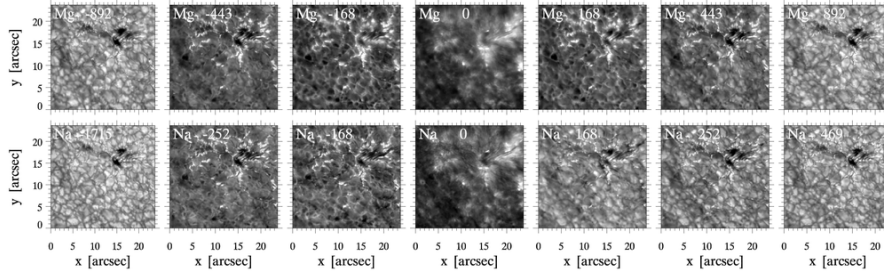
- The H α core is dominated by resonance scattering with a formation gap below the chromosphere filled by backscattered radiation. The ALC7 chromosphere acts as scattering attenuator building up its own irradiation. Most emerging photons are created in the deep photosphere where $\varepsilon_{\nu_0} \approx 1$ and $\bar{J}_{\nu_0} \approx B_{\nu_0}(T)$. The granulation pattern has larger contrast than the fibril pattern but is washed out in the scattering across the gap.
- The ALC7 H α core formation is well described by the Eddington-Barbier approximation for an irradiated finite isothermal scattering atmosphere.

HYDROGEN IN THE ALC7 and FCHHT-B PLANE-PARALLEL STARS

ALC7: 2008ApJS..175..229A FCHHT-B: 2009ApJ...707..482F discussion: 2017IAUS..327....1R

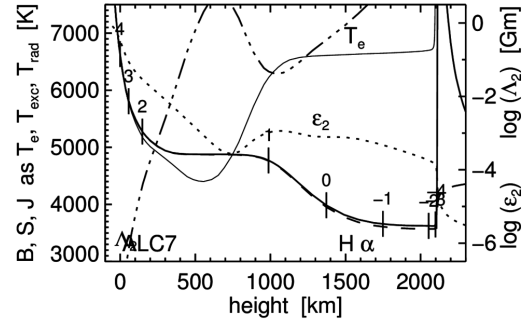
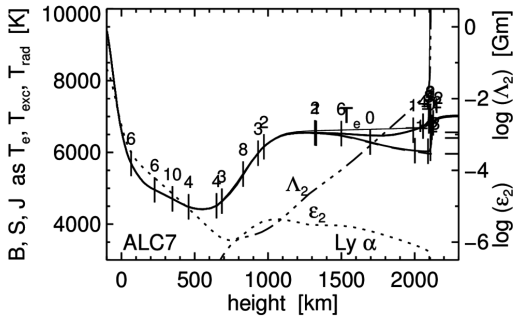
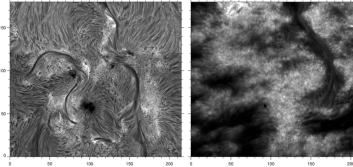


Na I D₁ AND Mg I b₂



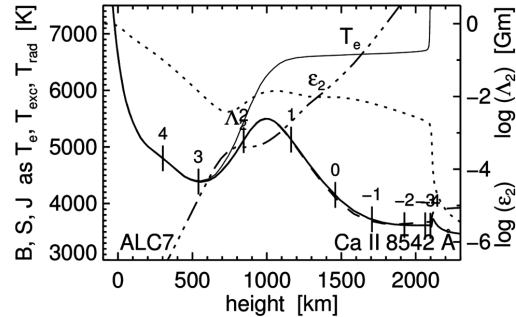
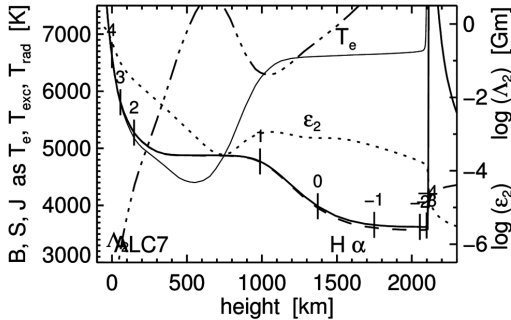
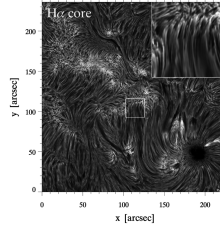
- similar NLTE formation = heavy two-level scattering
- core intensities do not sense ALC7 chromosphere
- narrow Na I D₁ flanks reverse reversed granulation
- minority stages: recombination $\propto N_e$ senses non-E Ly α settling and scattering
- SST: Dopplergrams \approx unsigned fluxtube magnetograms (Na I D₁ formation)
non-E enhanced in cooling recombining downflows? (SE = Bifrost snapshot OK)

Ly α and H α



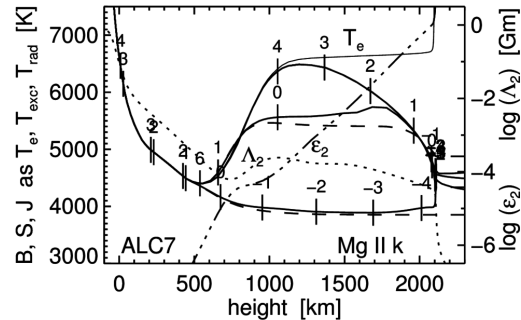
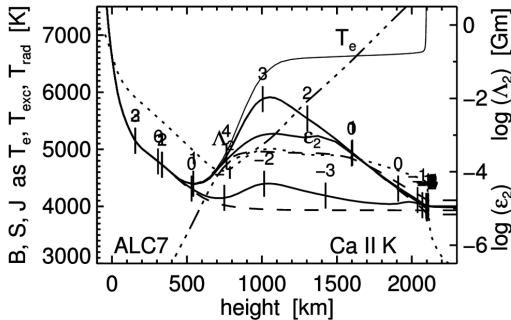
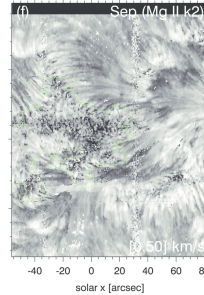
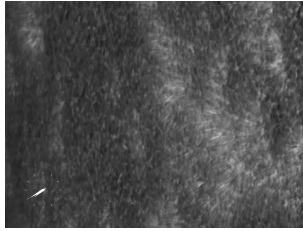
- both: heavy NLTE scatterers with $S \approx J$
- Ly α : boxed-in by enormous extinction \Rightarrow radiative detailed balance: $S = J$
 in shocks (\approx ALC7 chromosphere) collisional thermalization: $b_2 \approx b_1$
 in cool gas surrounding hot structures $b_2 \gg 1$ from Ly α surround scattering
 in post-hot cool gas slow $S \approx J$ thermalization with $b_2 \gg 1$: S^l memory of hot past
- H α : photons created in granulation
 scatter 3D across upper-photosphere opacity gap and through chromosphere
 in shocks etc. Boltzmann extinction $b_2 \approx b_1$
 in post-hot cool gas $b_2 \gg 1$: extinction memory of hot past
- Ly α scene: heating events bright down-throat, cooling contrails dark from scattering?
 H α scene: RBE/RRE heating events, cooling contrails dark from non-E opacity?

H α and Ca II 8542 Å



- both: heavy NLTE scatterers with $S \approx J$ sampled at similar $\tau = 1$ heights
- both: Saha-Boltzmann or larger extinction in shocks and ALC7
- core widths: both decrease away from network = decreasing temperature
- H α fibrils extend further, contradicting [Saha-Boltzmann extinction sensitivities](#)
- fibril opacity in Ca II 8542 Å instantaneous, in H α post-hot non-E?

Ca II K and Mg II k

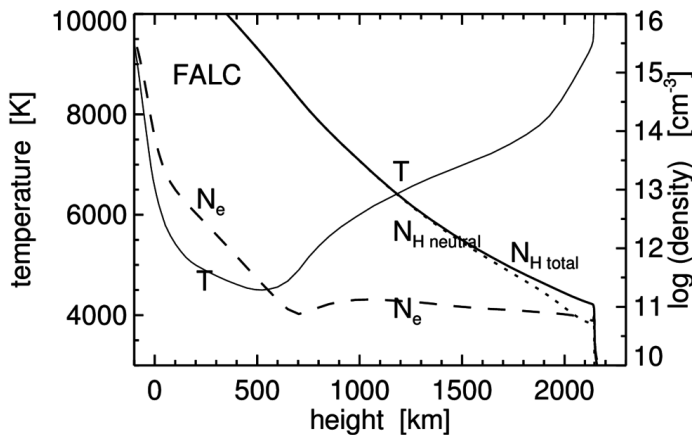
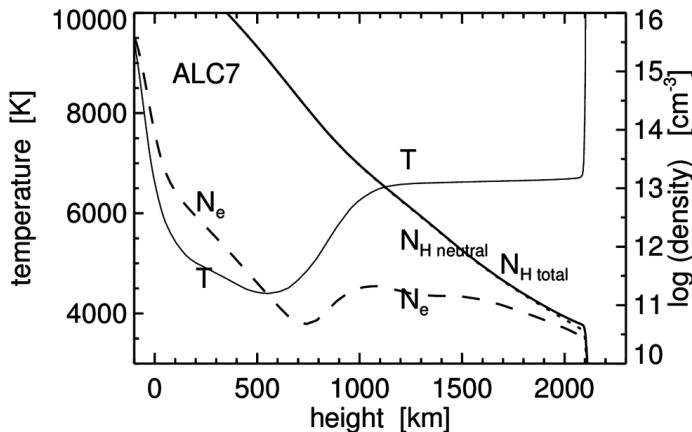


- both: heavy NLTE scatterers with PRD source function splits
- both: near-Saha-Boltzmann extinction everywhere; abundance ratio 18
- both: absence of non-E sensitivities = instantaneous chromosphere
- both: slender fibrils emanating from network, in Ca II H & K better at narrower bandwidth, in Mg II k best in k_2 peak separation
- slender fibrils = propagating heating events?

ALC7 ATMOSPHERE VERSUS FALC ATMOSPHERE

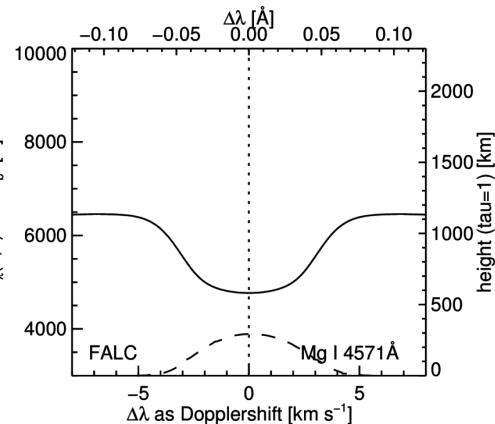
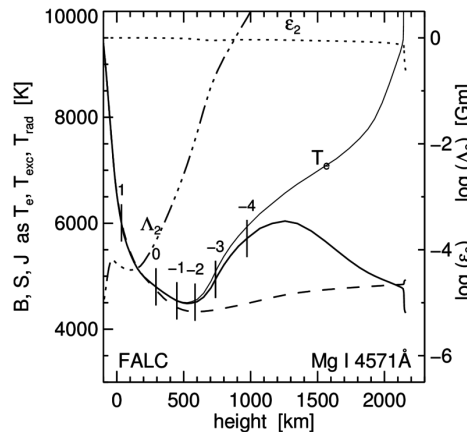
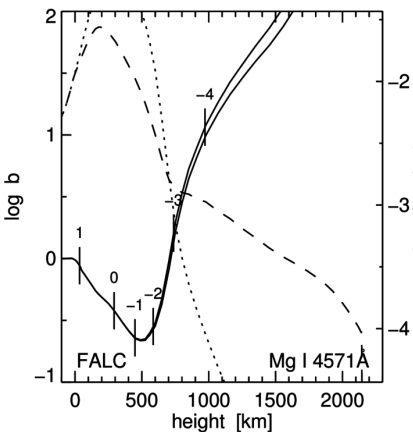
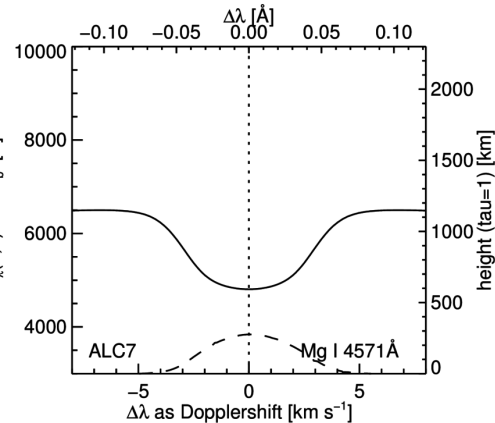
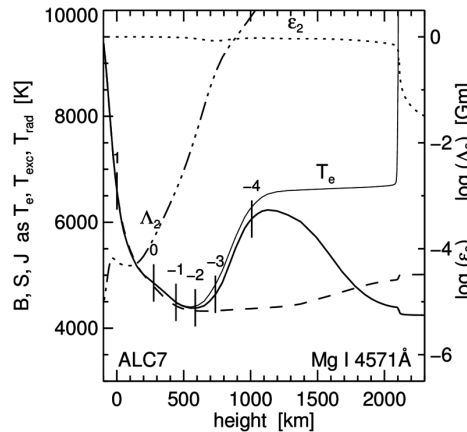
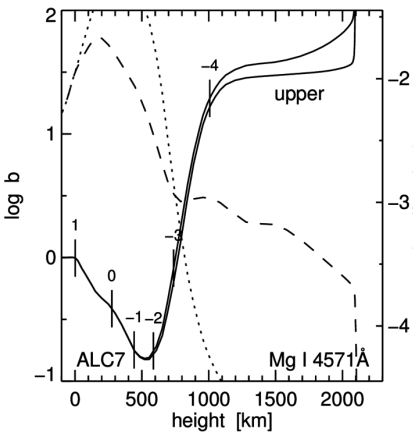
Avrett & Loeser 2008ApJS..175..229A

Fontenla, Avrett & Loeser 1993ApJ...406..319F



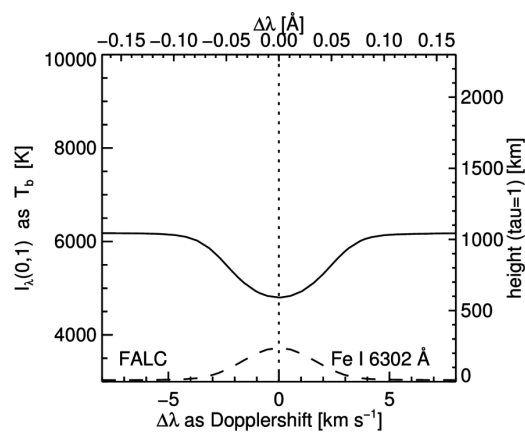
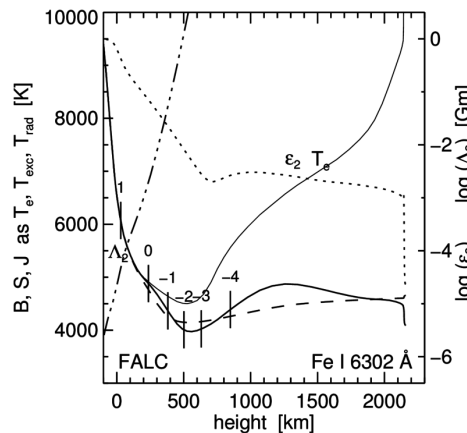
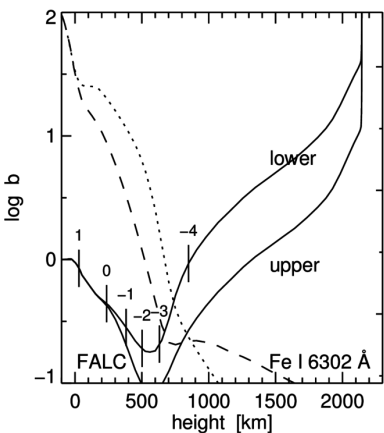
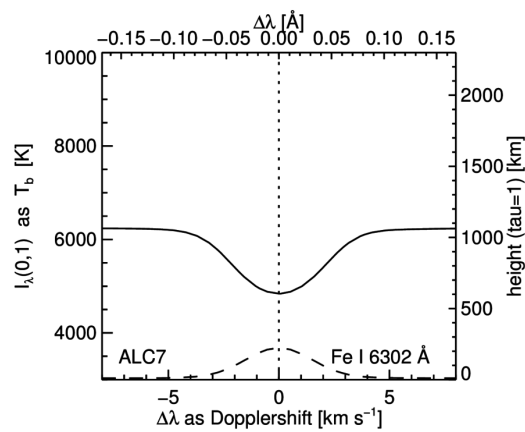
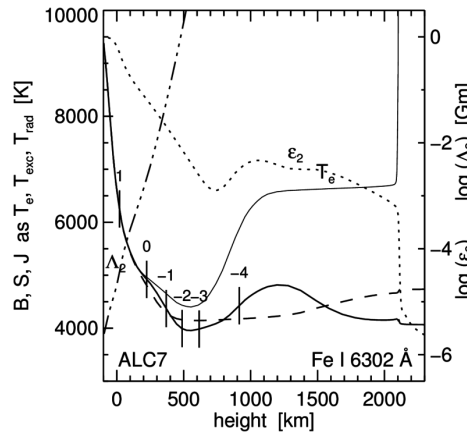
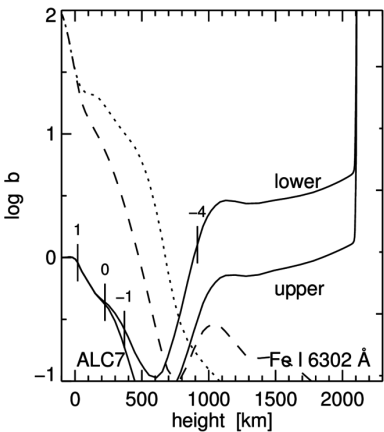
MgI4571 FeI6302 MgIb₂ NaID₁ BaII4554 CaII8542 CaIIK MgIIk Ly α H α H β HeI584

Mg I 4571 Å IN ALC7 AND FALC



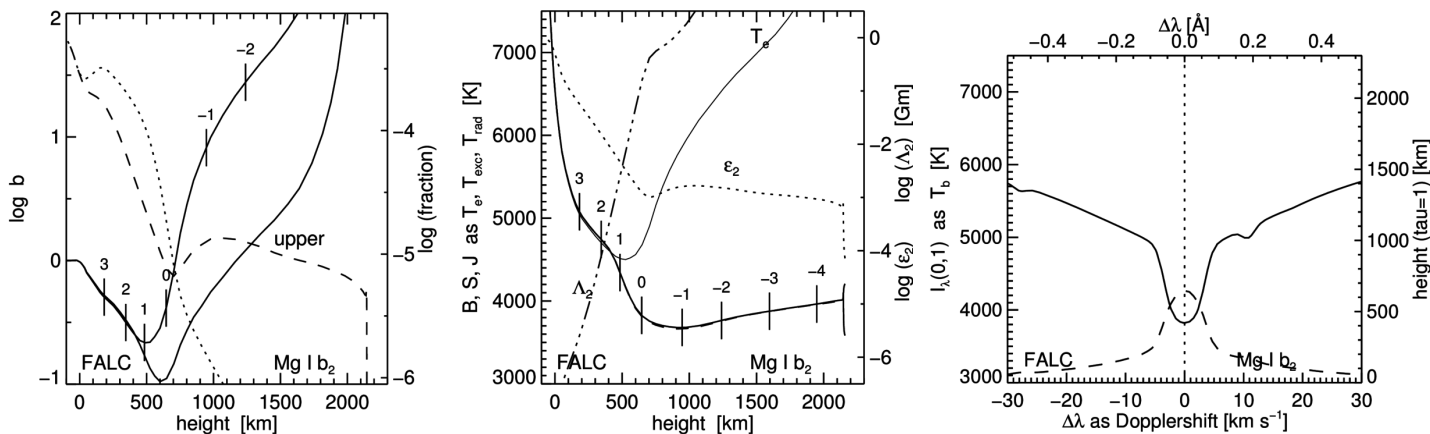
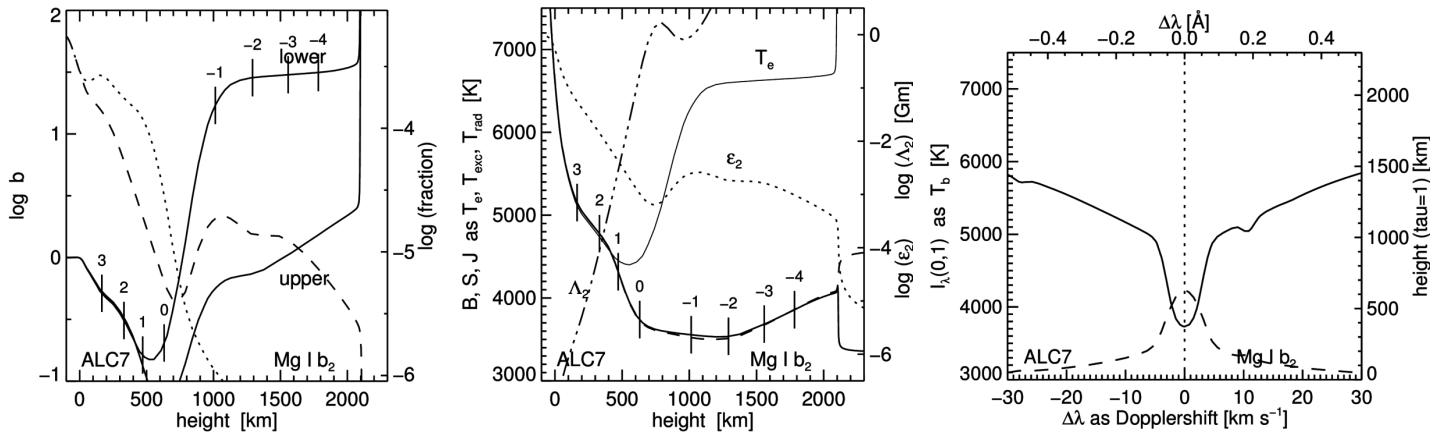
unique photospheric line with LTE source function

Fe I 6301.5 Å IN ALC7 AND FALC



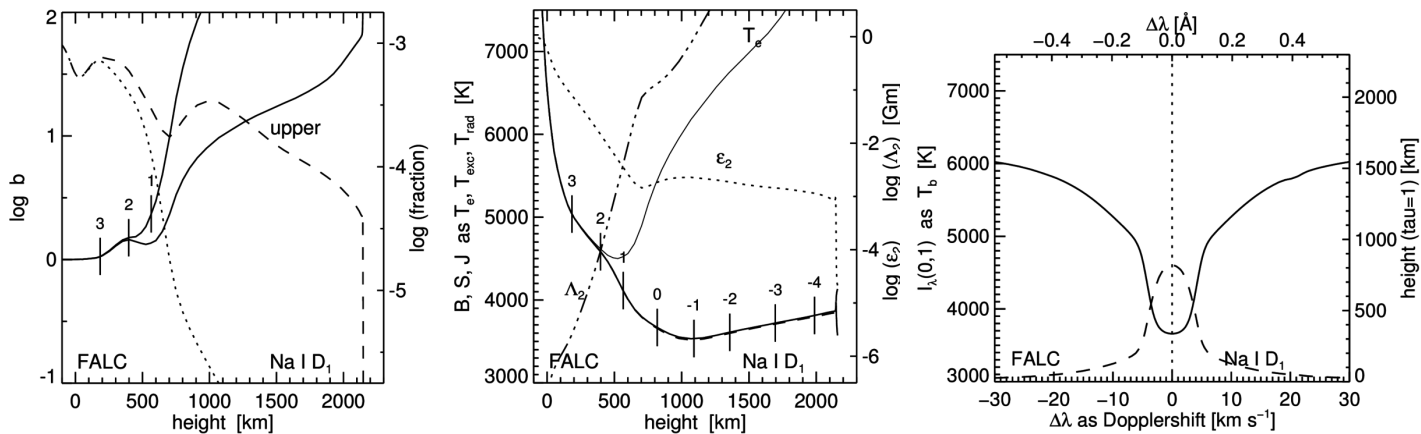
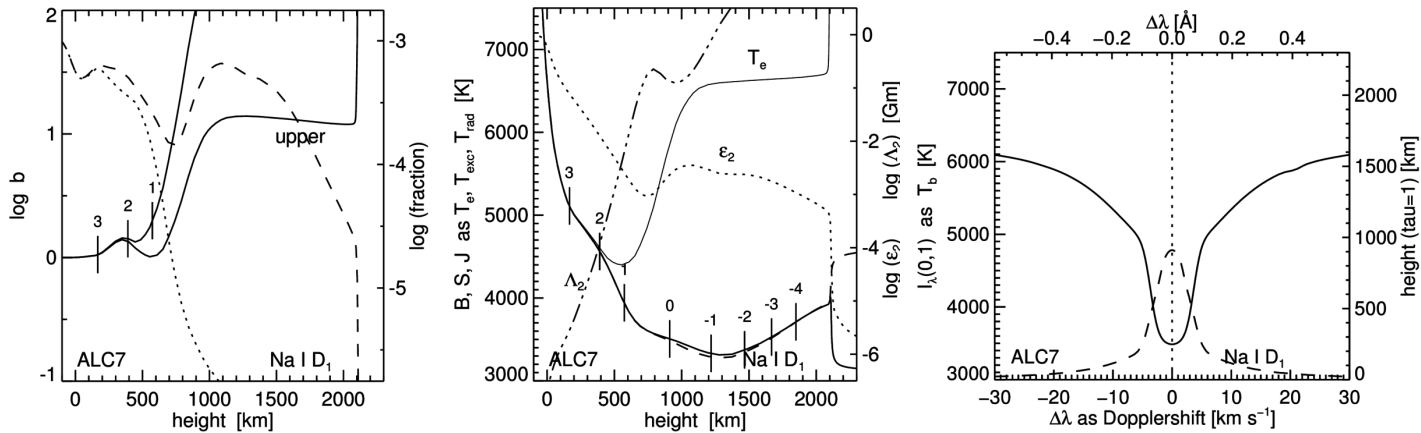
standard polarimetry line

Mg I b₂ 5173 Å IN ALC7 AND FALC



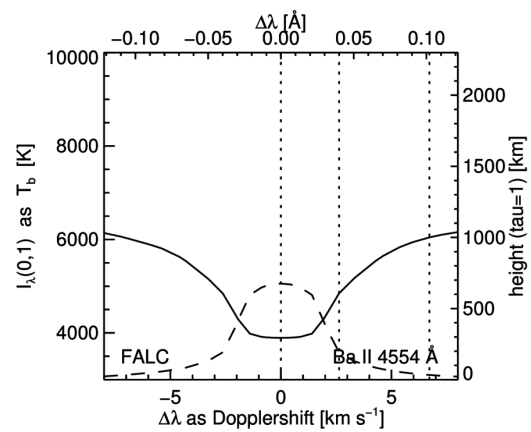
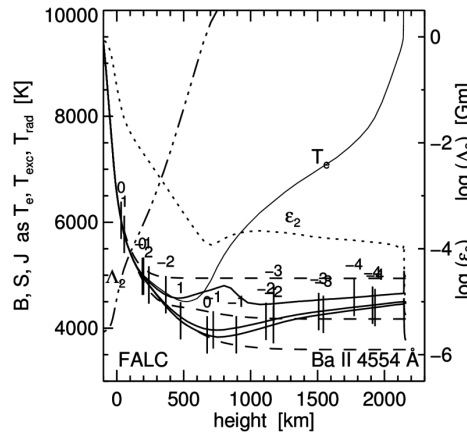
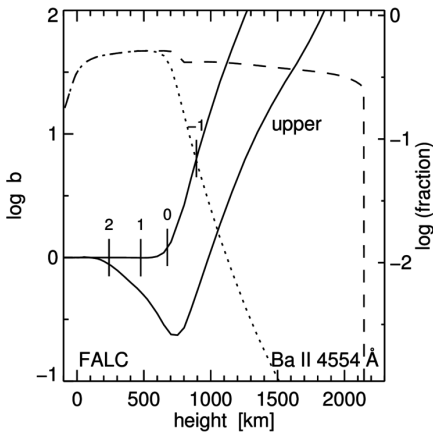
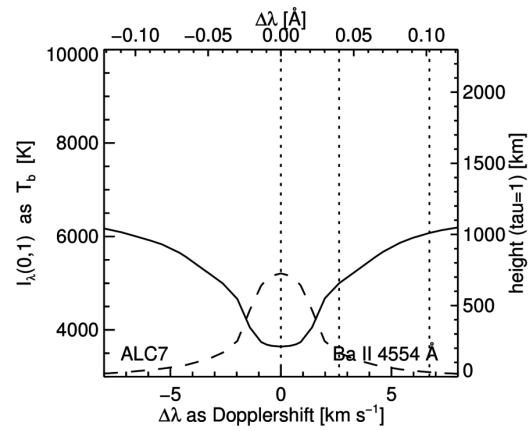
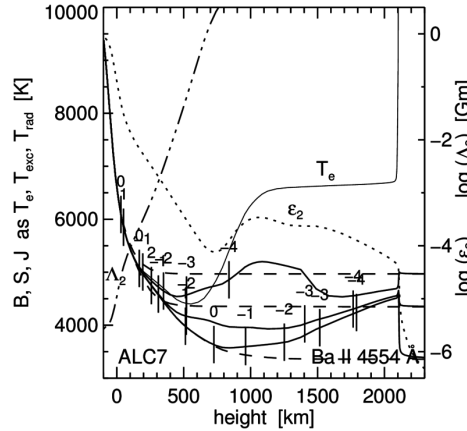
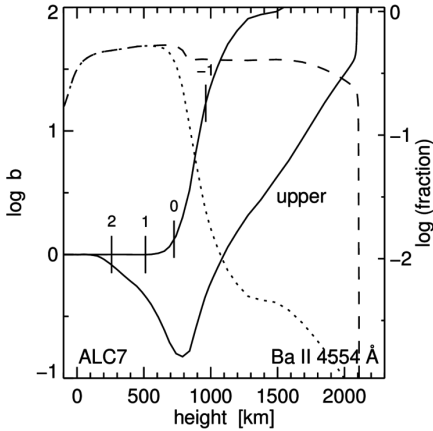
diagnostic of upper photosphere

Na I D₁ 5896 Å IN ALC7 AND FALC



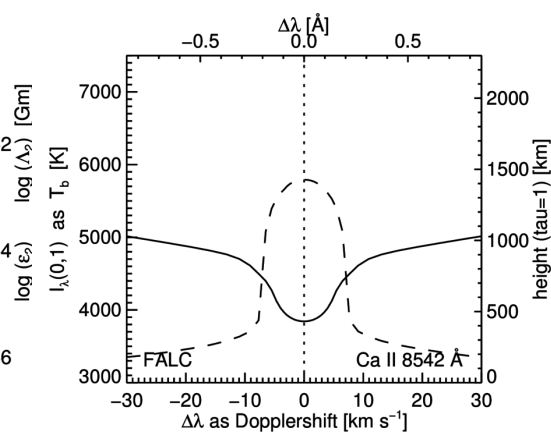
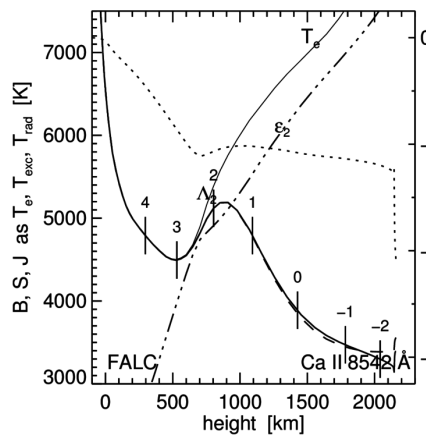
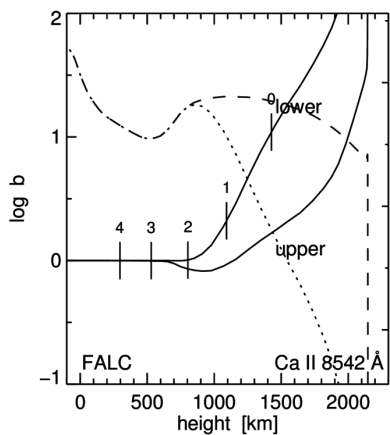
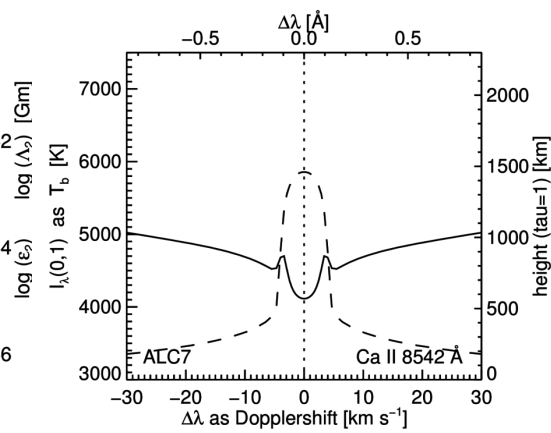
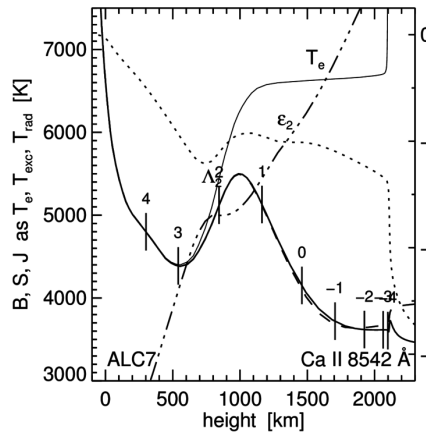
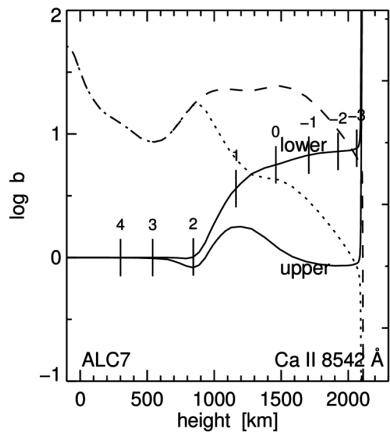
Na I D₁: darkest solar line in optical spectrum = textbook example of two-level scattering

Ba II 4554 Å IN ALC7 AND FALC



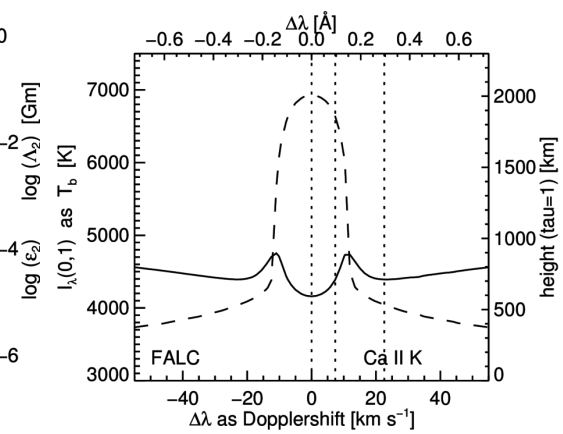
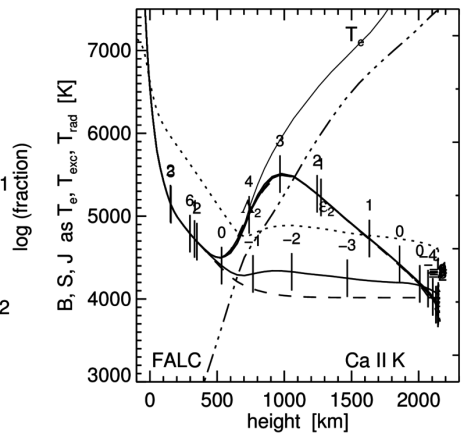
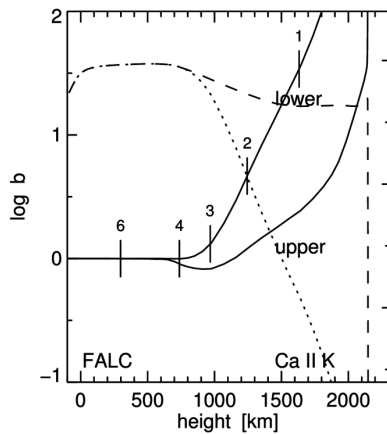
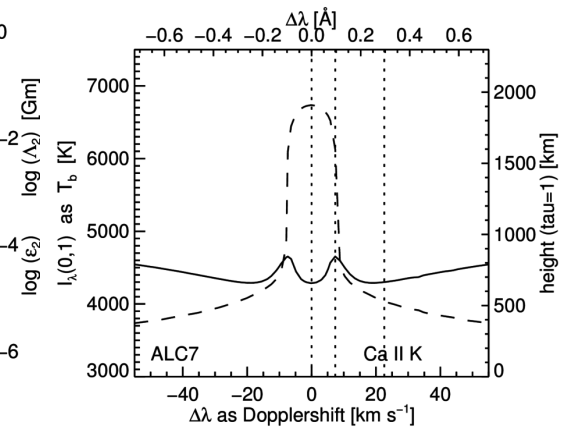
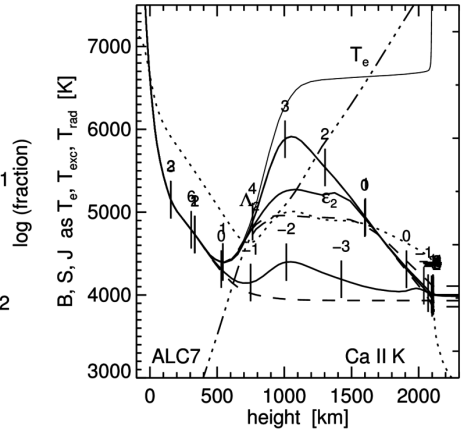
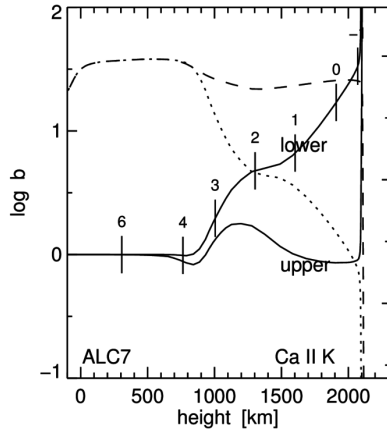
weakest PRD line, best velocity diagnostic, good Hanle diagnostic

Ca II 8542 Å IN ALC7 AND FALC



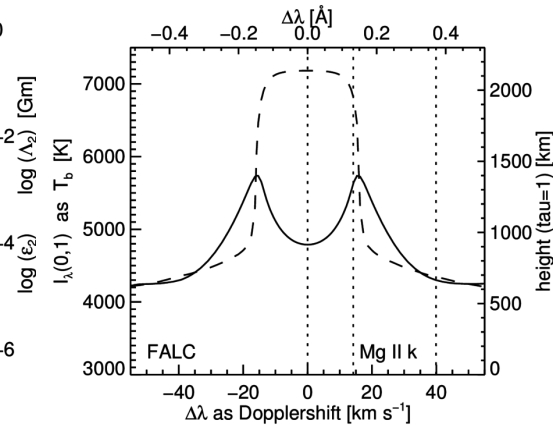
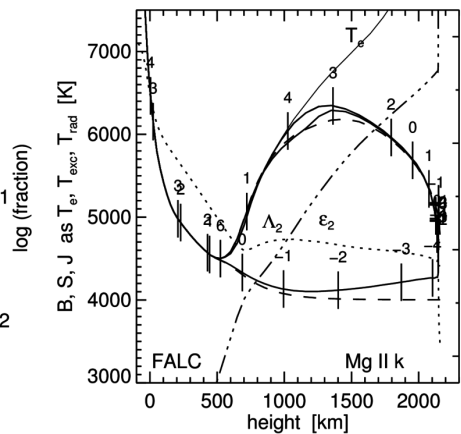
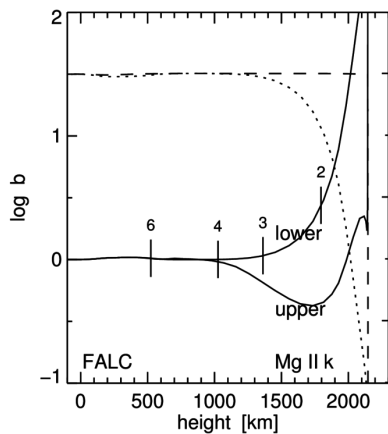
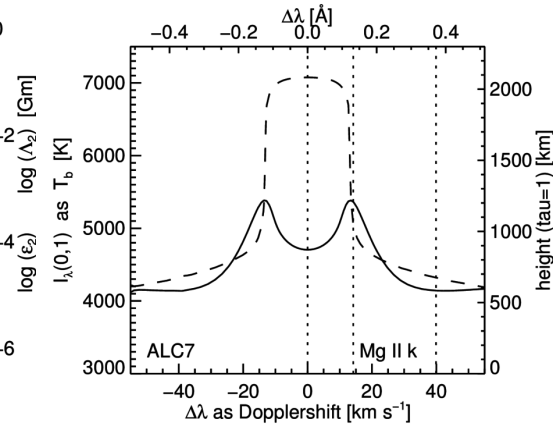
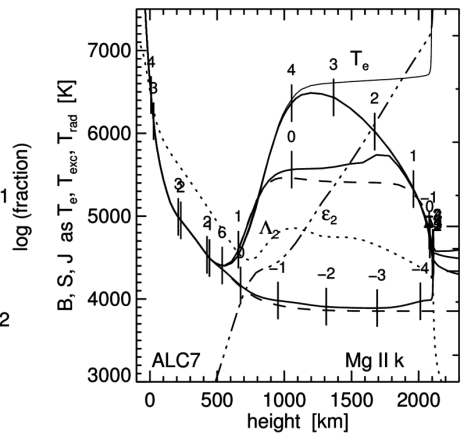
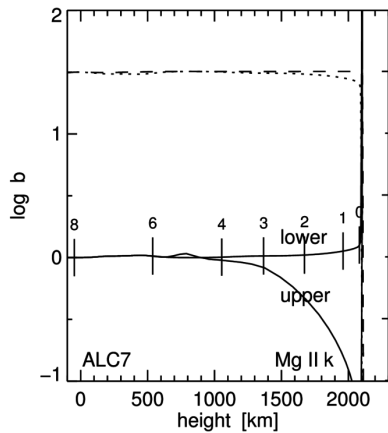
cleanest chromospheric diagnostic in the near infrared

Ca II K 3934 Å IN ALC7 AND FALC



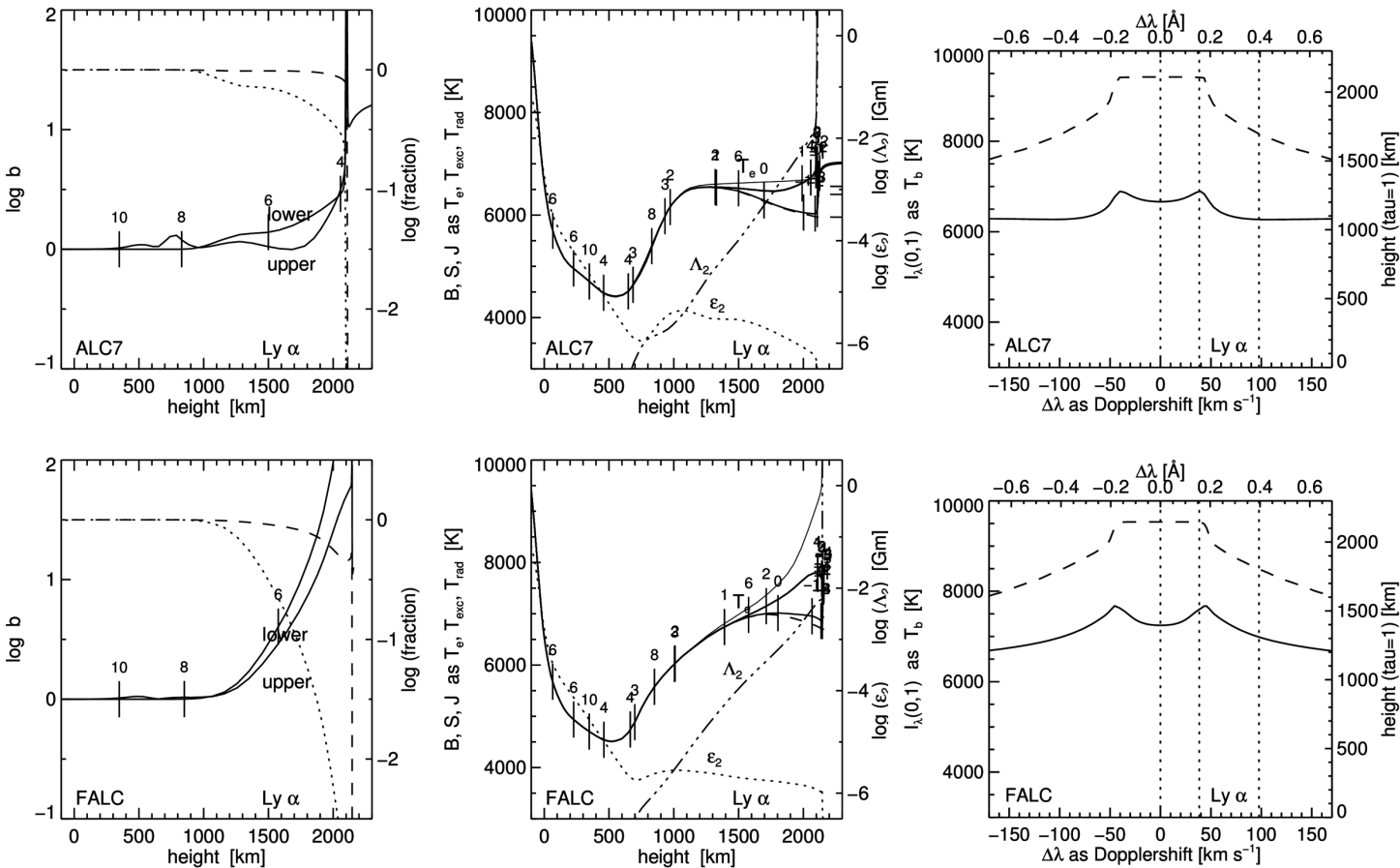
largest extinction in the optical spectrum

Mg II k 2796 Å IN ALC7 AND FALC



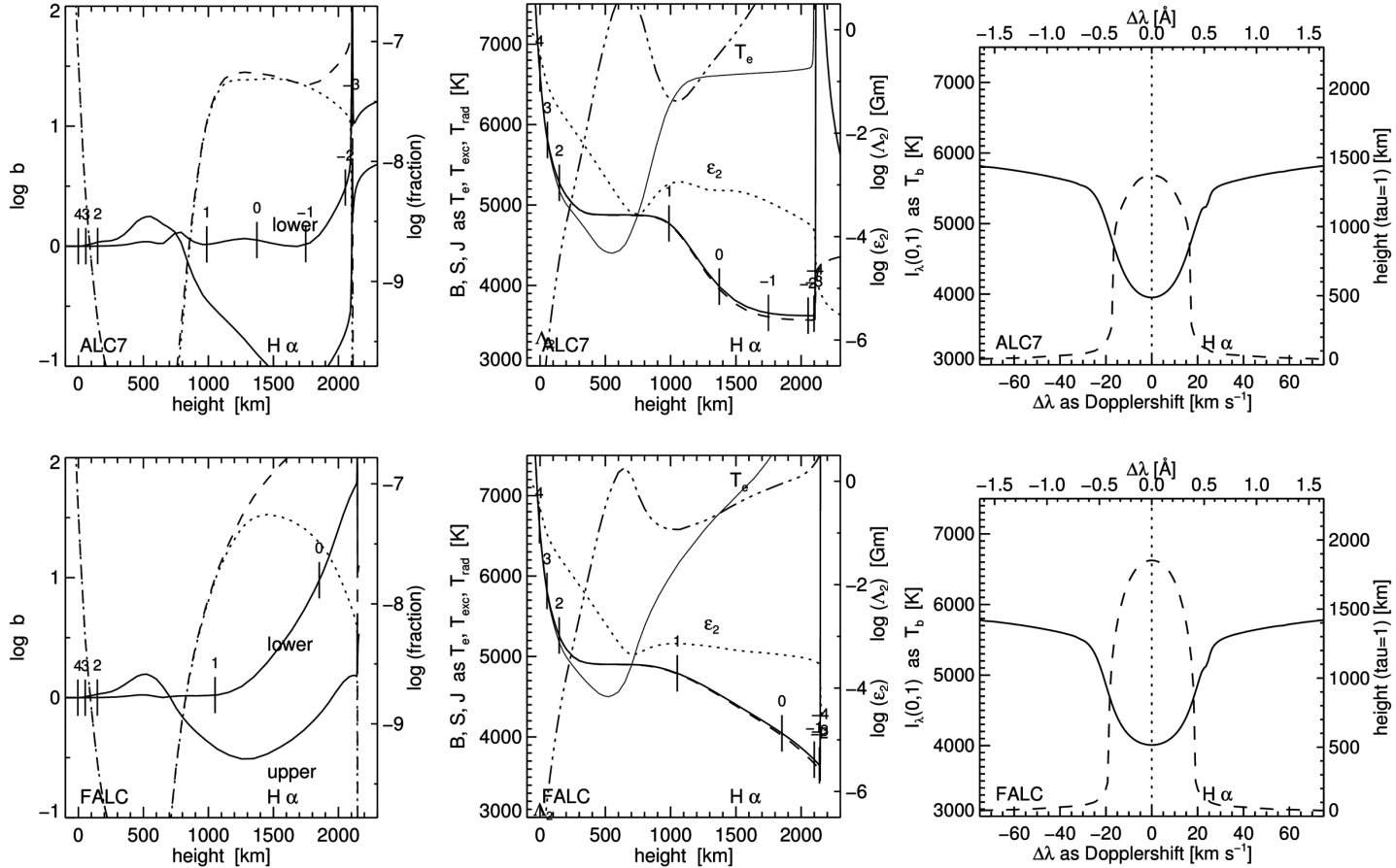
cleanest PRD line and yet larger extinction than Ca II K

Ly α 1216 Å IN ALC7 AND FALC



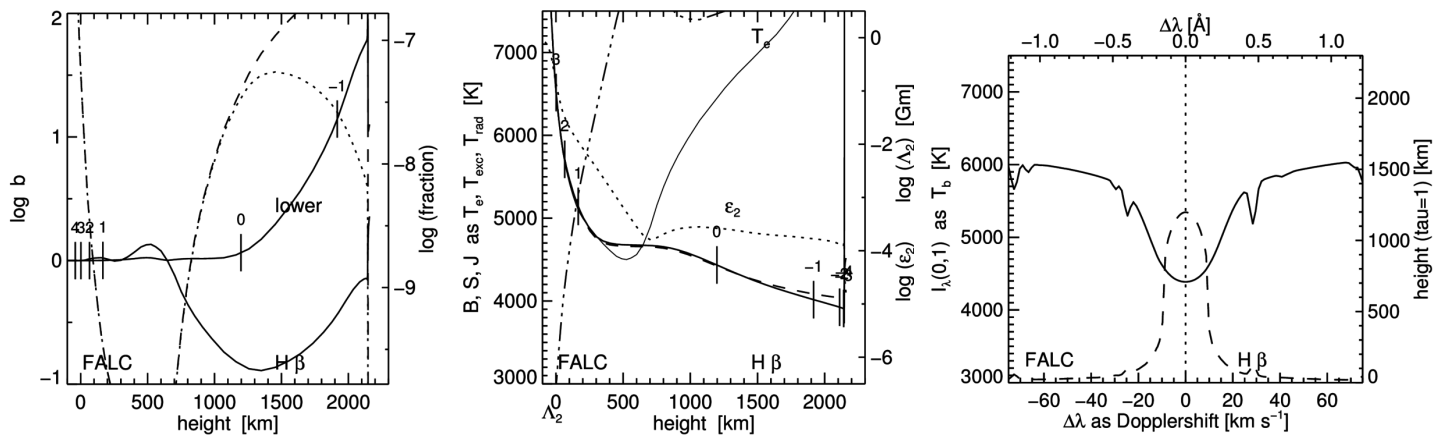
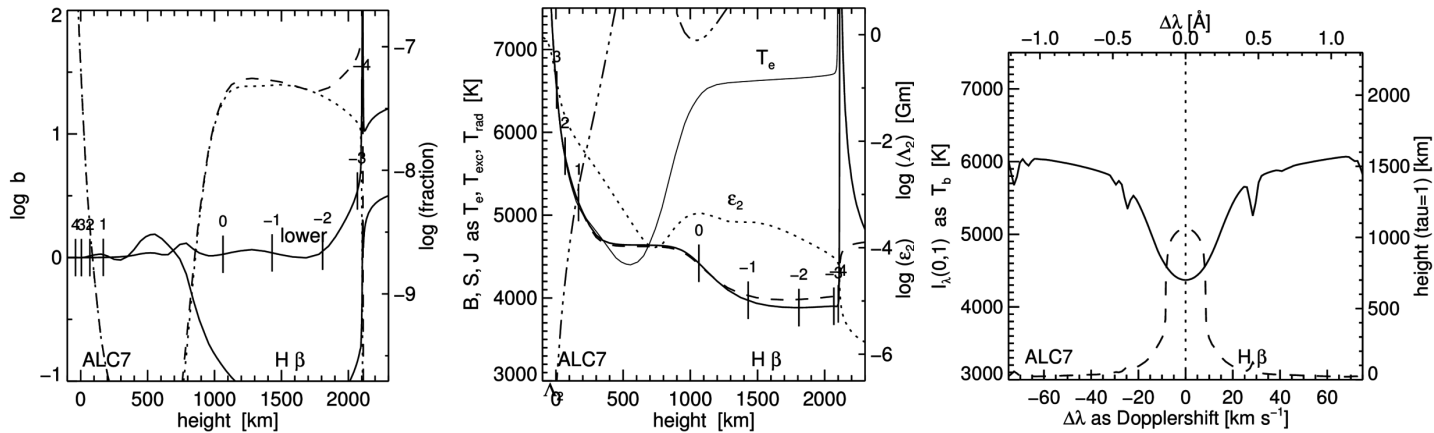
champion: largest extinction and most scattering of all lines

H α 6563 Å IN ALC7 AND FALC



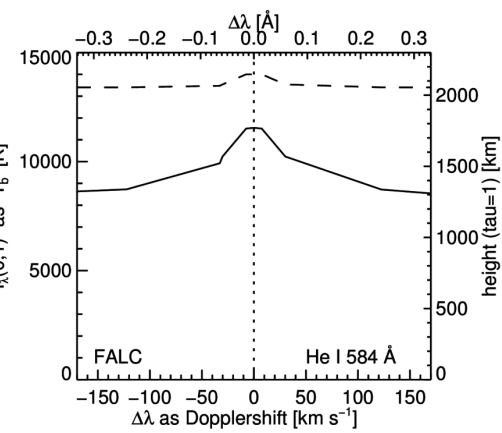
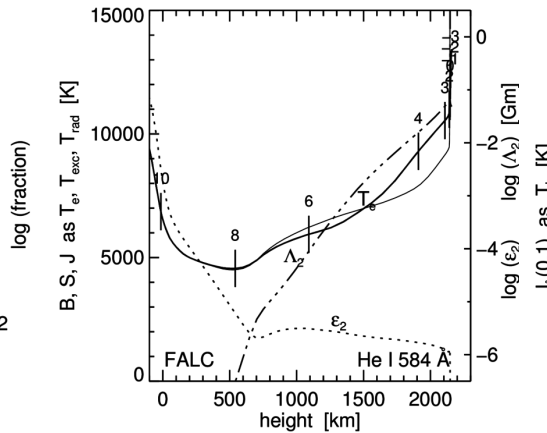
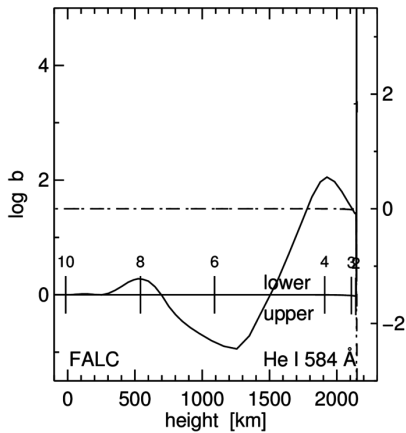
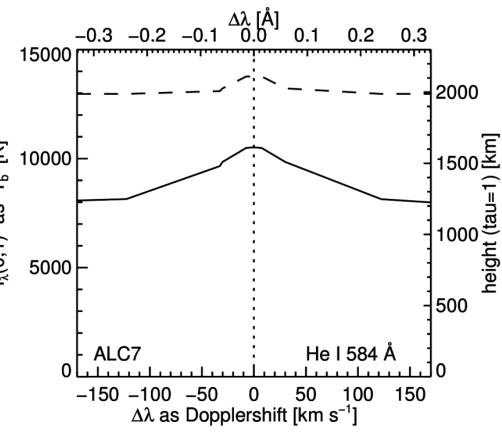
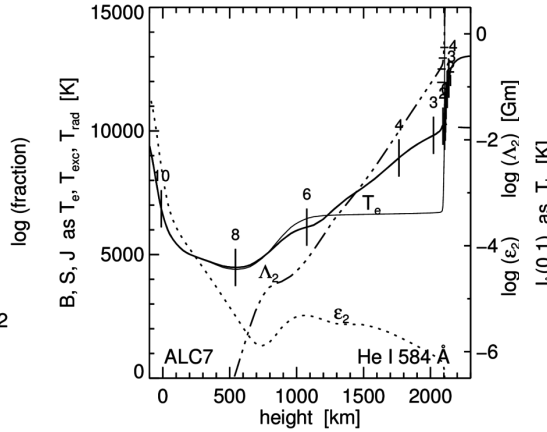
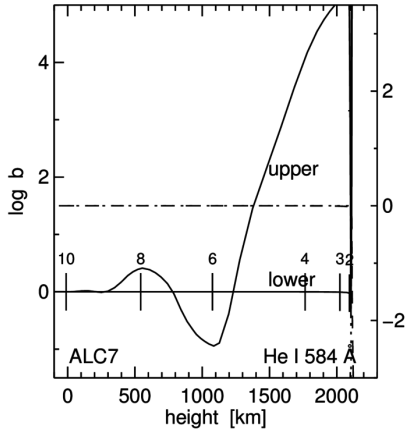
H α : extraordinary from high excitation energy, huge element abundance, on top of Ly α

$H\beta$ 4861 Å IN ALC7 AND FALC



$H\beta$: analogon to $H\alpha$ at $5.4\times$ smaller oscillator strength and in the blue

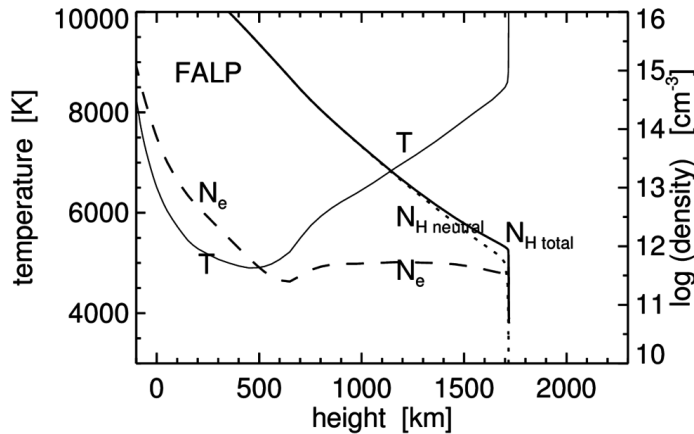
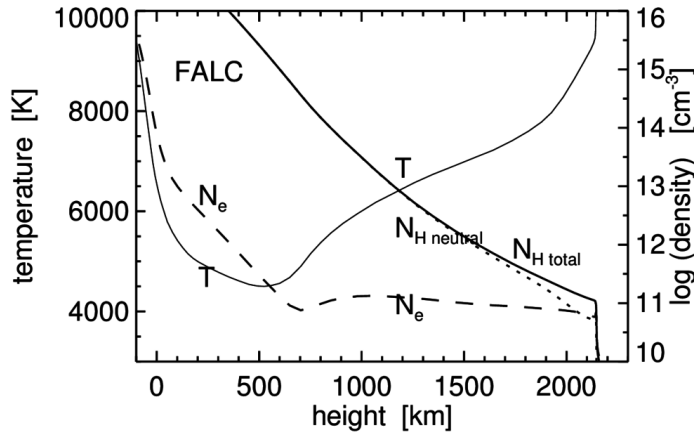
He I 584 Å IN ALC7 AND FALC



backradiator into chromosphere

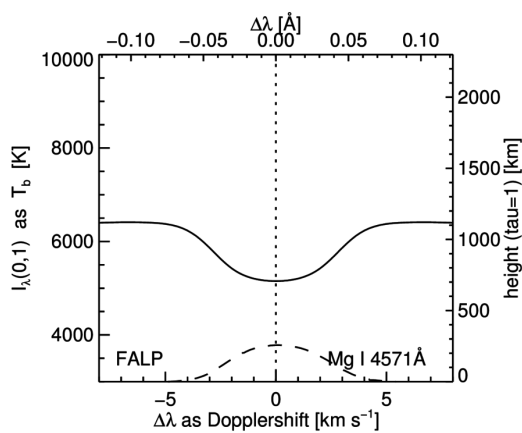
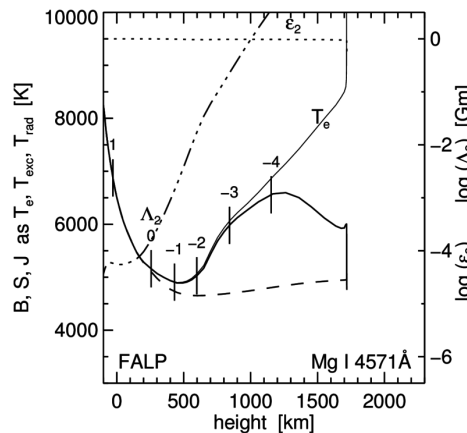
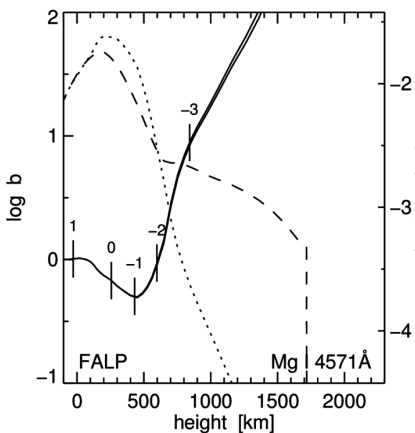
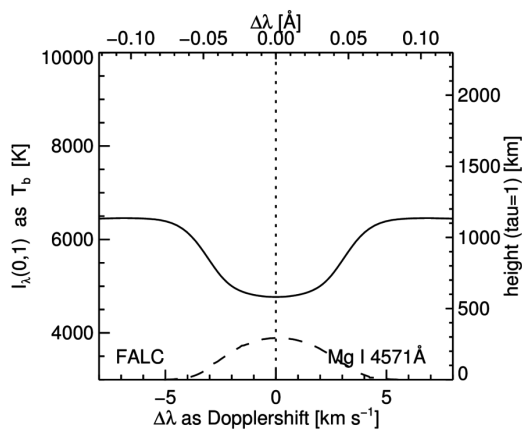
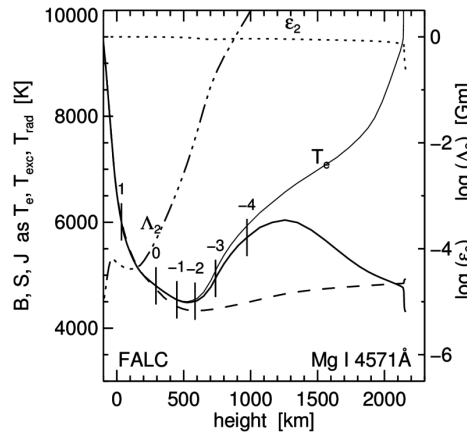
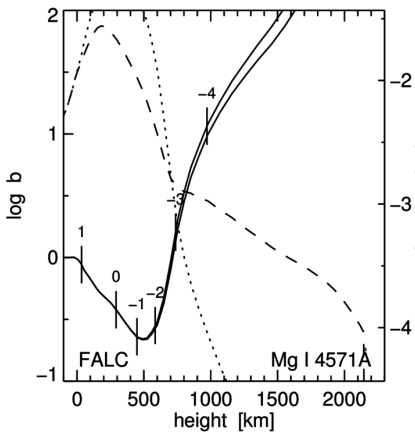
FALC ATMOSPHERE VERSUS FALP ATMOSPHERE

Fontenla, Avrett & Loeser 1993ApJ...406..319F



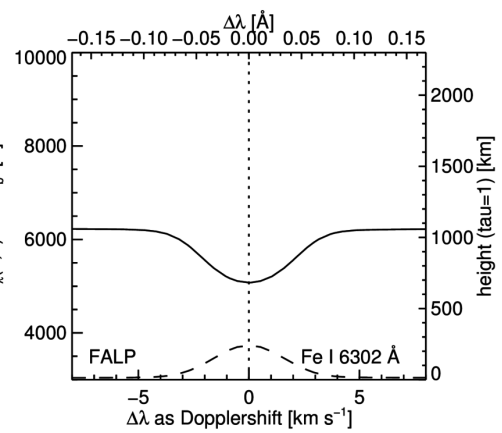
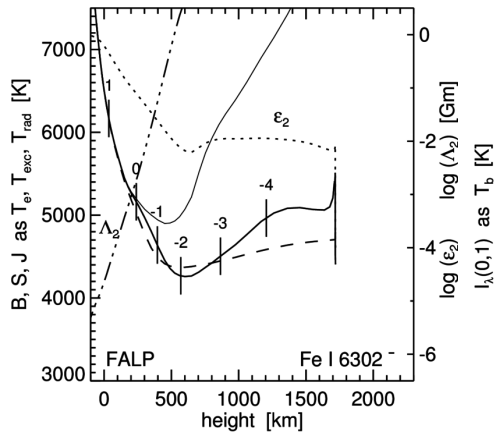
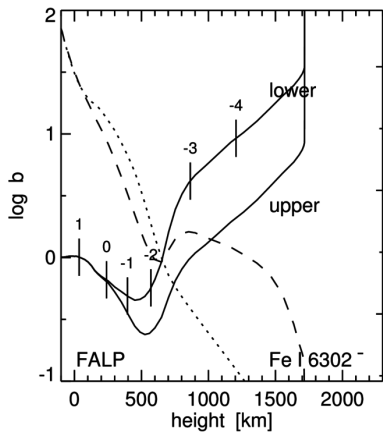
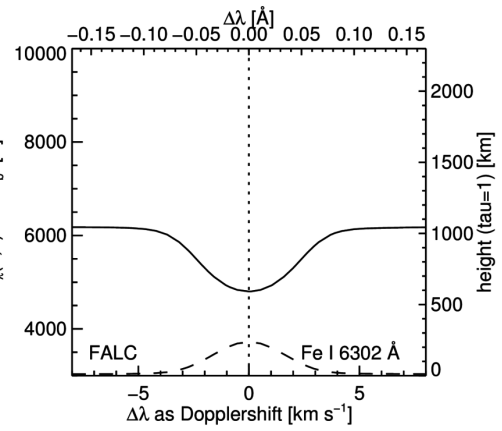
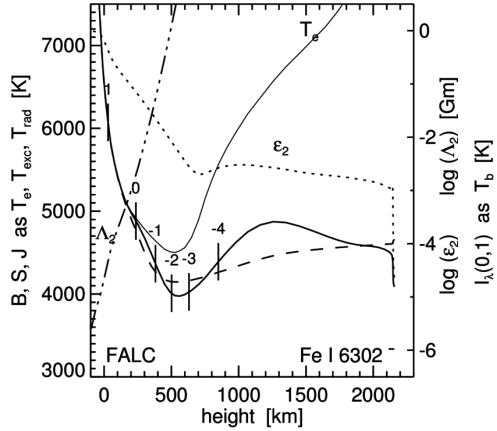
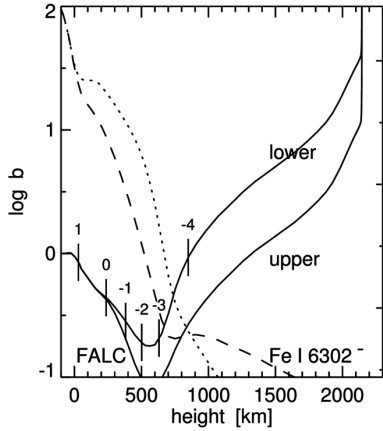
MgI4571 FeI6302 MgIb₂ NaID₁ BaII4554 CaII8542 CaIIK MgIIk Ly α H α H β HeI584

Mg I 4571 Å IN FALC AND FALP



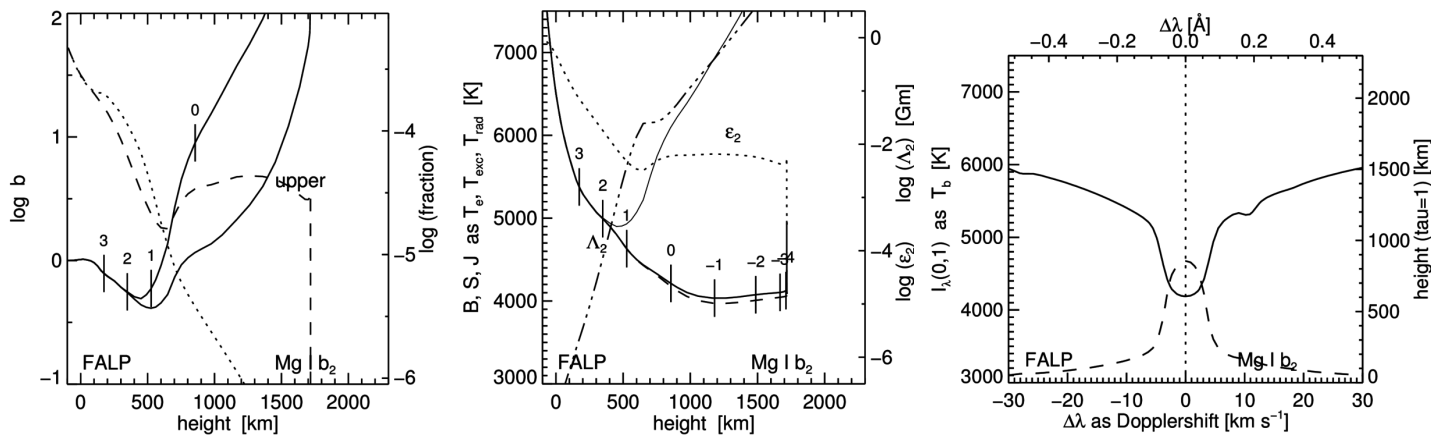
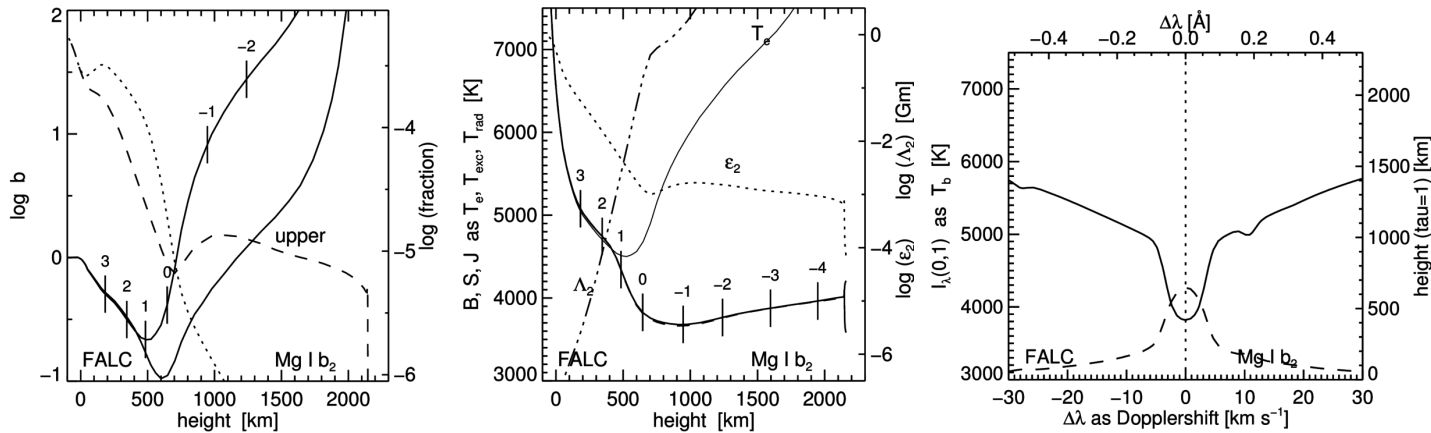
unique photospheric line with LTE source function

Fe I 6301.5 Å IN FALC AND FALP



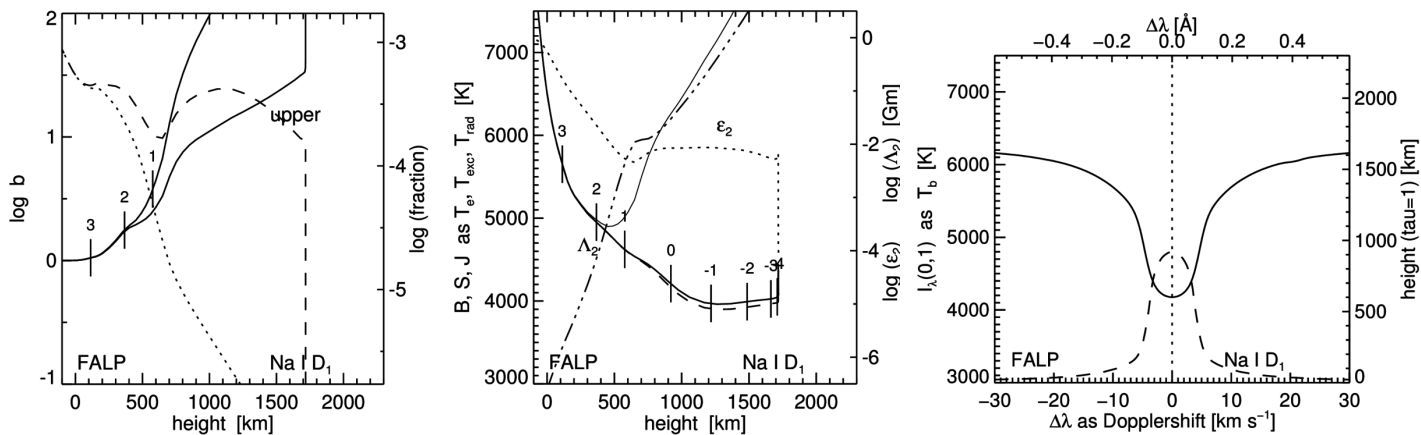
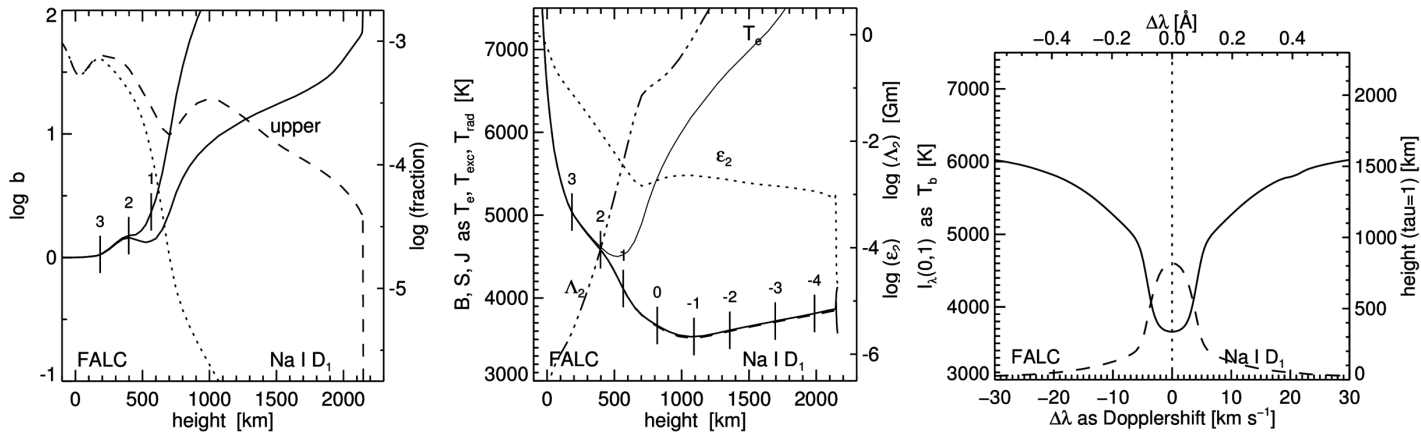
standard polarimetry line

Mg I b₂ 5173 Å IN FALC AND FALP



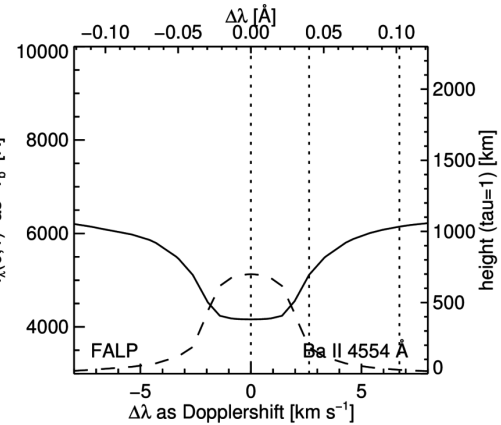
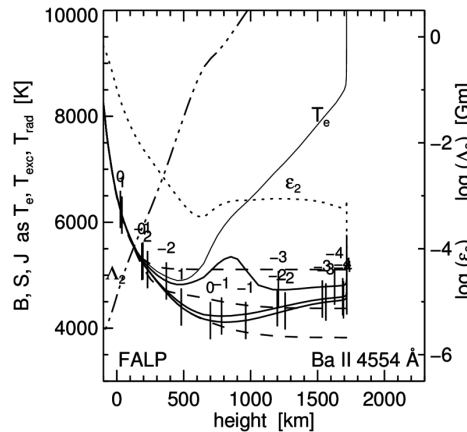
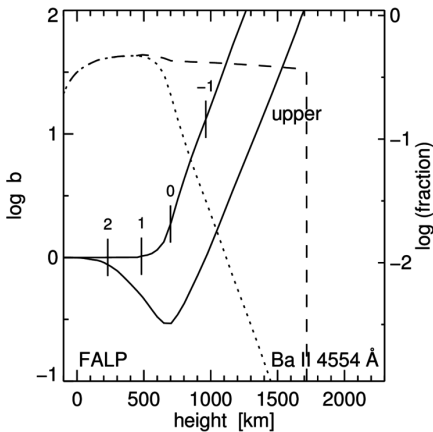
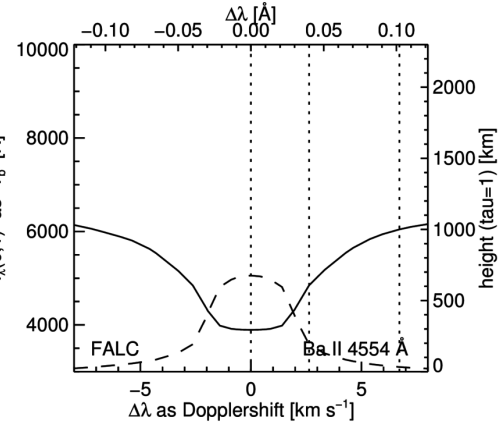
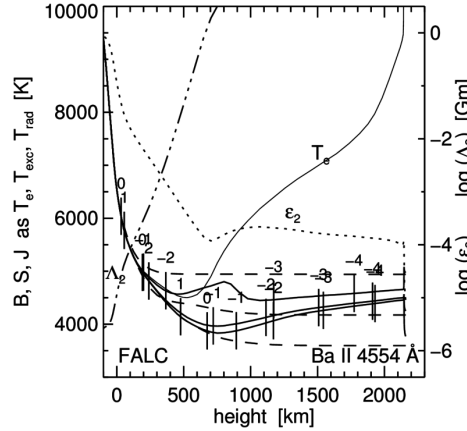
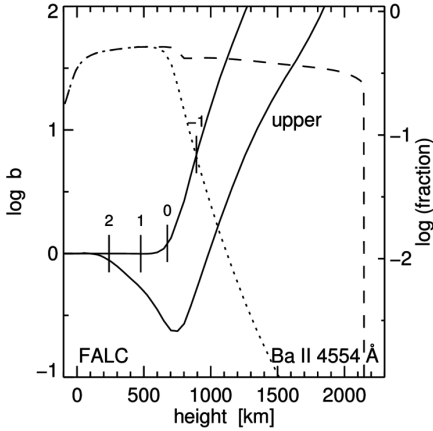
diagnostic of upper photosphere

Na I D₁ 5896 Å IN FALC AND FALP



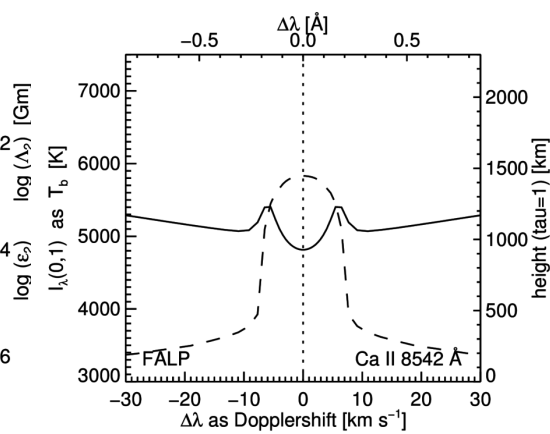
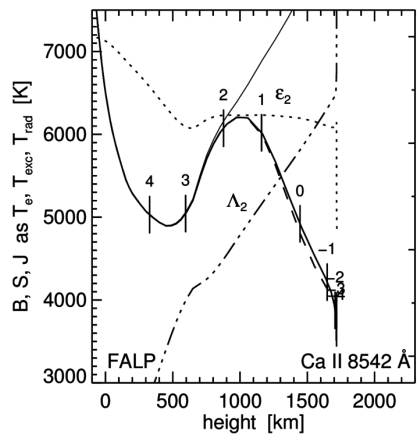
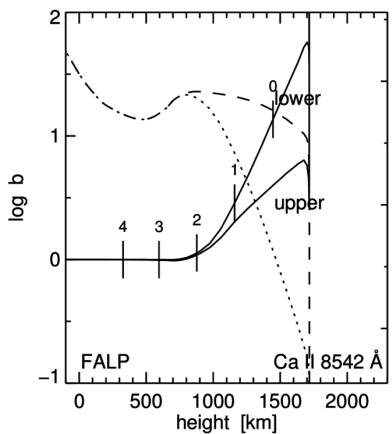
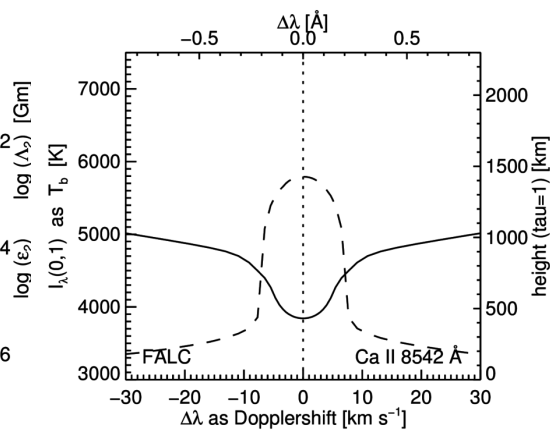
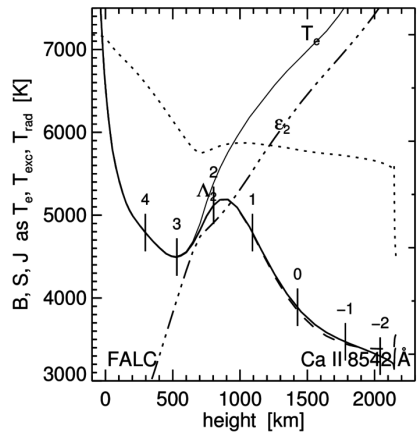
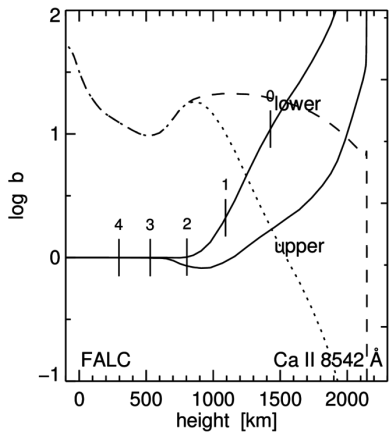
Na I D₁: darkest solar line in optical spectrum = textbook example of two-level scattering

Ba II 4554 Å IN FALC AND FALP



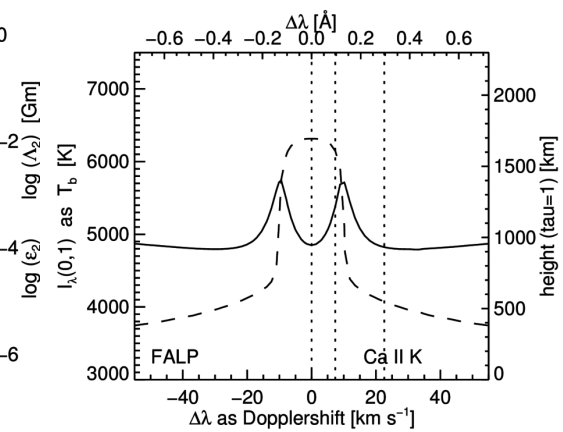
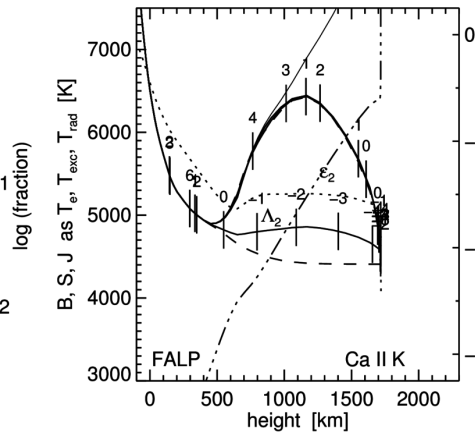
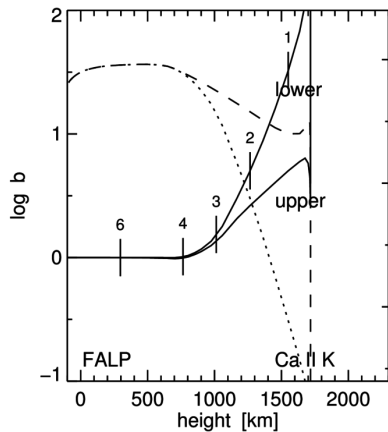
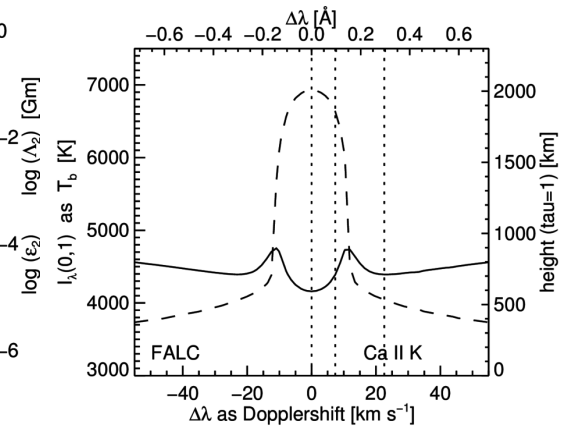
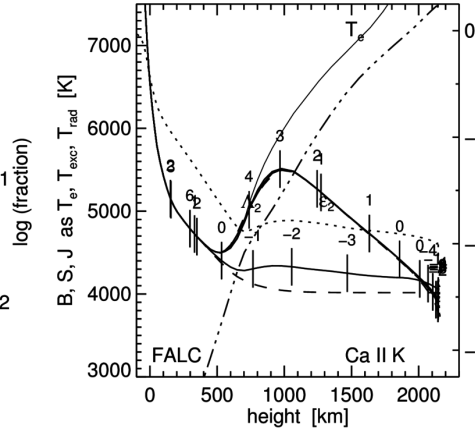
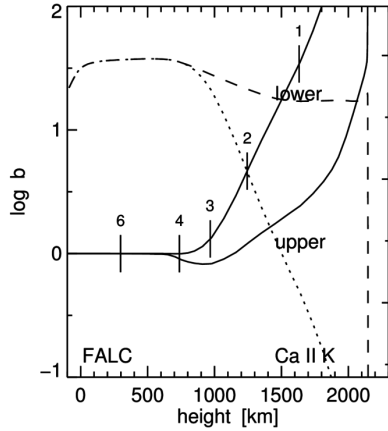
weakest PRD line, best velocity diagnostic, good Hanle diagnostic

Ca II 8542 Å IN FALC AND FALP



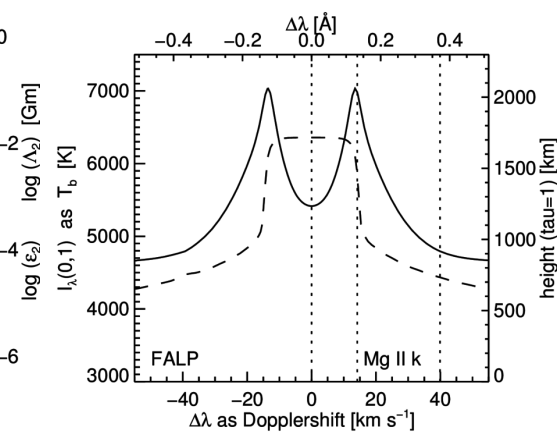
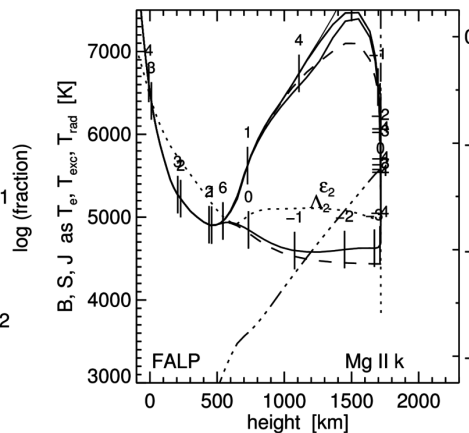
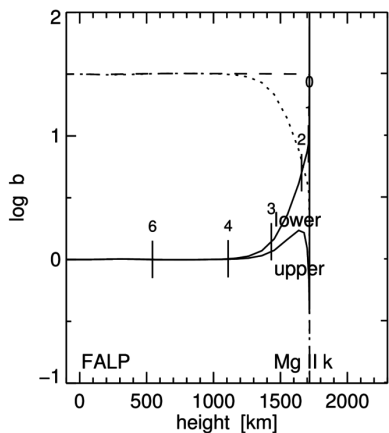
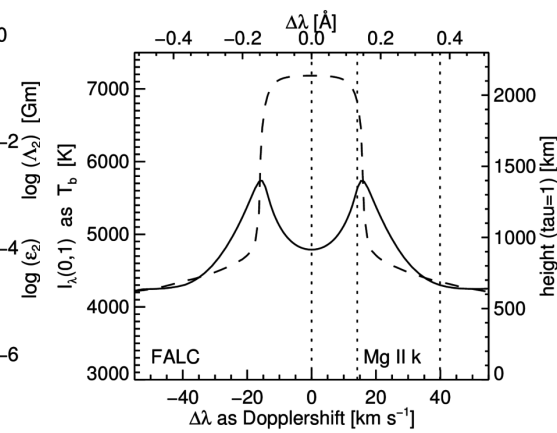
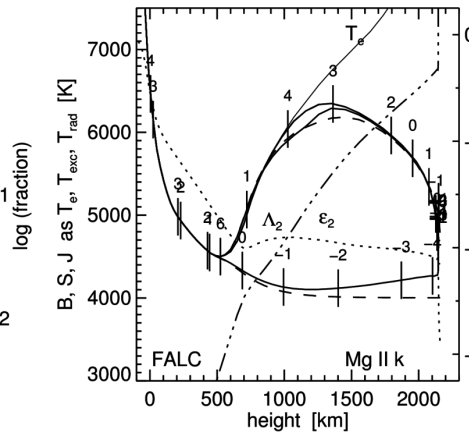
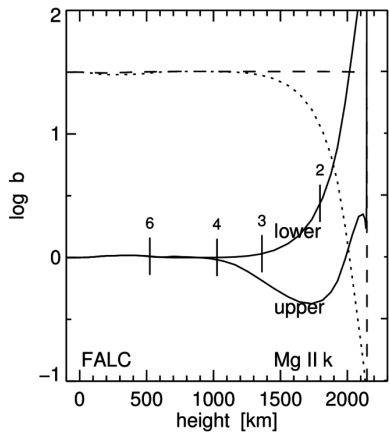
cleanest chromospheric diagnostic in the near infrared

Ca II K 3934 Å IN FALC AND FALP



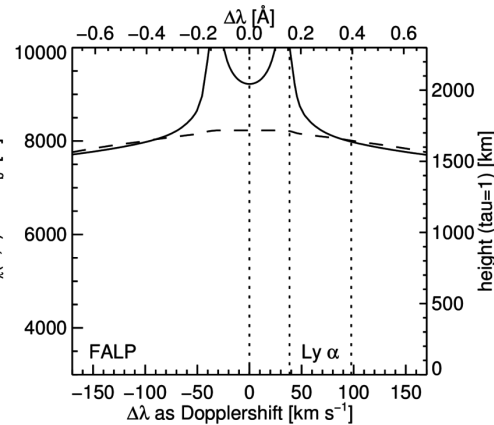
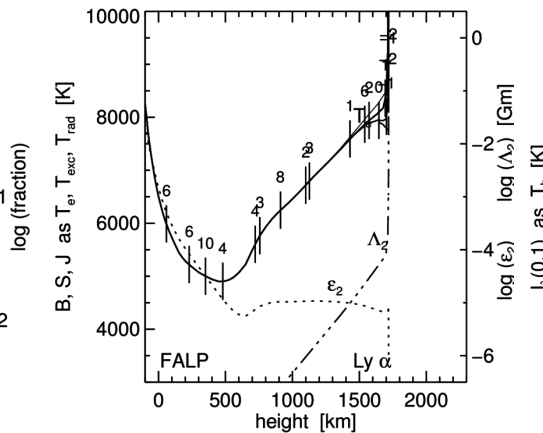
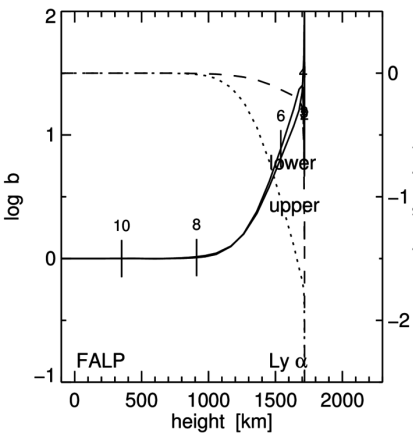
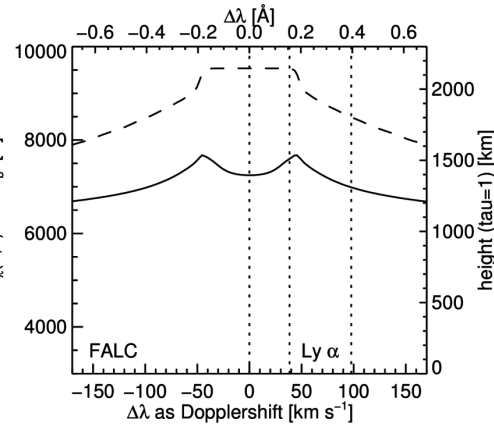
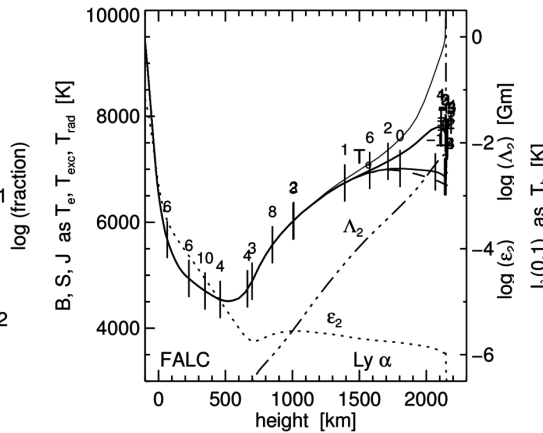
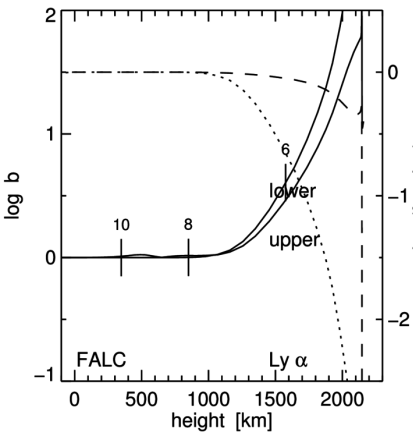
largest extinction in the optical spectrum

Mg II k 2796 Å IN FALC AND FALP



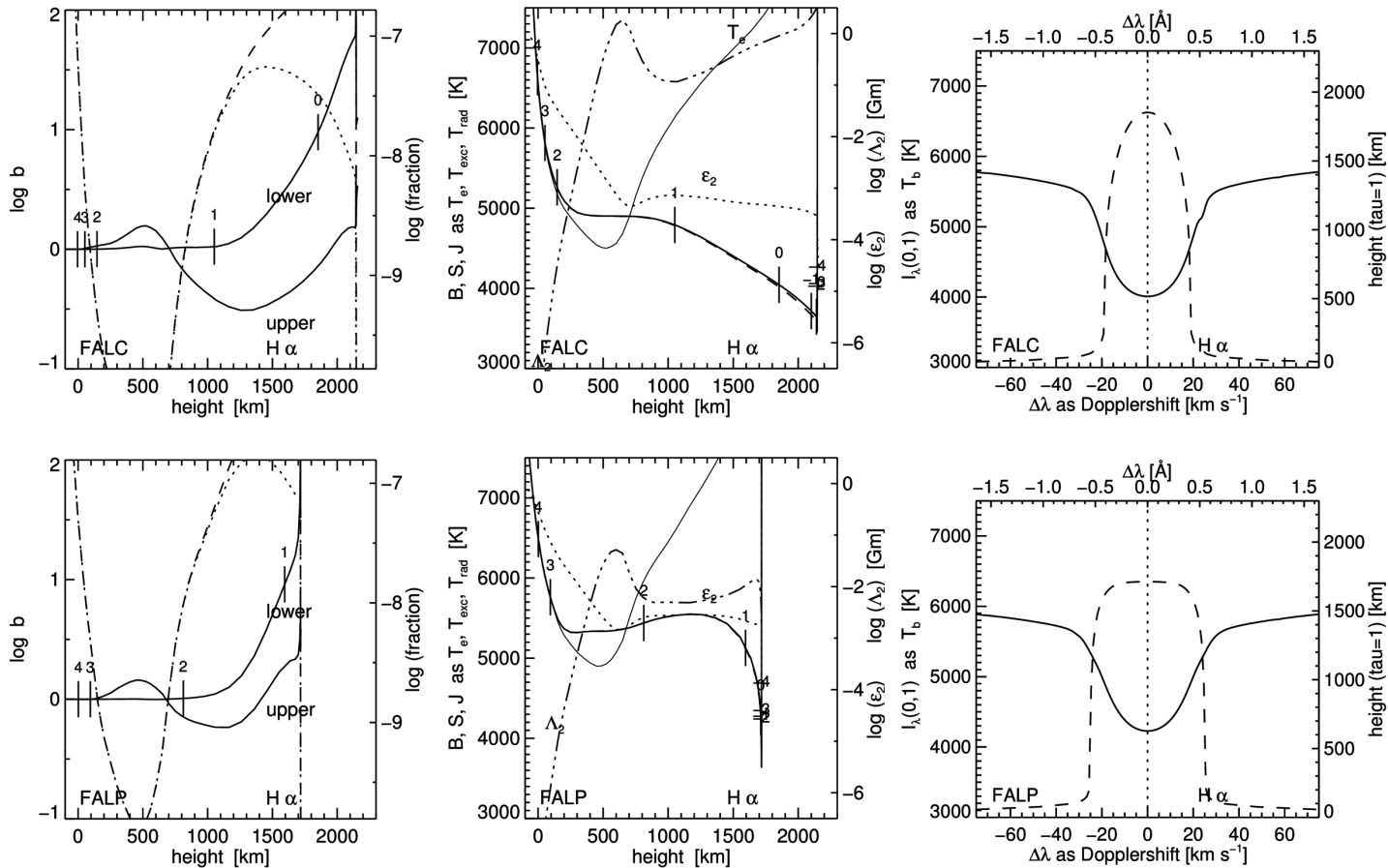
cleanest PRD line and yet larger extinction than Ca II K

Ly α 1216 Å IN FALC AND FALP



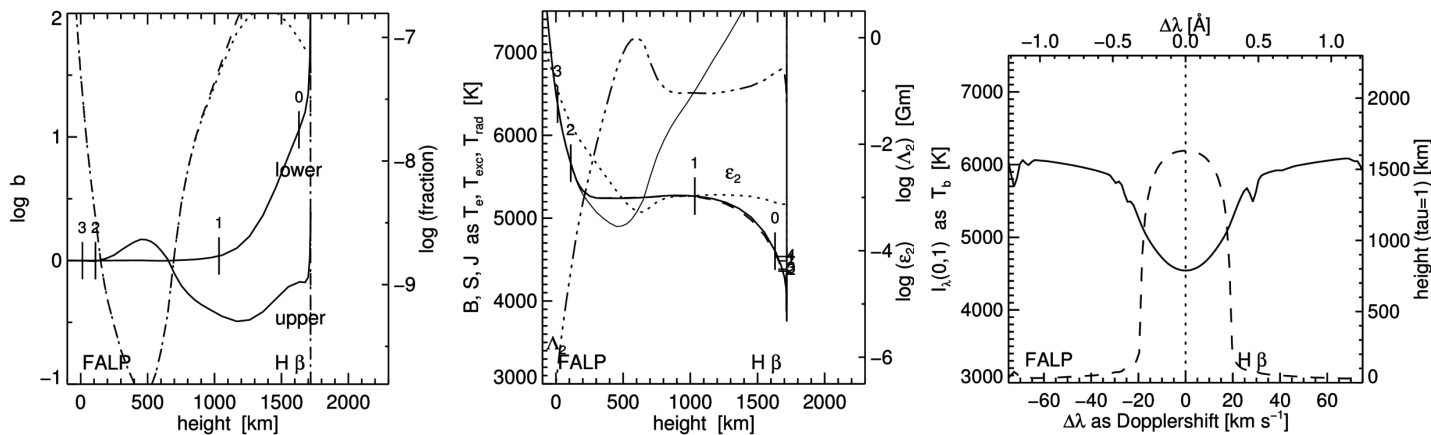
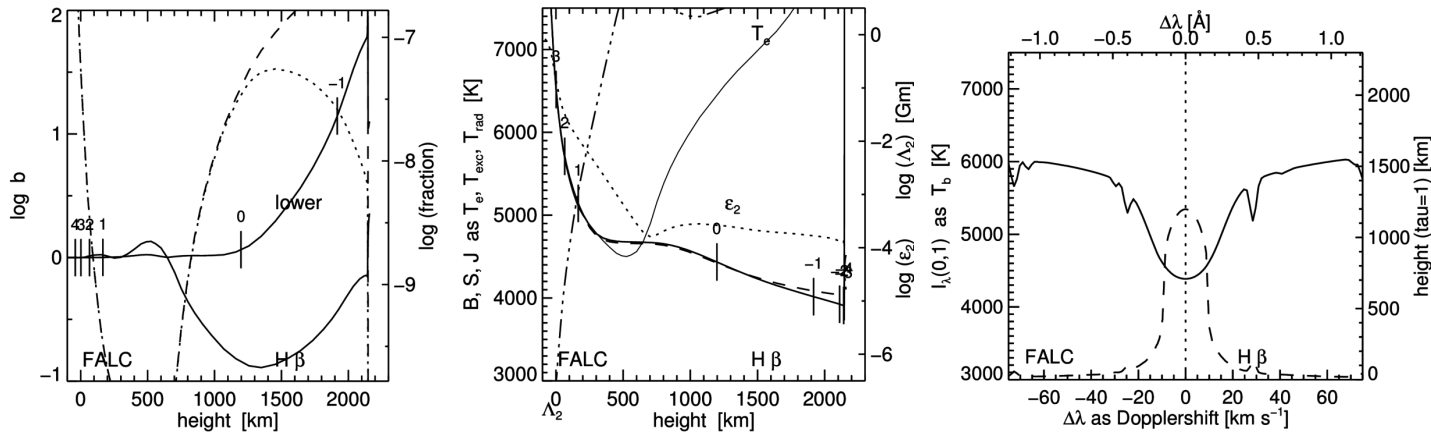
champion: largest extinction and most scattering of all lines

H α 6563 Å IN FALC AND FALP



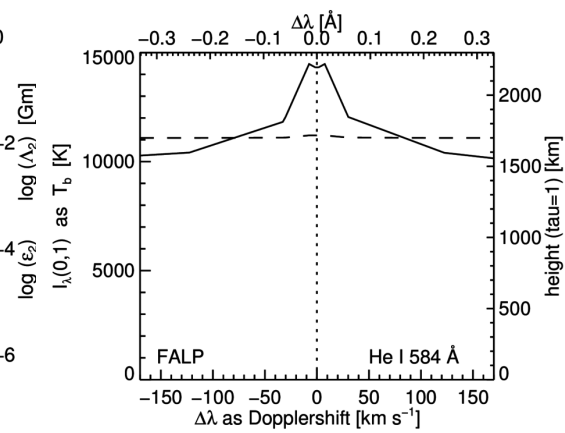
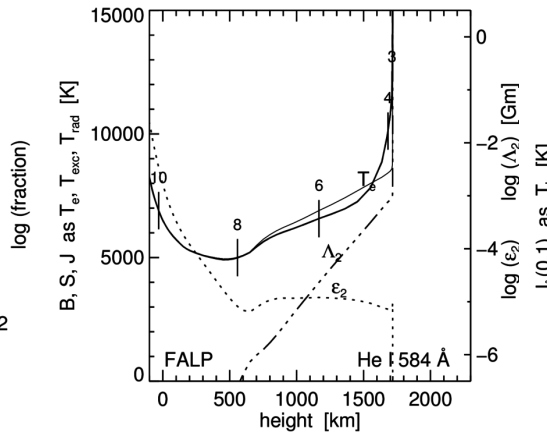
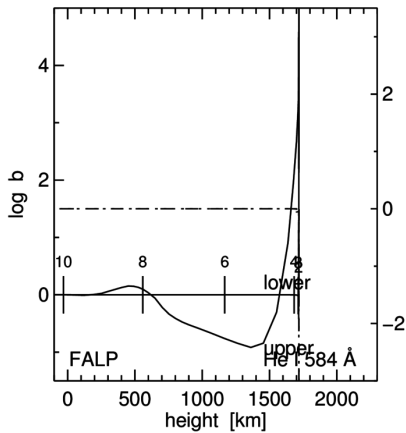
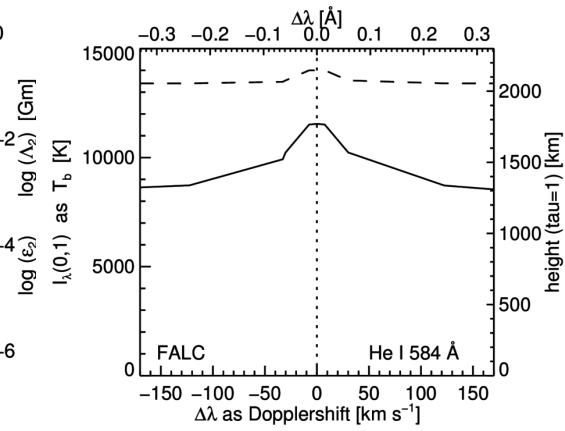
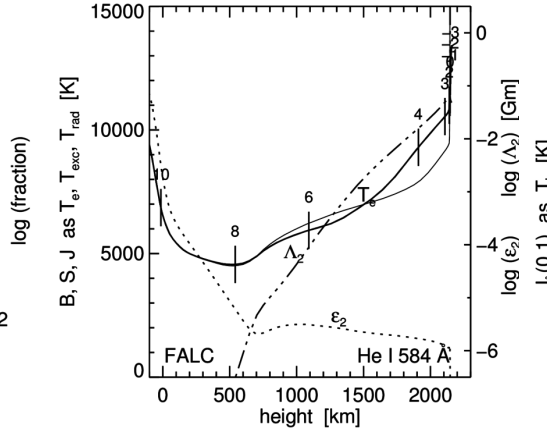
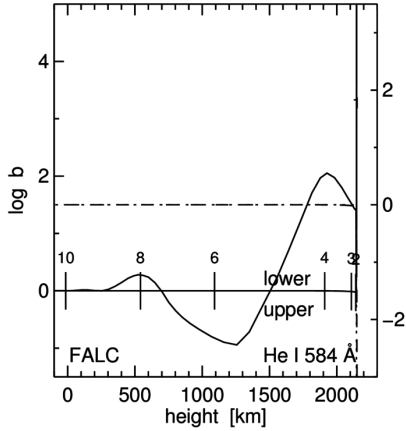
H α : extraordinary from high excitation energy, huge element abundance, on top of Ly α

H β 4861 Å IN FALC AND FALP



H β : analogon to H α at $5.4\times$ smaller oscillator strength and in the blue

He I 584 Å IN FALC AND FALP

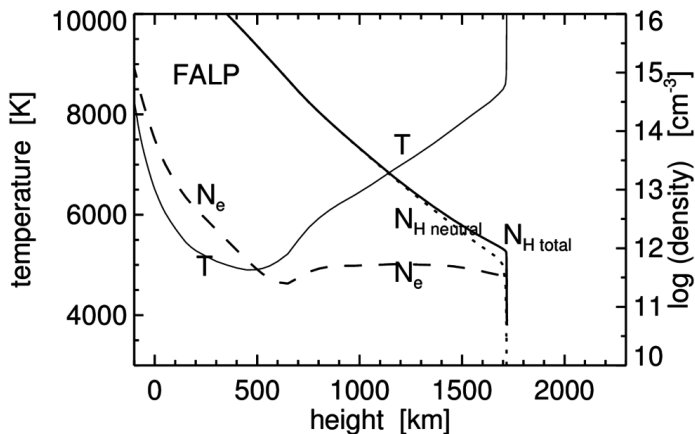
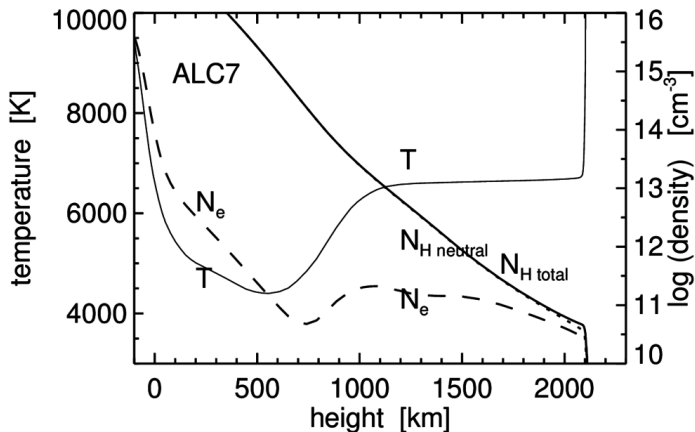


backradiator into chromosphere

ALC7 ATMOSPHERE VERSUS FALP ATMOSPHERE

Avrett & Loeser 2008ApJS..175..229A

Fontenla, Avrett & Loeser 1993ApJ...406..319F

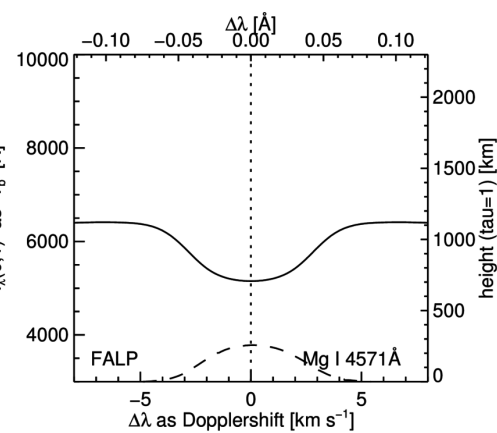
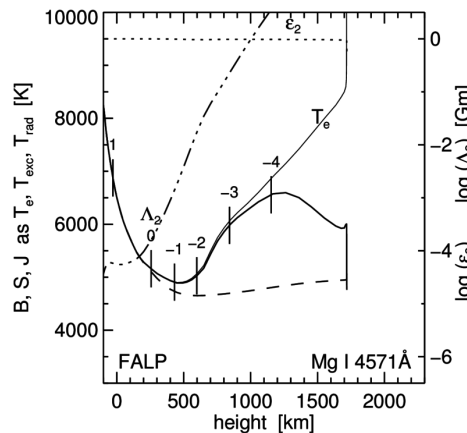
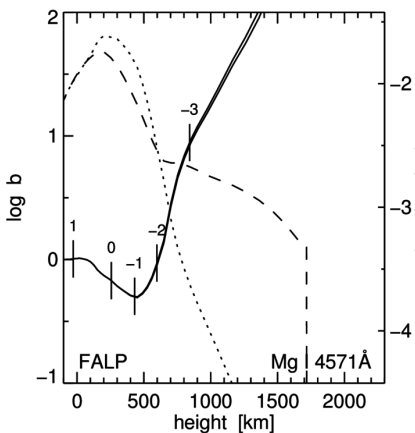
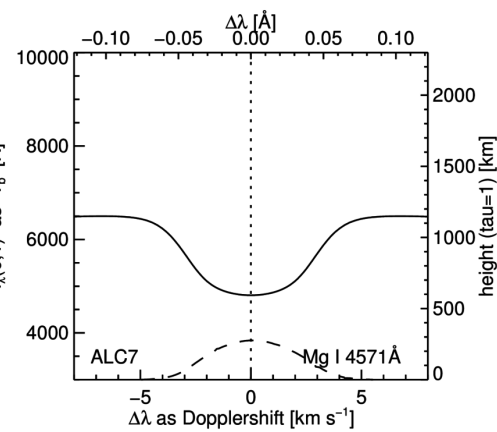
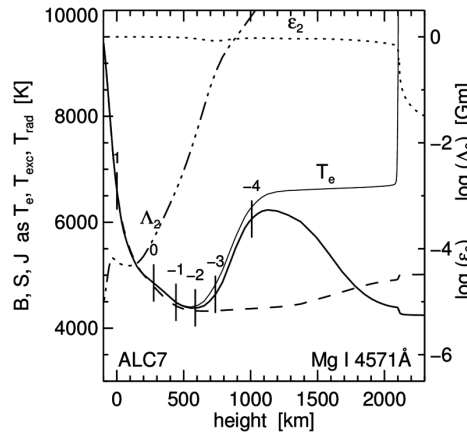
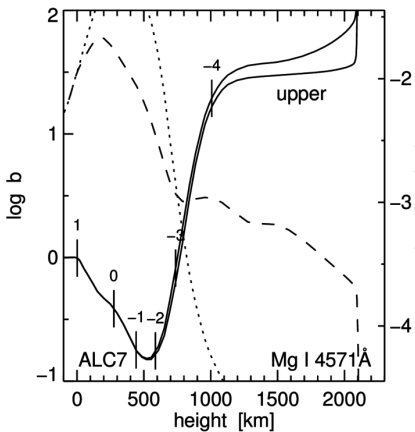


MgI4571 FeI6302 MgIb₂ NaID₁ BaII4554 CaII8542 CaIIK MgIIk Ly α H α H β HeI584

start

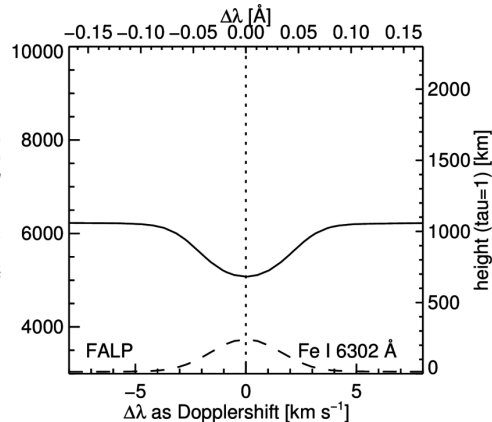
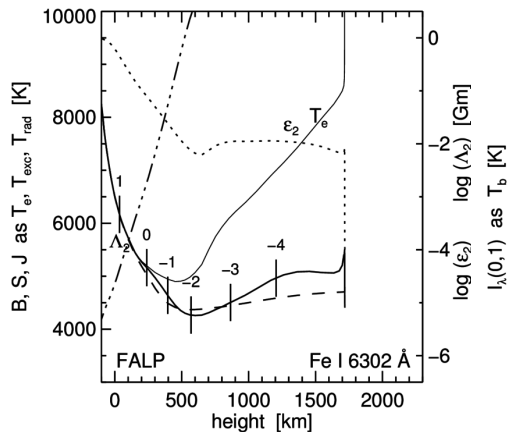
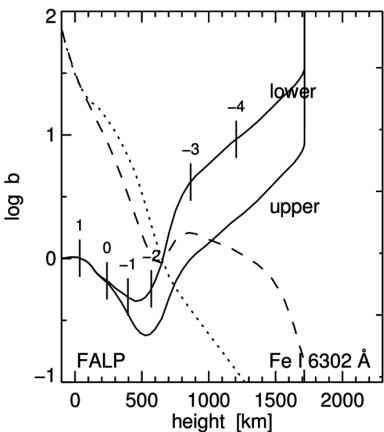
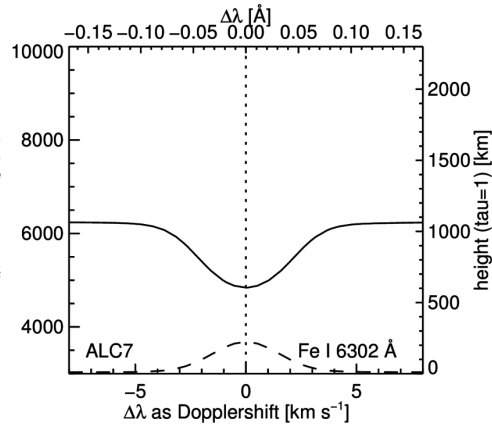
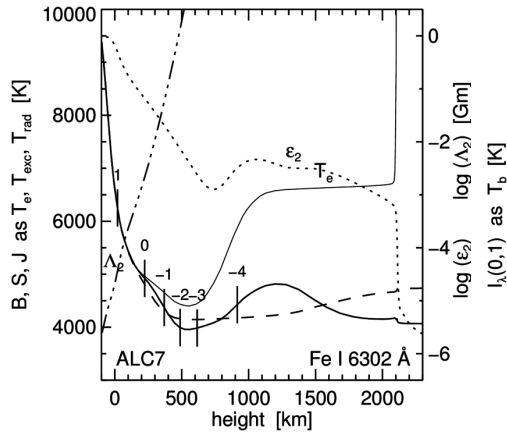
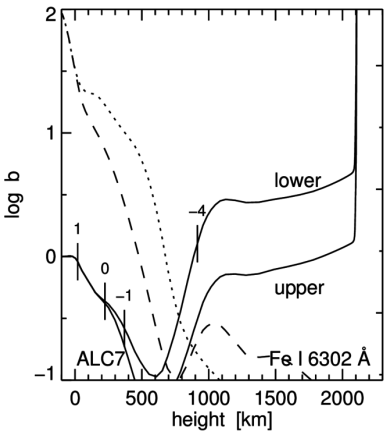
index

Mg I 4571 Å IN ALC7 AND FALP



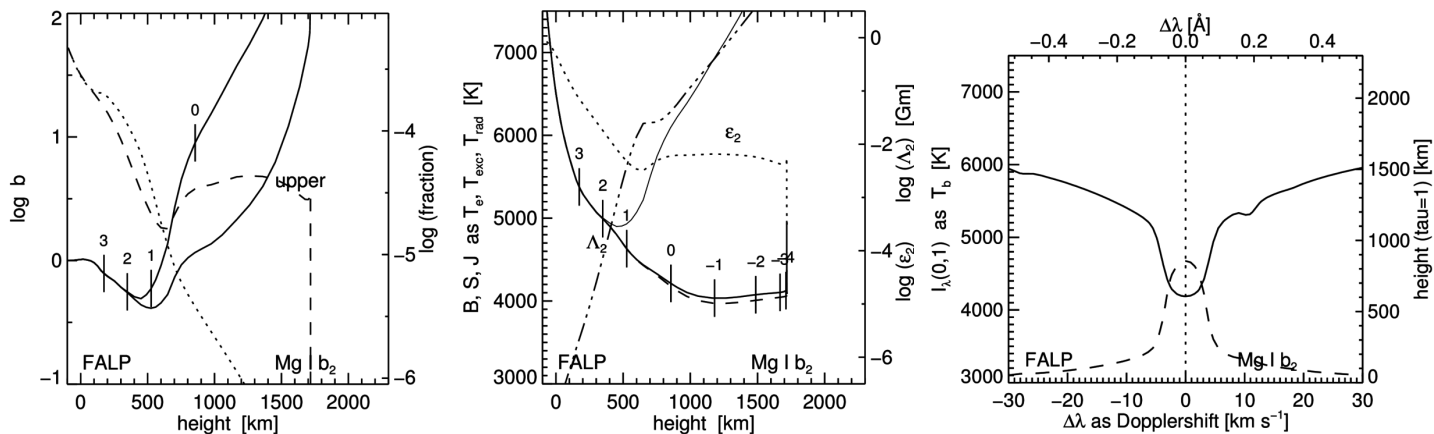
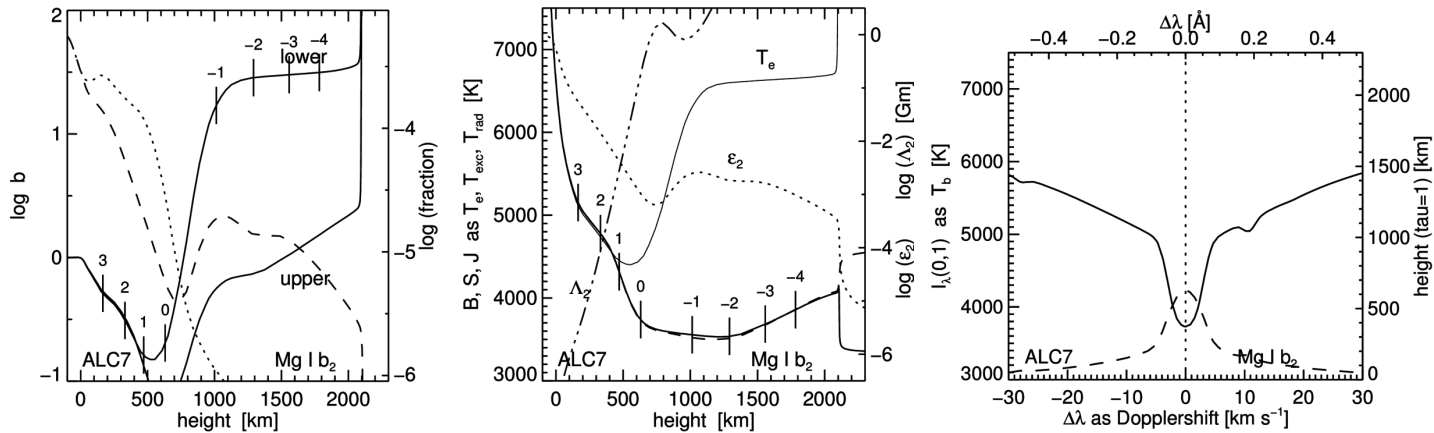
unique photospheric line with LTE source function

Fe I 6301.5 Å IN ALC7 AND FALP



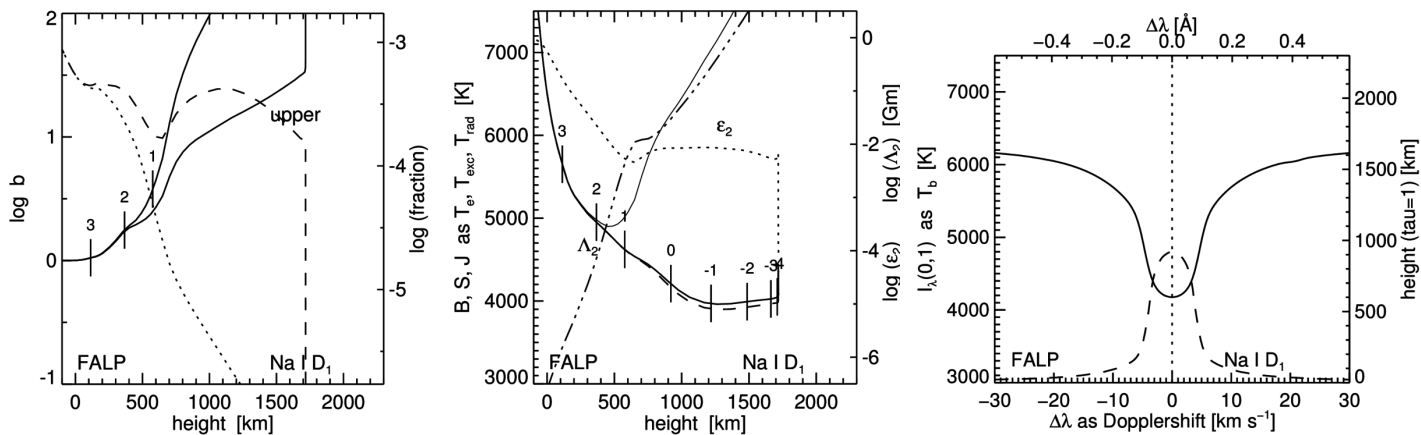
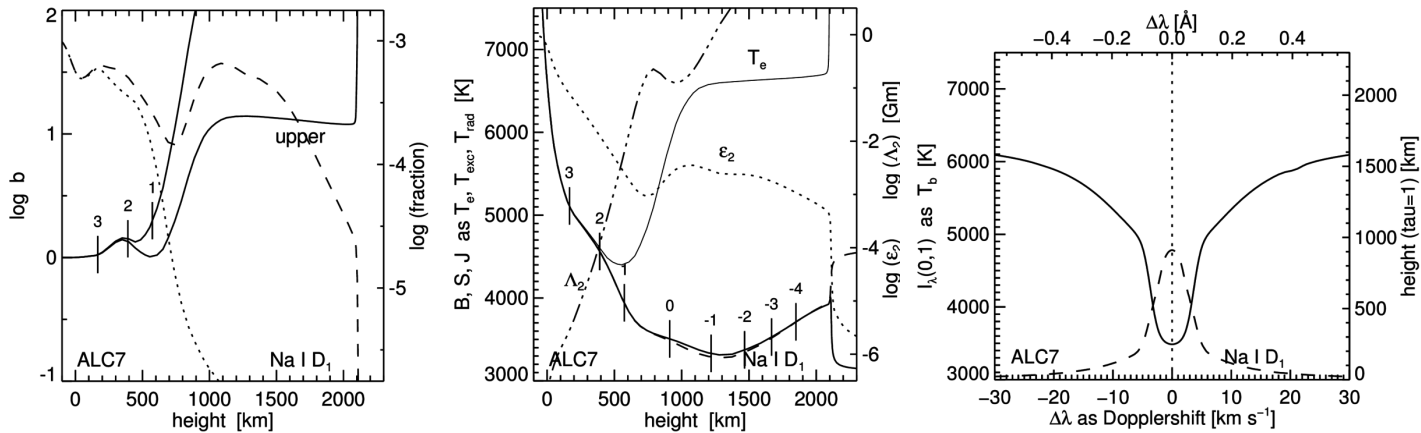
standard polarimetry line

Mg I b₂ 5173 Å IN ALC7 AND FALP



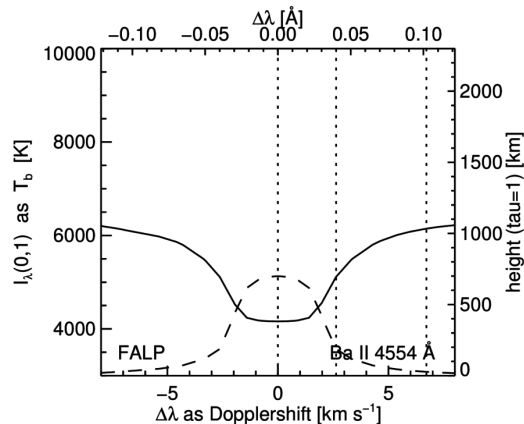
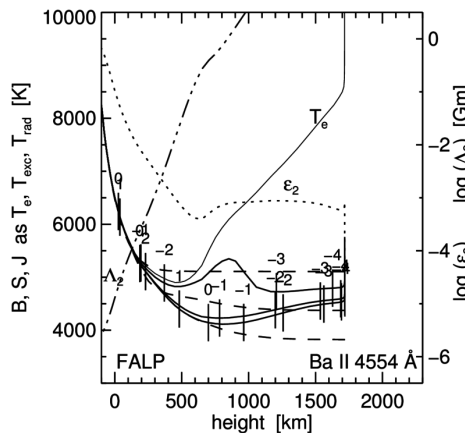
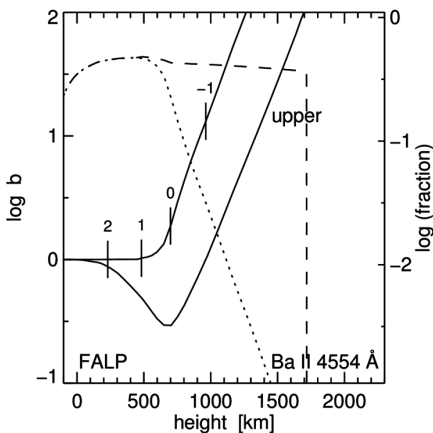
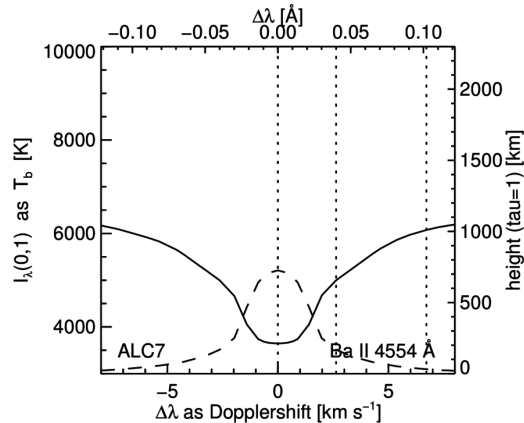
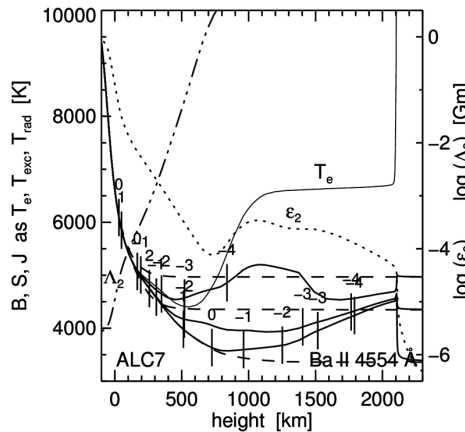
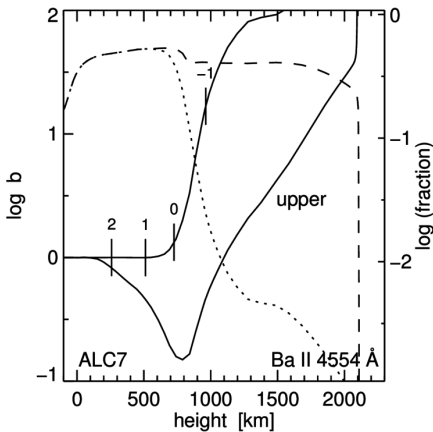
diagnostic of upper photosphere

Na I D₁ 5896 Å IN ALC7 AND FALP



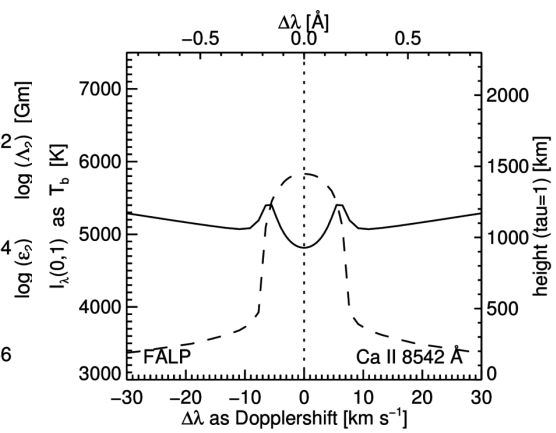
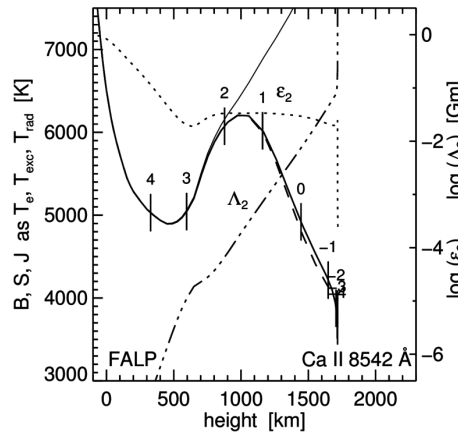
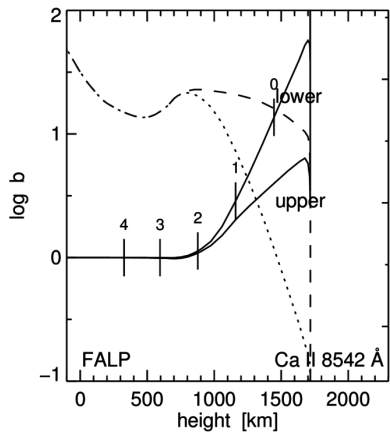
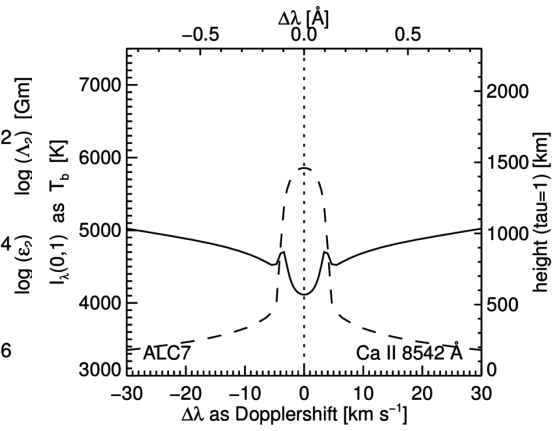
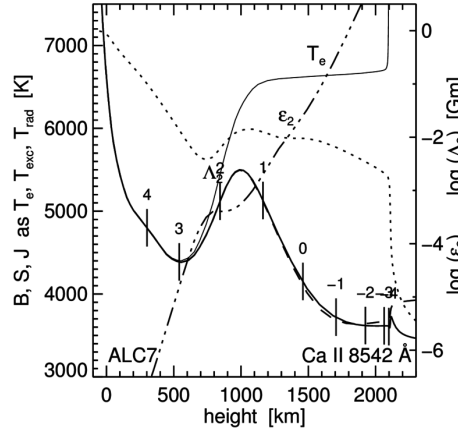
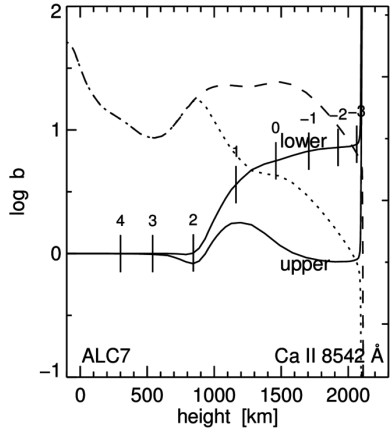
Na I D₁: darkest solar line in optical spectrum = textbook example of two-level scattering

Ba II 4554 Å IN ALC7 AND FALP



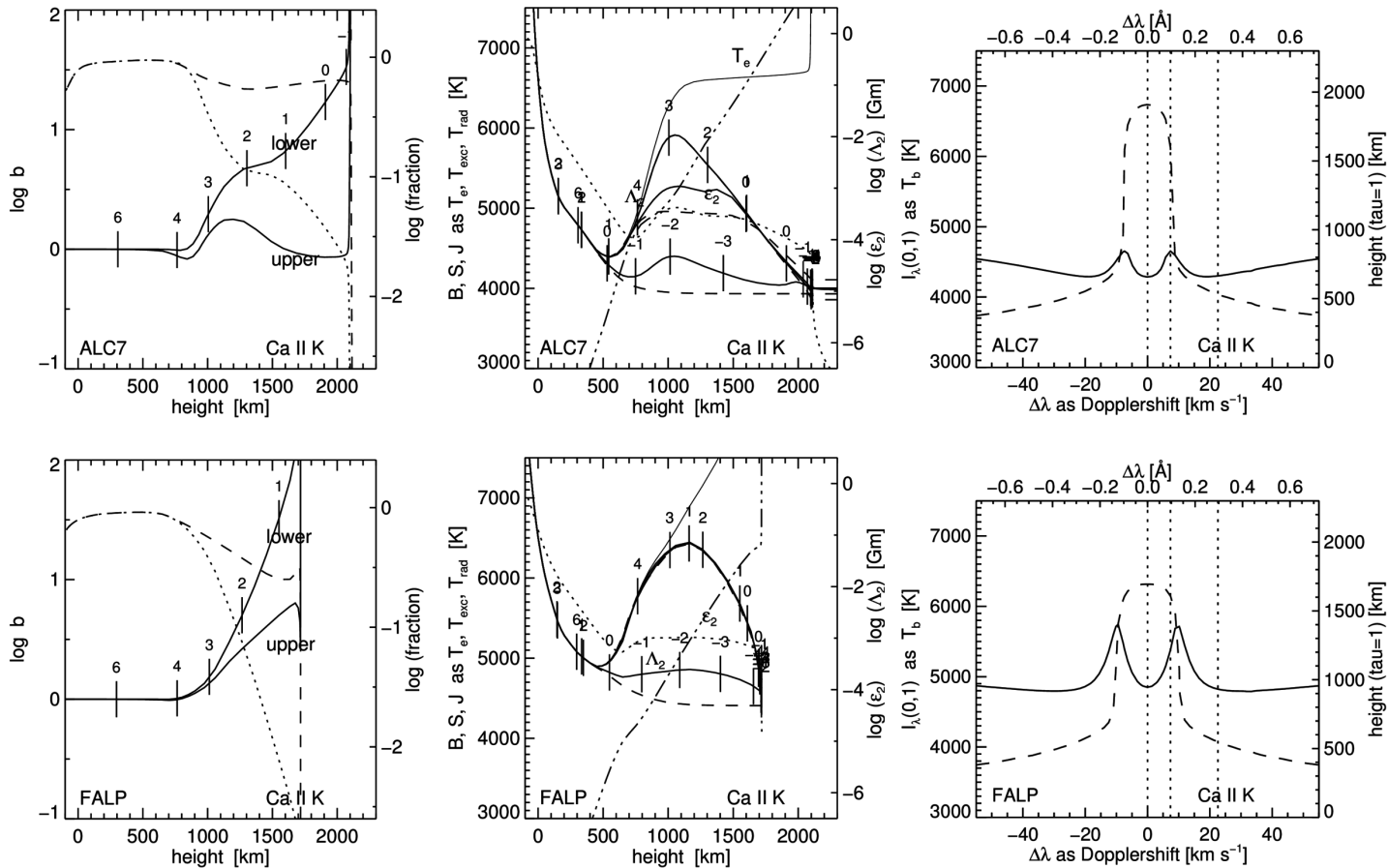
weakest PRD line, best velocity diagnostic, good Hanle diagnostic

Ca II 8542 Å IN ALC7 AND FALP



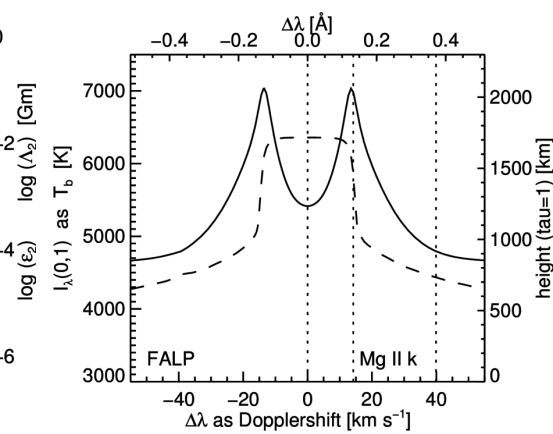
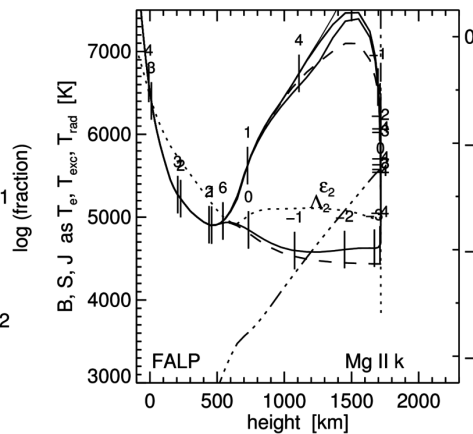
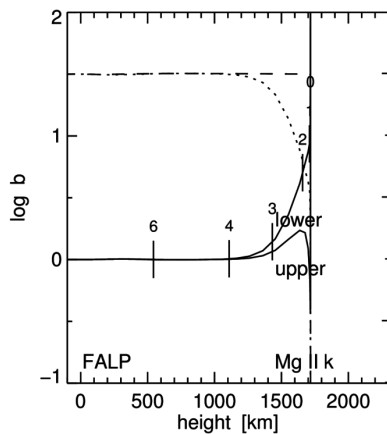
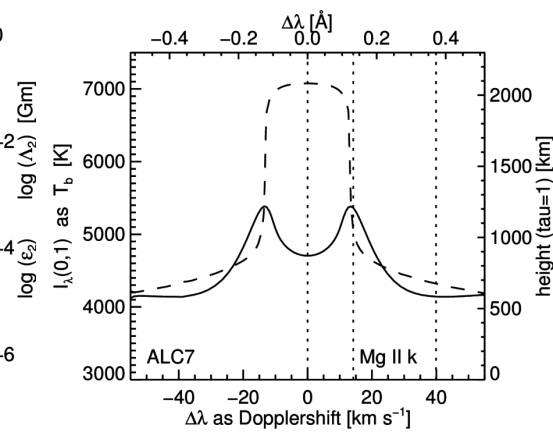
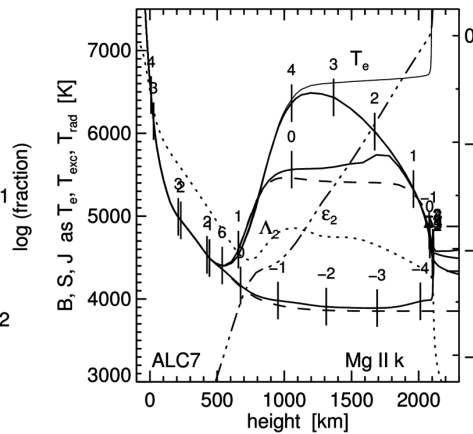
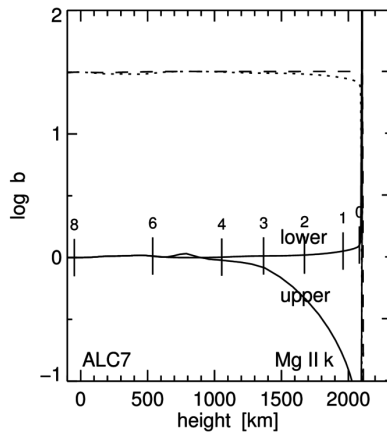
cleanest chromospheric diagnostic in the near infrared

Ca II K 3934 Å IN ALC7 AND FALP



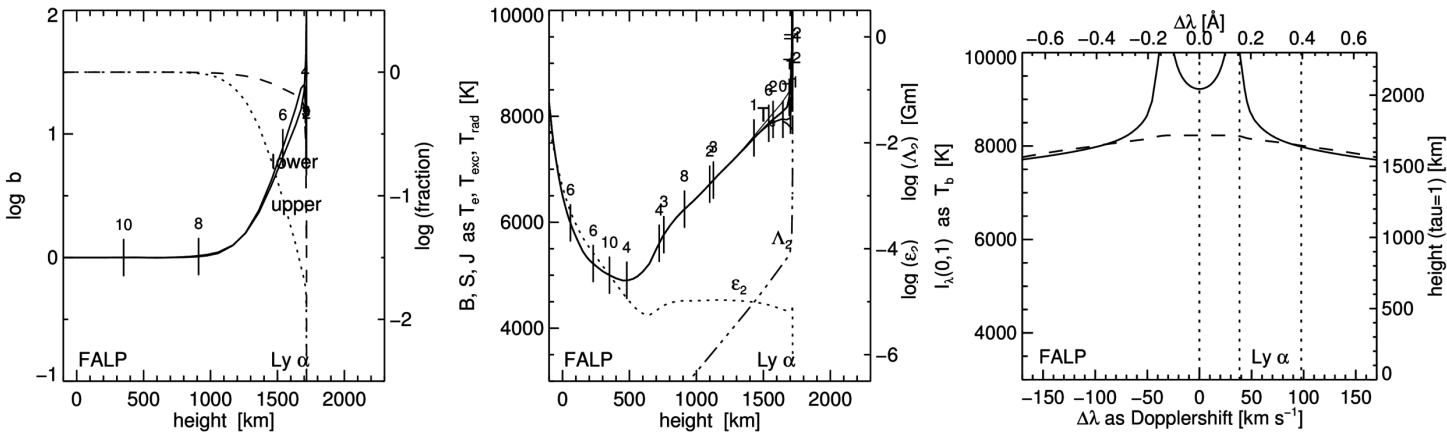
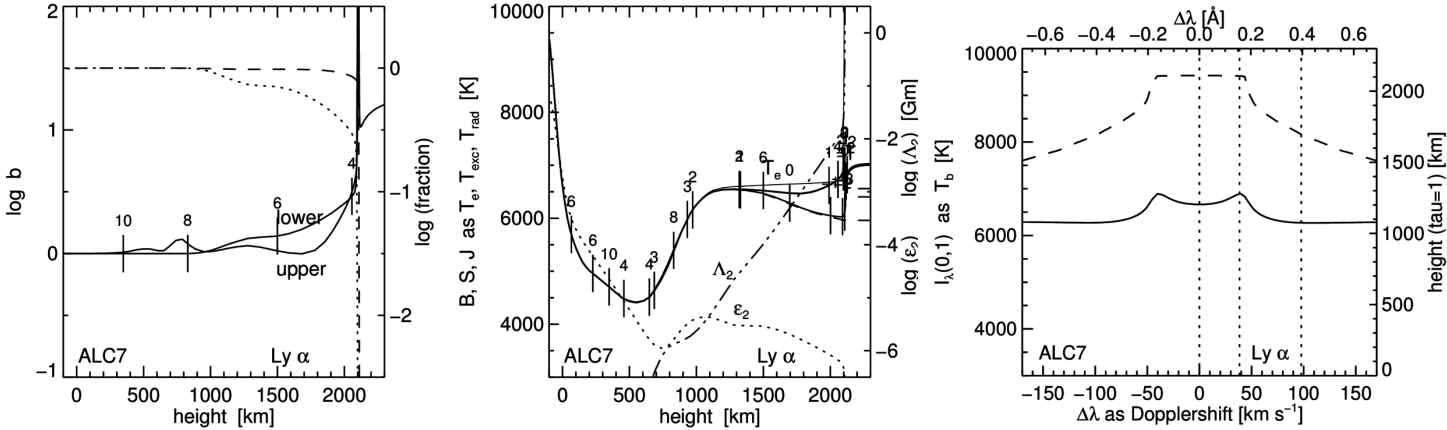
largest extinction in the optical spectrum

Mg II k 2796 Å IN ALC7 AND FALP



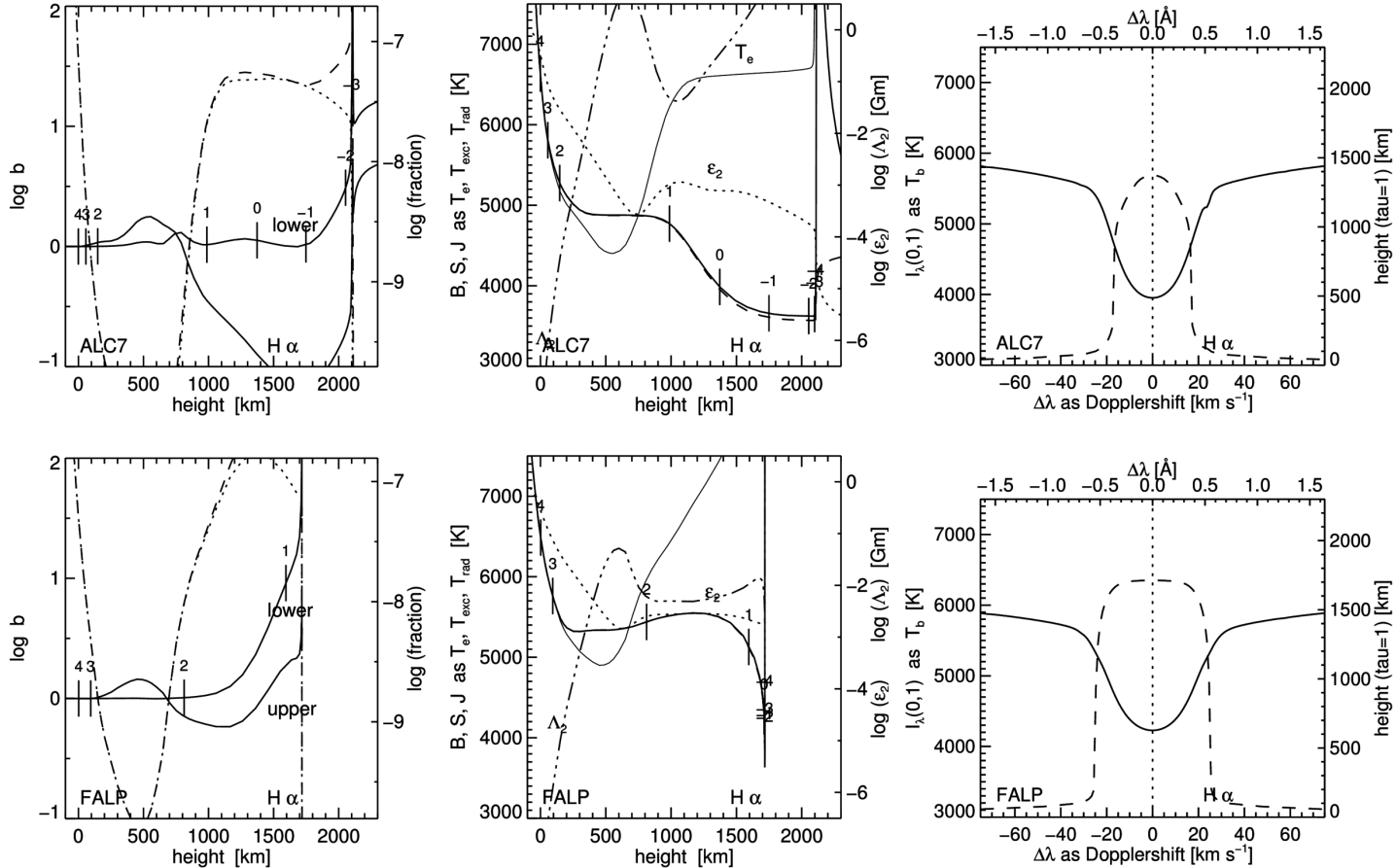
cleanest PRD line and yet larger extinction than Ca II K

Ly α 1216 Å IN ALC7 AND FALP



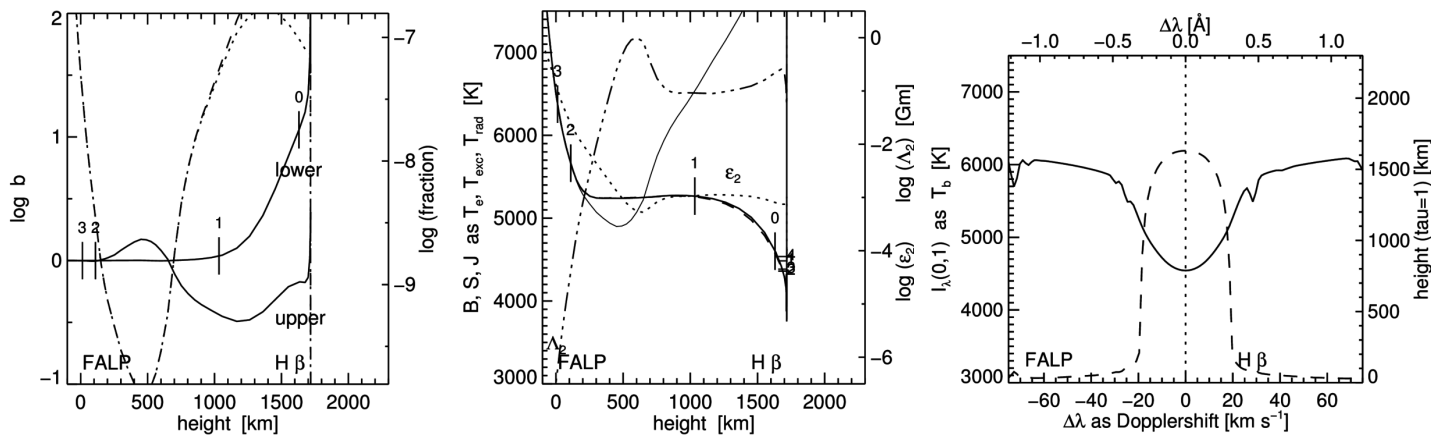
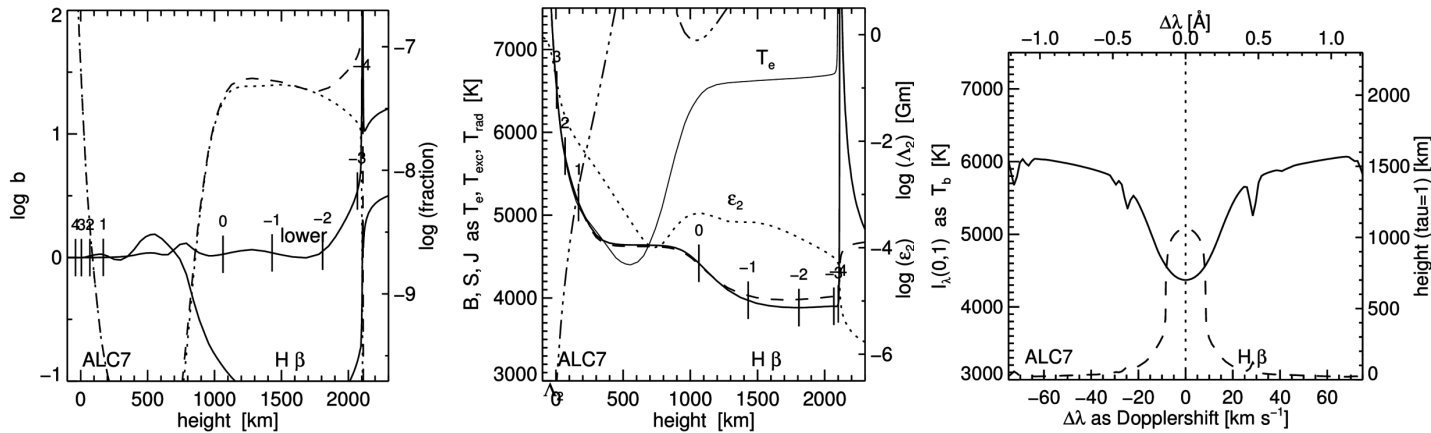
champion: largest extinction and most scattering of all lines

H α 6563 Å IN ALC7 AND FALP



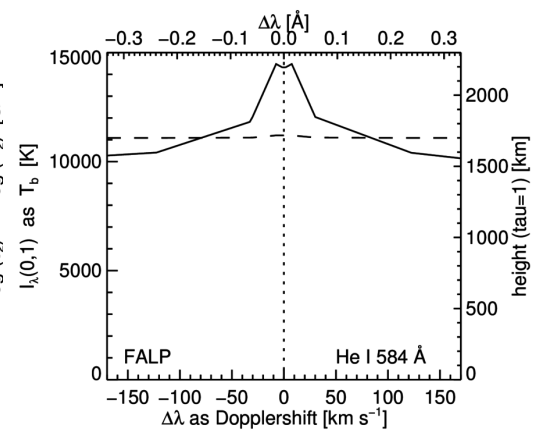
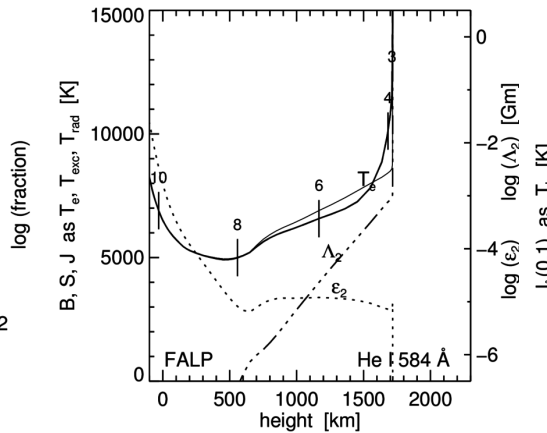
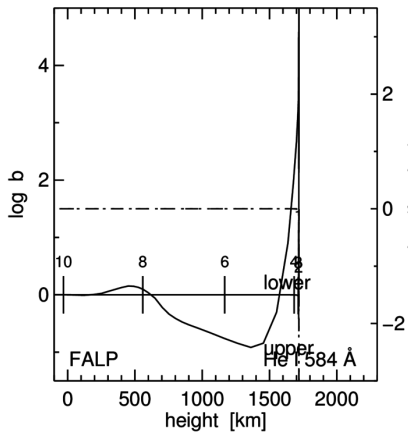
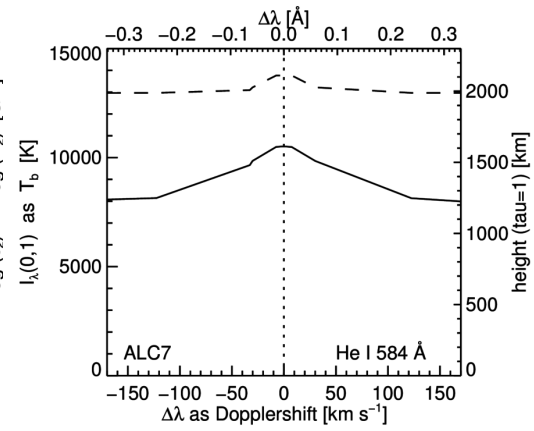
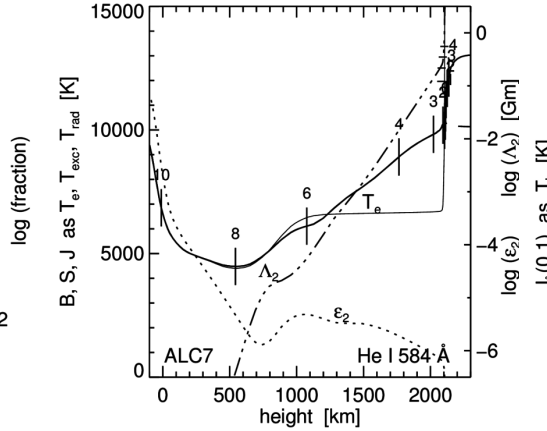
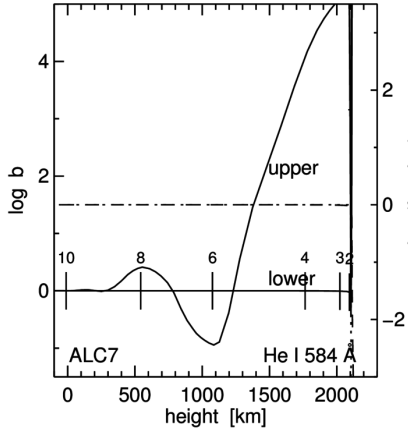
H α : extraordinary from high excitation energy, huge element abundance, on top of Ly α

H β 4861 Å IN ALC7 AND FALP



H β : analogon to H α at 5.4 \times smaller oscillator strength and in the blue

He I 584 Å IN ALC7 AND FALP



backradiator into chromosphere

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Robert J. Rutten

<https://webspacescience.uu.nl/~rutte101>

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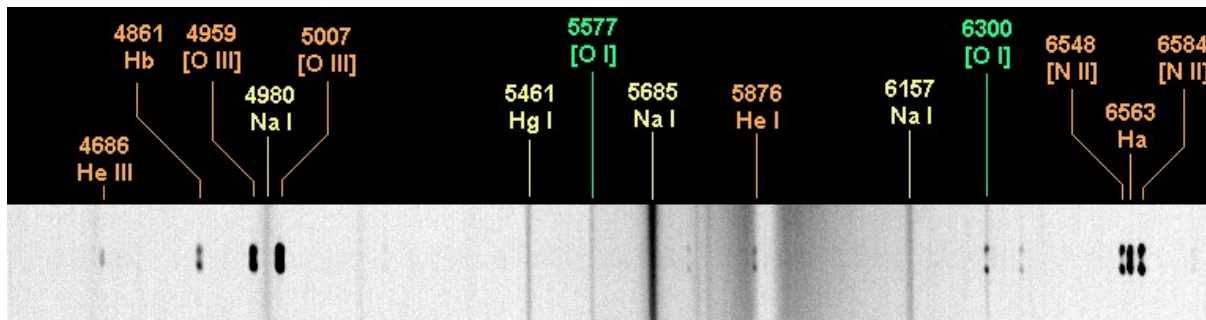
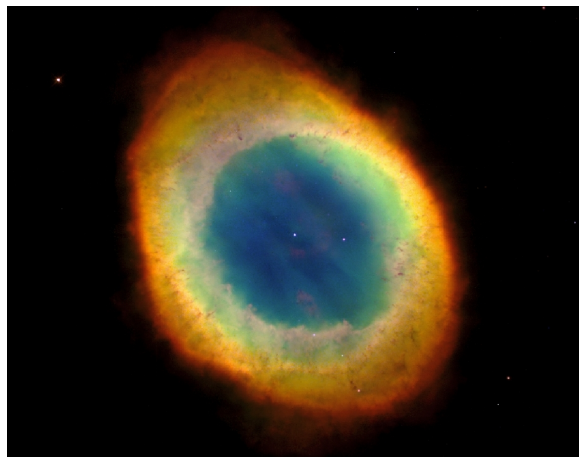
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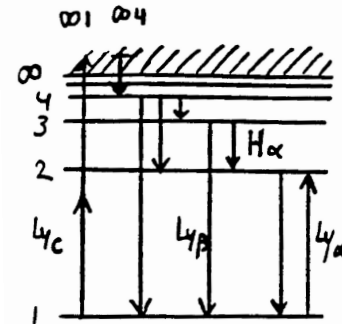
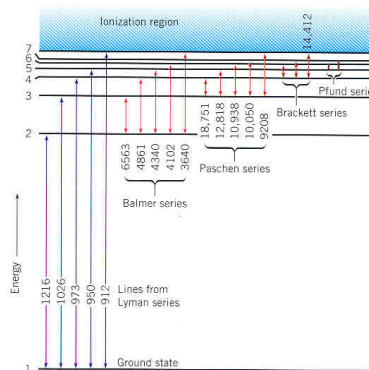
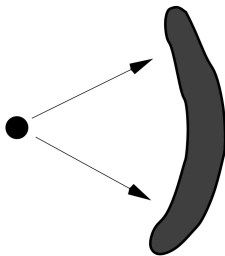
Ring Nebula – M57 – NGC 6720



Zanstra mechanism

Osterbrock: *In 1922 Russell, the very perceptive American astrophysicist, deduced on the basis of these observational results that the mechanism by which the gas in nebulae is excited to emit its line spectrum is radiation from the hot star or stars involved in a nebula. He suggested the radiation might be electromagnetic (light, visual and ultraviolet) or corpuscles (fast particles)*

Osterbrock re Herman Zanstra: *he considered only the hydrogen Balmer lines, $H\alpha$, $H\beta$, $H\gamma$, for they and a few He I lines had been identified in gaseous nebulae, but the origin of the rest of the observed nebular emission lines was still a mystery. Zanstra knew that these H I lines could be excited by absorption of ultraviolet continuum radiation in the higher-energy Lyman lines $Ly\beta$, $L\gamma$, $Ly\delta$, which, absorbed by neutral H atoms in its ground state with principal quantum number $n = 1$, excite them to levels with $n \geq 3$, leading to emission of the Balmer series. (The excitations to $n = 2$ lead only to scattering of $Ly\alpha$.) The hotter a star is, the stronger its ultraviolet continuum.*



THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

VOLUME LXVII

JANUARY 1928

NUMBER 1

THE ORIGIN OF THE NEBULAR LINES AND THE STRUCTURE OF THE PLANETARY NEBULAE

By I. S. BOWEN

ABSTRACT

Identification of nebular lines.—Eight of the strongest nebular lines are classified as due to electron jumps from metastable states in N_{II} , O_{II} and O_{III} . Several of the weaker lines are identified with recently discovered lines in the spectrum of highly ionized oxygen and nitrogen.

Behavior of lines in nebulae.—The lines thus identified are shown to behave in various nebulae in a way consistent with the foregoing classifications. A similar study of the few lines yet unknown makes it possible to estimate the stage of ionization from which they arise.

Structure of the planetary nebulae.—On the basis of the foregoing identifications, the relative sizes and intensities of the monochromatic images of the planetary nebulae are explained by an extension and modification of the ideas developed by Zanstra for hydrogen in the diffuse nebulae.

Bowen line pumping

Thesis Henrik Hartman, Lund 2003

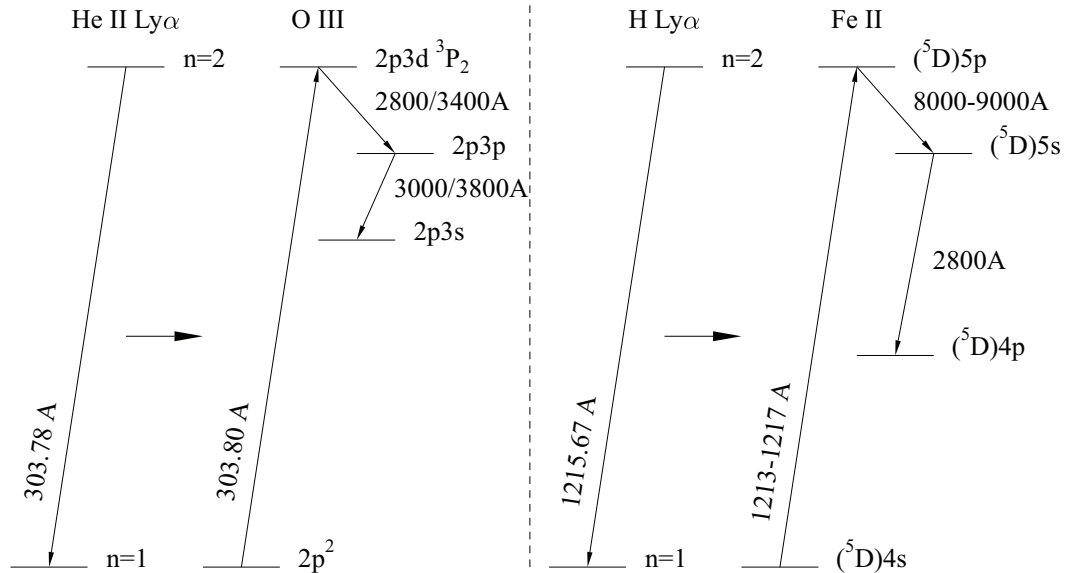


Figure 4.1: Principle for the Bowen mechanism in O III and a similar fluorescence case in Fe II.

Pumped Fe II lines from symbiotic Mira RR Tel

Thesis Henrik Hartman, Lund 2003

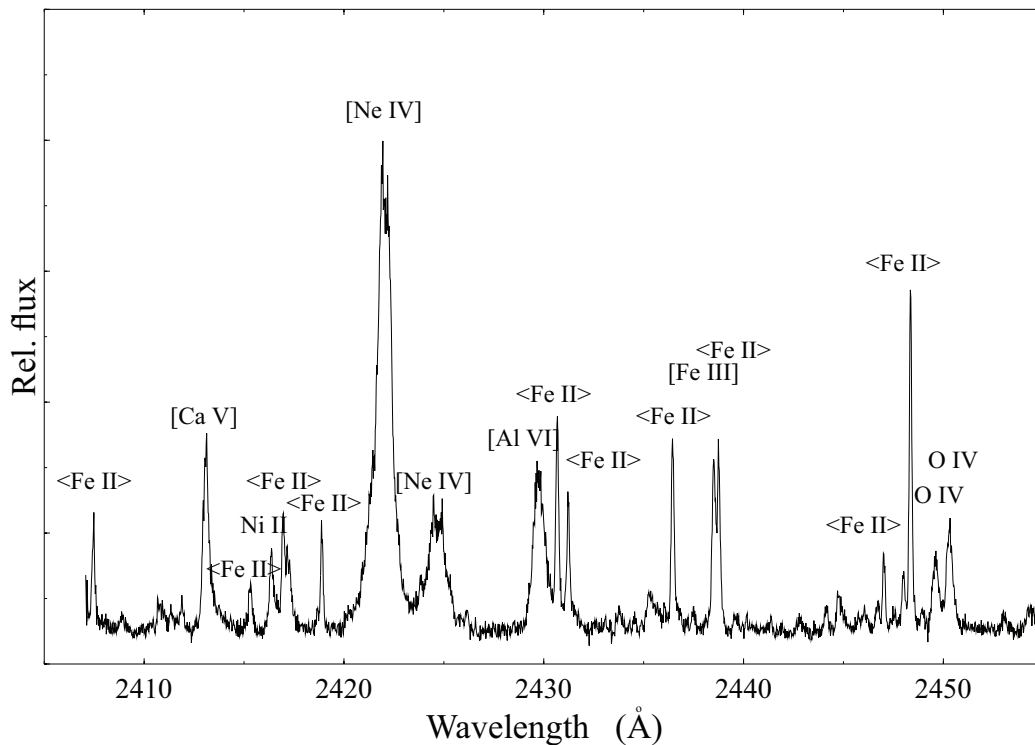


Figure 4.2: Part of the ultraviolet spectrum of RR Tel showing numerous fluorescent $\langle \text{Fe II} \rangle$ and high ionization lines.

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<https://webspacescience.uu.nl/~rutte101>

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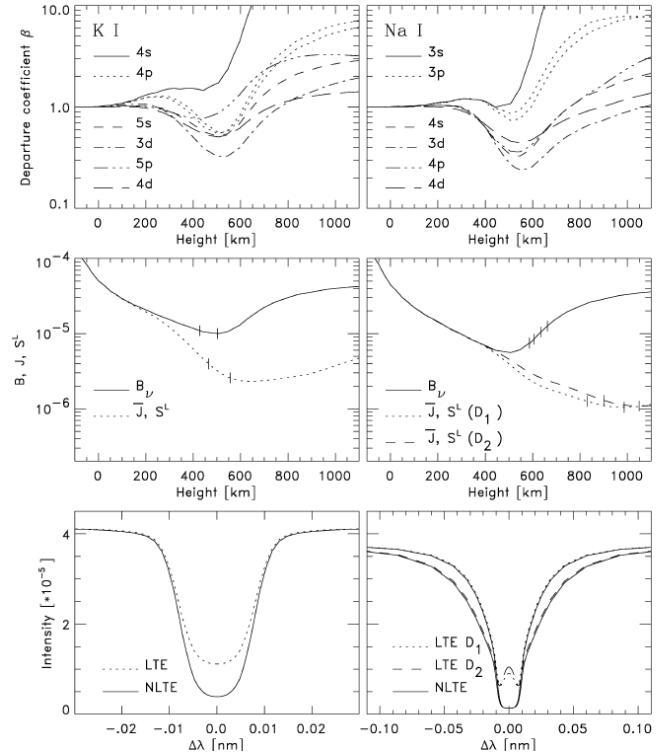
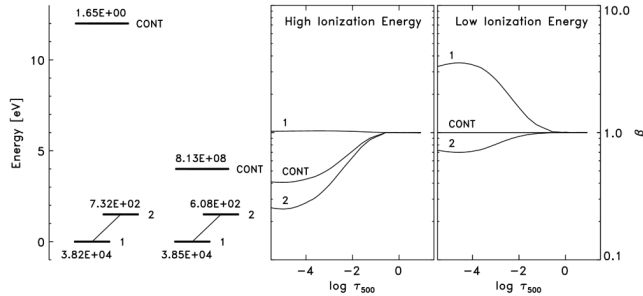
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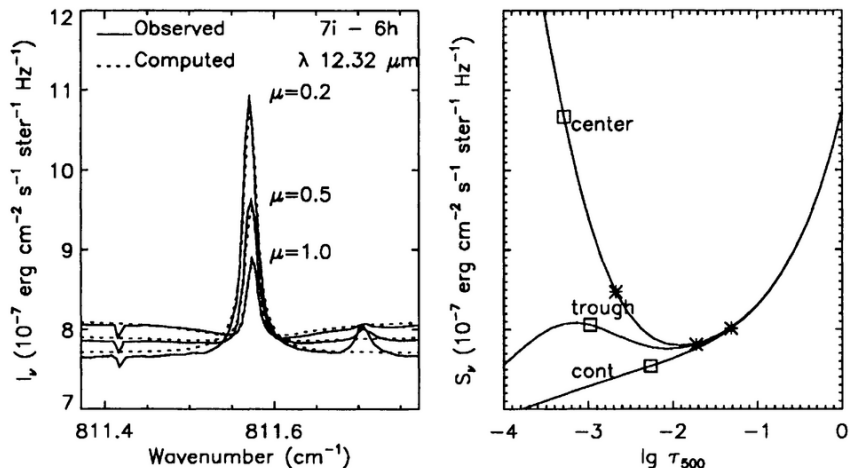
PHOTON SUCTION IN ALKALI ATOMS

Bruls, Rutten, Shchukina 1992A&A...265..237B



- minority atom: continuum = reservoir
- line photon losses drive replenishment recombination flow
- ground state gets overpopulated to reach photoionization balancing

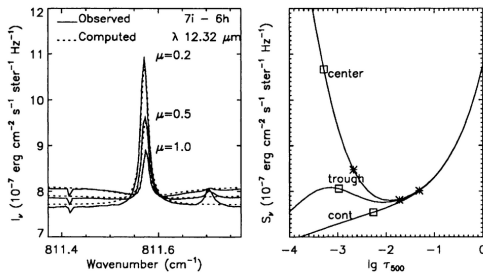
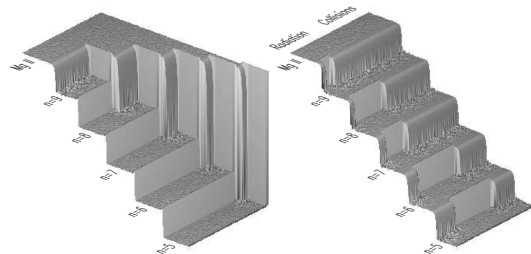
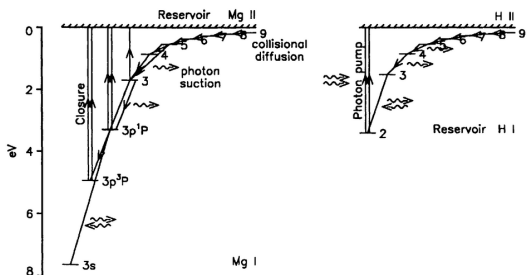
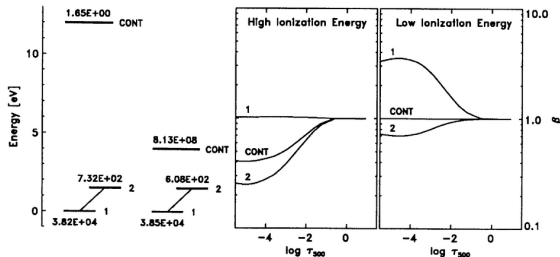
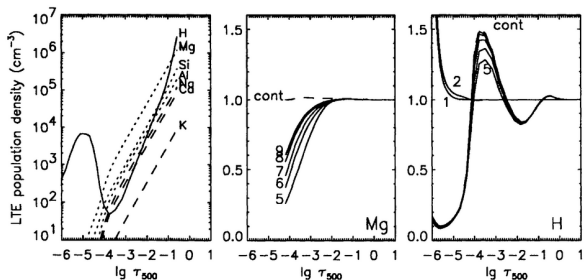
Mg I EMISSION FEATURES AT 12 MICRON



- *discovery*
 - Brault & Testerman 1980: McMath FTS, unpublished
 - Murcray, Murcray & Murcray 1981: South Pole FTS, handmasked
 - Brault & Noyes 1983ApJ...269L..61B: McMath FTS data
 - Chang & Noyes 1983ApJ...275L..11C: identification
- *explanation* (Carlsson, Rutten, Shchukina 1992A&A...253..567)
 - upper-level overpopulation toward laser rise
 - bound-bound suction and bound-free pumping
 - collisionally dominated recombination cascade

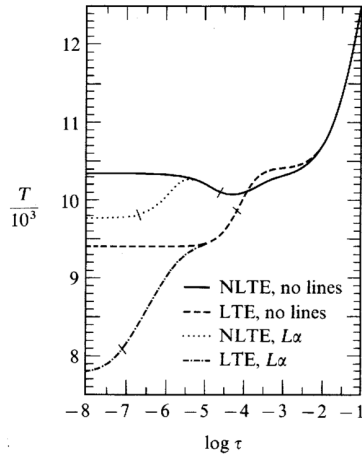
12 MICRON EMISSION FEATURES

Carlsson, Rutten & Shchukina 1992A&A...253..567C, Rutten & Carlsson 1994IAUS..154..309R

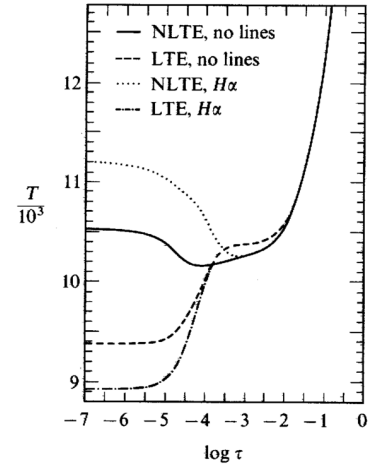


THE SIMPLEST HYDROGEN PROBLEM

Auer & Mihalas 1969ApJ...156..157A 1969ApJ...156..681A



- *simple*
 - plane-parallel HE + RE
 - 2-level + continuum + CRD
- *straightforward*
 - $\text{Ly}\alpha$ photon-loss cooling
 - Balmer continuum heating
- *intricate*
 - $\text{H}\alpha$ photon-loss cooling
 - $\text{H}\alpha$ photon-loss heating



- work through final problem in RTSA course notes
(only 5 pages of questions + 3 pages of footnotesize answers)
- explain every curve in every graph of Wiersma et al. 2003ASPC..288..130W

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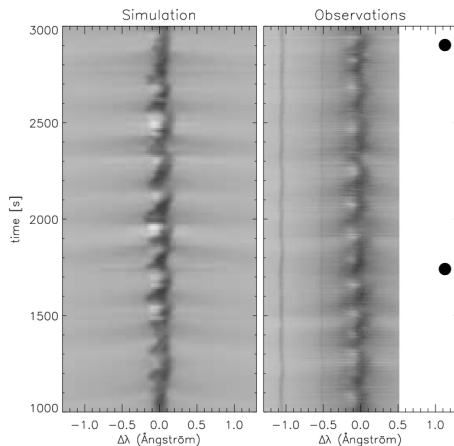
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IRIS diagnostics: overview diagnostics

INTERNETWORK H_{2V} GRAINS = ACOUSTIC SHOCKS

- *Ca II K_{2V} grains* (Rutten & Uitenbroek 1991SoPh..134...15R)
 - extended and confused literature (600 references)
 - most likely non-magnetic phenomenon
 - most likely acoustic shocks
 - wave interference reminiscent of “clapotis”



- *observation* (Lites, Rutten & Kalkofen 1993ApJ...414..345L)
 - sawtooth line-center shift
 - triangular whiskers
 - H_{2V} grains
- *simulation* (Carlsson & Stein 1997ApJ...481..500C)
 - 1D radiation hydrodynamics
 - subsurface piston derived from Fe I Doppler
 - emulation of observer’s diagnostics
- *analysis*
 - source function breakdown
 - dynamical chromosphere

CLAPOTISPHERE

Rutten 1995soho....1..151R "The internetwork chromosphere is inherently a clapotisphere"

"The extensive literature on the Ca II K_{2V} grains and related cell-interior phenomena leads us to the conclusion that bright cell grains are of hydrodynamical origin, due to oscillations that are present all over the solar surface but which produce grains only at places and moments set by pattern interference between the velocity oscillations in the K_3 layer and the evanescent wave trains of the p -mode oscillation deeper down. They remind us of what is called "clapotis" on sea charts for areas where wave interference produces waterspouts on the ocean (Dowd 1981)."

Rutten & Uitenbroek 1991SoPh..134...15R

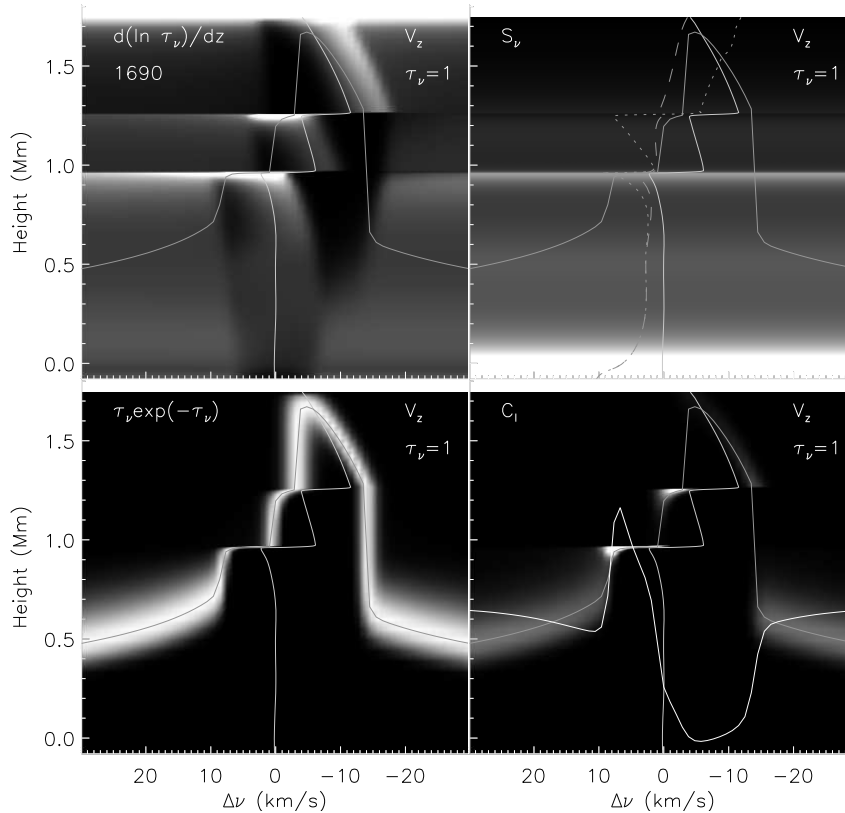
"When the crests of such waves coincide, their amplitudes combine, creating huge standing waves, much steeper than traveling waves. This phenomenon is called "clapotis". Off the northern tip of New Zealand, where major wave patterns collide in deep water, clapotis is regularly seen. The pinnacled waves formed here have so much vertical power that they can throw a laden kayak clear out of the water."

Dowd 1981 (not on ADS)

SHOCK GRAIN DIAGNOSIS

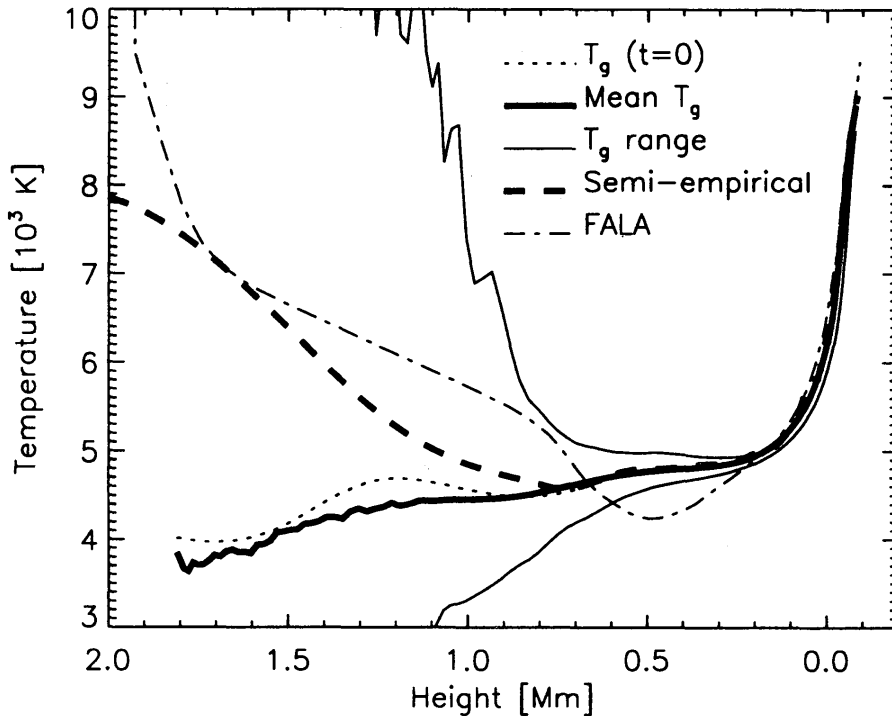
Carlsson & Stein 1997ApJ...481..500C

$$I_\nu(0) = \int_0^\infty S_\nu e^{-\tau_\nu} d\tau_\nu = \int_0^\infty S_\nu \tau_\nu e^{-\tau_\nu} \frac{d \ln \tau_\nu}{dz} dz$$



SHOCK-RIDDEN COOL LOWER CHROMOSPHERE

Carlsson & Stein 1995ApJ...440L..29C



- mean $T(h)$ (thick solid) remains close to RE starting model (dotted)
- bandwidth of T fluctuations (thin solid borders) very large above 1000 km
- a fit of the mean ultraviolet intensities needs a temperature rise (dashed)

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BIFROST SOLAR-ANALOG STAR

- *Bifrost: a Modular Python/C++ Framework for Development of High-Throughput Data Analysis Pipelines* [2017AAS...22923605C](#)
- *Vertical crustal motion observed in the BIFROST project* [2003JGeo...35..425S](#)
- *BIFROST project: 3-D crustal deformation rates derived from GPS confirm post-glacial rebound in Fennoscandia* [2001EP&S...53..703S](#)
- *"SPACE" 2013-2015: ASGARD Balloon and BIFROST Parabolic Flights: Latest Developments in Hands-On Space Education Projects for Secondary School Students* [2015ESASP.730..635D](#)
- *BIFROST: conference hotel in Iceland* ([not on ADS](#))
- Bifrost: computational star in Carlssonscandia, remarkably like the Sun in its spectral characteristics and likewise non-plane-parallel, inconstant, and inconsistent, with the virtue of showing much spatio-temporal fine structure similar to solar fine structure:
 - granules and intergranules
 - acoustic box modes similar to solar p -mode interference patterns
 - non-diagnosed internal gravity waves
 - clapotispheric internetwork shocks
 - magnetic network concentrations
 - dynamic fibrils
 - Ellerman reconnection bursts*but lacking: spicules-II, long fibrils, $k_2 - h_2$ peak separation, Si IV in UV bursts, more?*
- Bifrost analogs in chromosphere-formation stage: CO5BOLD MURaM Mancha

BIFROST

- *heritage*
 - Nordlund & Stein 3D HD \Rightarrow granulation
 - Carlsson & Stein 1D HD RADYN \Rightarrow Ca II H_{2V} shocks
 - Nordlund et al. 2D MHD Stagger \Rightarrow MCs, internetwork
- *code*
 - Gudiksen et al. [2011A&A...531A.154G](#) Bifrost description
 - Carlsson & Leenaarts [2012A&A...539A..39C](#) cooling + heating approximations
 - Leenaarts et al. [2012A&A...543A.109L](#) fast angle-dependent PRD
 - Martínez-Sykora et al. [2012ApJ...753..161M](#) ambipolar diffusion
 - Pereira et al. [2013A&A...554A.118P](#) 3D simulation better than standard 1D models
 - Olluri et al. [2013AJ....145...72O](#) non-E 3D solver
 - Golding et al. [2014ApJ...784...30G](#) non-E He ionization
 - Carlsson et al. [2016A&A...585A..4C](#) publicly available snapshot
 - Sukhorukov & Leenaarts [2016A&A...597A..46S](#) PRD in 3D simulations
 - Martínez-Sykora et al. [2017ApJ...847...36M](#) 2D (“2.5D”) ion-neutral
 - Leenaarts [2018arXiv180506666L](#) tracer particles \Rightarrow Lagrangian flow lines
- *warnings*
 - if no Ly α RT no N_e boosting from Ly α surround scattering around hot structures
 - 3D RT may be needed (MULTI3D of Leenaarts & Carlsson [2009ASPC..415...87L](#)) beyond columnwise (RH1.5D of Pereira & Uitenbroek [2015A&A...574A...3P](#))
 - non-E RT may be needed beyond snapshot-wise SE (especially H, He)

BIFROST ANALYSES 1

- Hayek et al. [2010A&A...517A..49H](#) solar-type stars
- Martínez-Sykora et al. [2011ApJ...732...84M](#) EUV line asymmetries
- Leenaarts et al. [2012ApJ...749..136L](#) 3D H α formation
- Stepán et al. [2012ApJ...758L..43S](#) Ly α Hanle
- de la Cruz Rodriguez et al. [2012A&A...543A..34D](#) Ca II 8542 Å inversion test
- Olluri et al. [2013ApJ...767...43O](#) non-E in O IV ratios
- Martínez-Sykora et al. [2013ApJ...771...66M](#) Ca II and H α from a spicule-II
- Leenaarts et al. [2013ApJ...772...89L](#) Mg II h & k for IRIS I
- Leenaarts et al. [2013ApJ...772...90L](#) Mg II h & k for IRIS II
- Pereira et al. [2013ApJ...778..143](#) Mg II h & k for IRIS
- Hansteen & Archontis [2014ApJ...788L...2A](#) reconnecting strong-field simulation
- Olluri et al. [2015ApJ...802....5O](#) optically thin emission lines
- Leenaarts et al. [2015ApJ...802..136L](#) H α fibrils versus field
- Stepán et al. [2015ApJ...803...65S](#) scattering polarization Ly α
- Pereira et al. [2015ApJ...806...14P](#) MgII triplet formation
- Carlsson et al. [2015ApJ...809L..30C](#) Mg II k from plage
- Hansteen et al. [2015ApJ...811..106H](#) heating from footpoint braiding
- Rathore et al. [2015ApJ...811...81R](#) IRIS C II formation
- Guerreiro et al. [2015ApJ...813...61G](#) quiet-Sun heating events

BIFROST ANALYSES 2

Martínez-Sykora et al. [2016ApJ...817...46M](#) non-E Si IV/O IV ratios
Golding et al. [2016ApJ...817..125G](#) non-E He ionization
Nóbrega-Siverio et al. [2016ApJ...822...18N](#) 2D ($H\alpha$) surges
Kato et al. [2016ApJ...827....7K](#) waves from magnetic pumping
de la Cruz Rodriguez et al. [2016ApJ...830L..30D](#) Mg II h & k + Mg II triplet inversions
Schmit+DePontieu [2016ApJ...831..158S](#) IRIS Si IV QS internetwork versus IRIS
Leenaarts et al. [2016A&A...594A.104L](#) spatial structure in He I 10830
Schmit & De Pontieu [2016ApJ...831..158S](#) TR emission from internetwork
Martínez-Sykora et al. [2016ApJ...831L...1M](#) 2.5D ambipolar misalignment fibrils-field
Fleischman et al. [2017ApJ...839...30F](#) try NLFFF on Bifrost snapshot
Golding et al. [2017A&A...597A.102G](#) He resonance lines
Kanella & Gudiksen [2017A&A...603A..83K](#) detect reconnection sites and current sheets
Guerreiro et al. [2017A&A...603A.103G](#) small-scale heating events
Martínez-Sykora et al. [2017Sci...356.1269M](#) spicules from ambipolar diffusion
Hansteen et al. [2017ApJ...839...22H](#) generation of bombs and nano/micro-flares
Nóbrega-Siverio et al. [2017ApJ...850..153N](#) 2D non-E Si IV surges
Roupe van der Voort et al. [2017ApJ...851L...6R](#) plasmoids in UV-burst reconnection

BIFROST ANALYSES 3

Bjørngen et al. [2018A&A...611A..62B](#) Ca II H & K insufficient peak separation

Liu et al. [2018arXiv180402931L](#) automatic swirl detection

Nóbrega-Siverio et al. [2018ApJ...858....8N](#) 2D non-E Si IV, O IVsurges

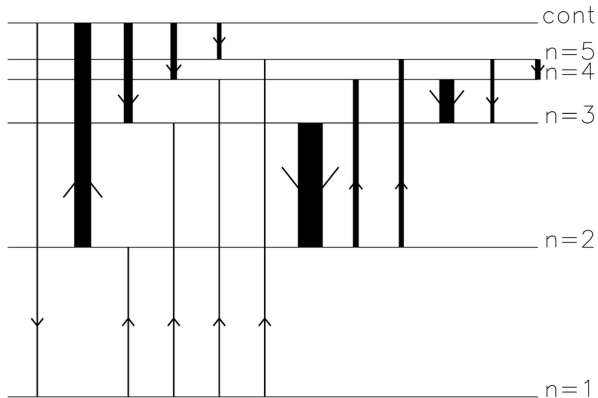
Martínez-Sykora et al. [2018arXiv180506475M](#) ion-neutral 2D: spicules-II

RECENT DEVELOPMENTS IN PRD LINE SYNTHESIS

- *RH code: Uitenbroek 2001ApJ...557..389U*
 - Rybicky & Hummer: not $\Lambda(S)$ but $\Psi(j)$ iteration; preconditioning
 - overlapping lines
 - 1D, 2D, 3D, spherical versions
- *RH 1.5D: Pereira & Uitenbroek 2015A&A...574A...3P*
 - 1.5D = column-by-column
 - massively parallel
 - also molecular lines (but Kurucz lines in LTE)
- *angle-dependent redistribution: Leenaarts et al. 2012A&A...543A.109L*
 - good summary PRD theory and equations
 - non-stationary atmosphere requires angle-dependent PRD
 - hybrid approximation: transform to gas parcel frame, assume angle-averaged PRD (\approx angle dependent from deep isotropy), transform back
- *towards Bifrost PRD: Sukhorukov & Leenaarts 2017A&A...597A..46S*
 - hybrid approximation for small memory
 - linear frequency interpolation for speed
 - $252 \times 252 \times 496$ grid, 1024 CPUs: 2 days for Mg II k \approx doable
- *next: 3D PRD with multigrid (Bjørgen & Leenaarts 2017A&A...599A.118B)*

NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

Carlsson & Stein 2002ApJ...572..626C



atom top ~ 3.4 eV alkali: NLTE-SE ionization loop

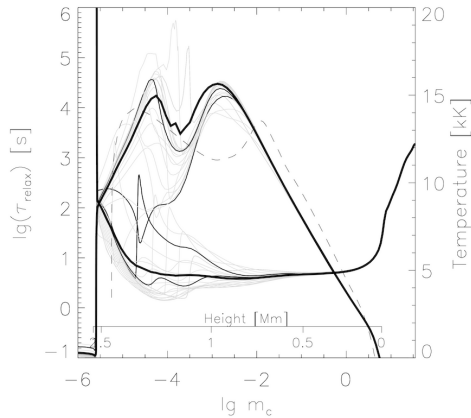
- driven by photon pumping Balmer continuum, scattering from deep, ≈ 5300 K, smooth
- closure by photon losses in n_α lines

atom bottom actually up to 10 eV: non-E Ly α

- tremendous scattering from small ε
- tremendous opacity from huge H abundance
- small structures already detailed radiative balance
- non-E: fast settling at high T, slow at low T

- RADYN code: 1D(t) hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed subphotosphere piston drives acoustic waves up that shock near $h=1000$ km
- Ly α scatters in radiative balance and controls $n=2$. Within shocks $S \approx J$ saturates to B from radiation lock-in (increased ε from partial hydrogen ionization) so that $b_2 \approx 1$
- collisional Ly α balancing has Boltzmann temperature sensitivity: fast (seconds) in hot gas, slow (minutes) in cool gas, resulting in retardation: post-shock cooling gas maintains the high n_2 shock value at increasing b_2 during minutes, up to huge overpopulation ($b_2 \approx 10^{10}$)
- ionization from $n=2$: instantaneous statistical-equilibrium balance driven by Balmer continuum $J \neq B$ and closed by cascade recombination, with $b_{\text{cont}}/b_2 \approx 10^{-1}$ in hot and $\approx 10^{+3}$ in cool gas, the latter adding to much larger retarded b_2
- between shocks hydrogen remains hugely overionized versus SE and LTE predictions

DETAILED BALANCING



Hydrogen ionization/recombination relaxation timescale throughout the solar-like shocked RAdyn atmosphere. The timescale for settling to equilibrium at the local temperature is very long, 15–150 min, in the chromosphere but much shorter, only seconds, in shocks in which hydrogen partially ionizes.

Carlsson & Stein 2002ApJ...572..626C

net radiative and collisional downward rates (Wien approximation)

$$n_u R_{ul} - n_l R_{lu} \approx \frac{4\pi}{h\nu_0} n_l^{\text{LTE}} b_u \sigma_{\nu_0}^l \left(B_{\nu_0} - \frac{b_l}{b_u} \bar{J}_{\nu_0} \right) \quad \text{zero for } S = \bar{J}, \text{ no heating/cooling}$$

$$n_u C_{ul} - n_l C_{lu} = n_l C_{lu} \left(\frac{b_u}{b_l} - 1 \right) = b_u n_l^{\text{LTE}} C_{lu} \left(1 - \frac{b_l}{b_u} \right) \quad \text{zero for } b_u = b_l, \text{ LTE } S^l$$

dipole approximation for atom collisions with electrons (Van Regemorter 1962)

$$C_{ul} \approx 2.16 \left(\frac{E_{ul}}{kT} \right)^{-1.68} T^{-3/2} \frac{g_l}{g_u} N_e f$$

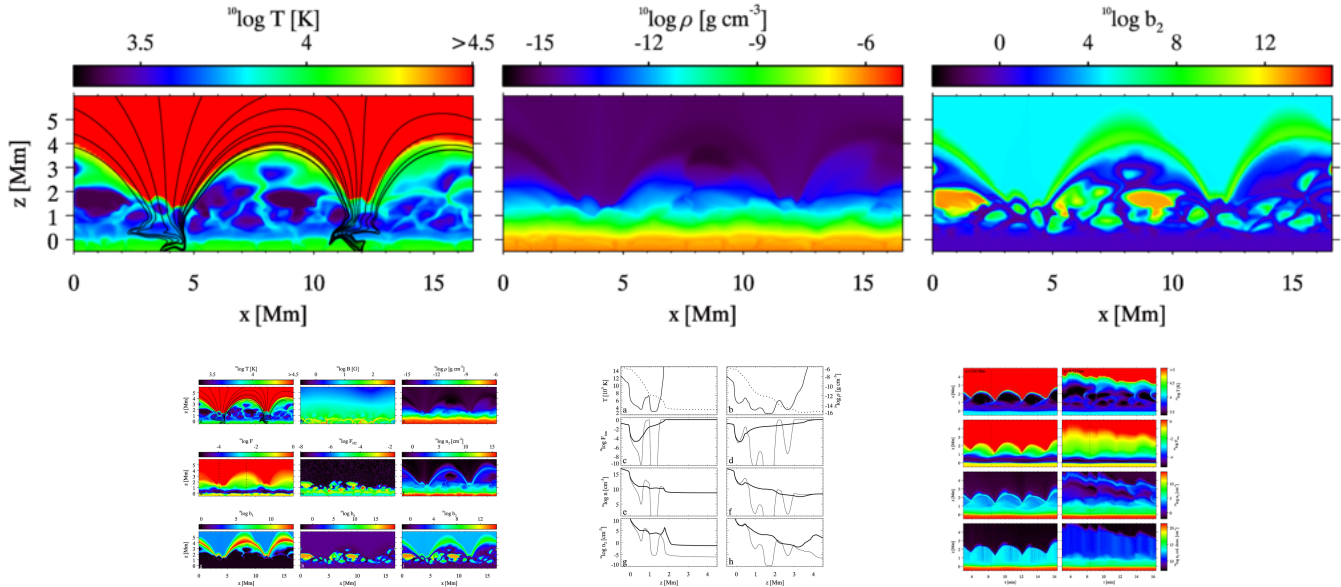
Einstein relation

$$C_{lu} = C_{ul} \frac{g_l}{g_u} e^{-E_{ul}/kT}$$

C_{ul} is not very temperature sensitive (any collider will do); C_{lu} has Boltzmann sensitivity

NON-E HYDROGEN IONIZATION IN 2D MHD SHOCKS

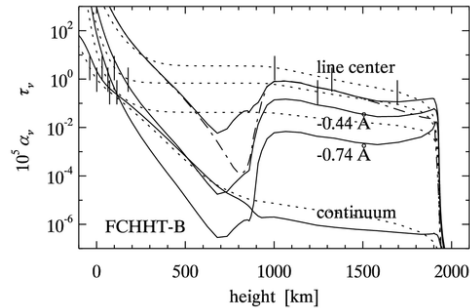
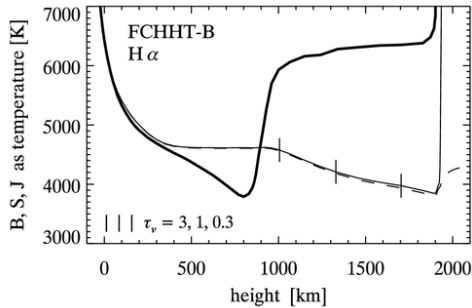
Leenaarts et al. 2007A&A...473..625L



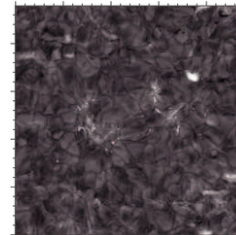
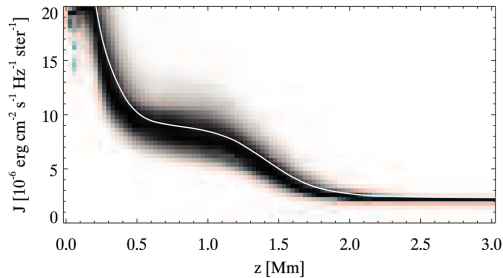
- in shocks $\text{Ly}\alpha$ has $S \approx B$ from high T (fast balancing) and N_e (10% H ionization)
- retarded collisional balancing in $\text{Ly}\alpha$: n_2 hangs near high shock value $n_2 \approx n_2^{\text{LTE}}$
- gigantic post-shock $n=2$ overpopulations versus LTE (“S-B underestimates”)
- yet larger post-shock overionization from hydrogen-top Balmer balancing
- no Lyman RT: green arches artifacts, no lateral N_e boost from $\text{Ly}\alpha$ scattering

H α IN BIFROST

1D plane-parallel SE: Rutten & Uitenbroek 2012A&A...540A..86R

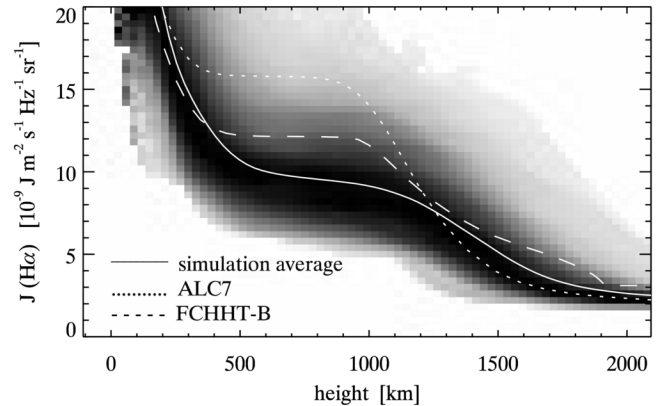
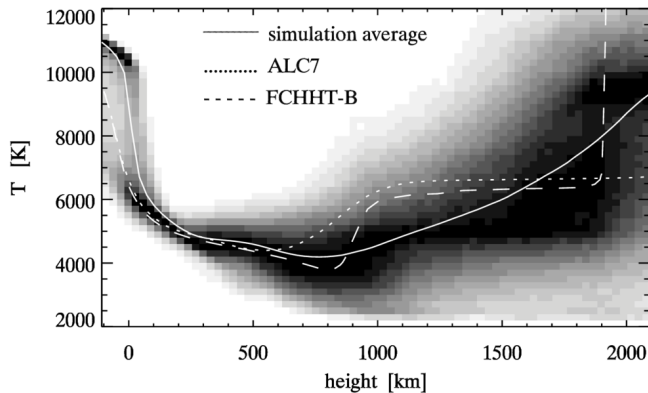


3D non-E MHD: Leenaarts et al. 2012ApJ...749..136L



- H α is a pure scattering line with $S \approx J$ and a deep opacity dip in the upper photosphere
- 3D scattering across the opacity gap enhances fibril visibility
- core darkness measures density, core width measures temperature
- caveats: Bifrost snapshot, no non-E RT, lacking spicules-II, long fibrils

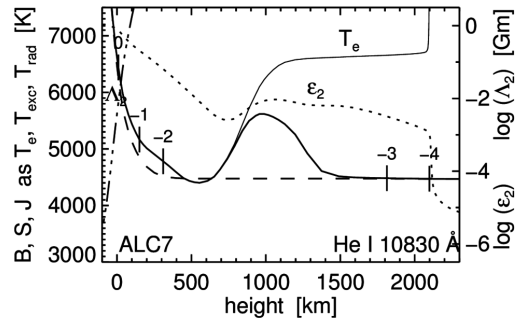
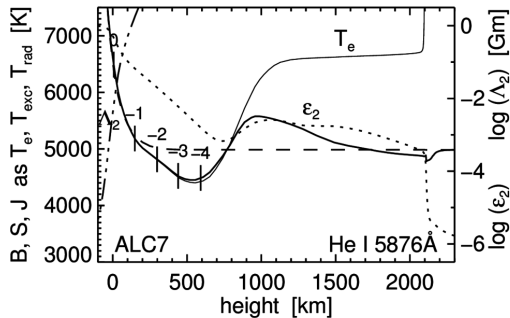
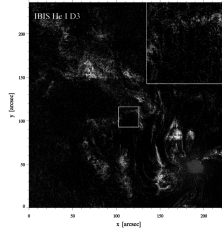
OSLO SIMULATION VERSUS 1D STANDARD MODELS



- simulation = state-of-the-art: 3D(t), \vec{B} , non-HE, SE populations but NE for H
Leenaarts, Carlsson & Rouppe van der Voort [2012ApJ...749..136L](#)
- ALC7 = UV fit: 1D static, no \vec{B} , HE + microturbulence, SE populations
Avrett & Loeser [2008ApJS..175..229A](#)
- FCHHT-B = UV fit: 1D static, no \vec{B} , HE + imposed acceleration, SE populations
Fontenla, Curdt, Haberreiter, Harder & Tian [2009ApJ...707..482F](#)

The T and $J_\nu(\text{H}\alpha)$ behavior seems arguably similar. However, the conceptual differences between plane-parallel static hydrostatic-equilibrium modeling and the 3D(t) MHD simulation are enormous (cf. Newtonian gravitation versus general relativity). The $T(h)$ stratifications in the simulation vary tremendously, with shocks propagating upwards and sideways and the increase to coronal temperature dancing up and down over a large height range.

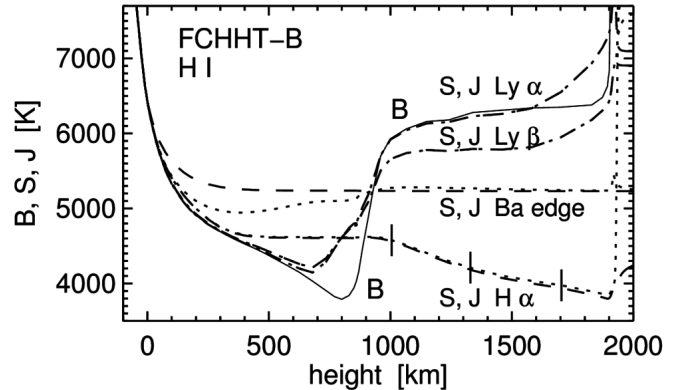
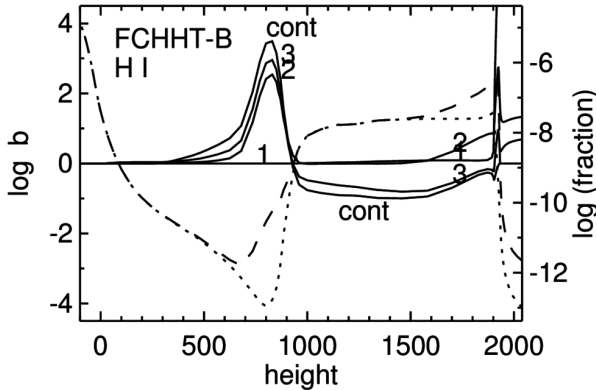
He I and He II



- optical He I lines: nothing in ALC7, nor in atlases, nor in Moore-Minnaert-Houtgast
- more complex non-E formation than H I: not only He I 584 acting as Ly α but ionization/recombination not limited to the atom top as for H I (smooth Balmer continuum driving from below) but sensing hot and structured irradiation from above
- see Bifrost He papers and more to come
- to-do for 2018 = 150 years after Lockyer: explain He I D₃ in flash spectrum
long dark H α -like He II 304 fibrils also memorial-opacity contrails?

HYDROGEN AUREOLE BOOSTING IN COOL GAS BESIDE HOT GAS

Fontenla et al. 2009ApJ...707..482F Rutten & Uitenbroek 2012A&A...540A..86R Rutten 2016A&A...590A.124R



FCHHT-B: steep B rises to chromosphere and corona emulate adjacent cool and hot features

$\text{Ly}\alpha$: scattering back-radiation boosts $S_{\text{Ly}\alpha} \approx J_{\text{Ly}\alpha}$ and $\text{H}\alpha$ extinction $\propto b_2 \approx S_{\text{Ly}\alpha} / B_{\text{Ly}\alpha}$ towards hot-feature value (left: dotted $n_2^{\text{LTE}} / N_{\text{Htot}}$, dashed actual n_2 / N_{Htot})

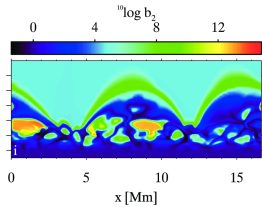
ionization: also b_2 -boosted, with additional b_{cont} / b_2 offset defined by the Balmer continuum

$\text{Ly}\beta$: b_3 between b_2 and b_{cont} and sharing $\text{H}\alpha$ photon losses

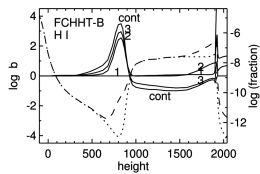
$\text{H}\alpha$: the FCHHT-B chromosphere is a back-scattering attenuator just as in the [ALC7 atmosphere](#). The b_2 peak from $\text{Ly}\alpha$ irradiation does not affect $\text{H}\alpha$ because even with this boost the $\text{H}\alpha$ extinction in the temperature minimum remains negligible.

A hot feature embedded in cooler gas has a similar $\text{Ly}\alpha$ scattering aureole enhancing H ionization and $\text{H}\alpha$ extinction around it. A temporary hot disturbance leaves such spread-out boost behind (a wake when moving).

H α EXTINCTION RECIPE



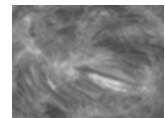
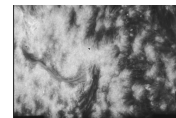
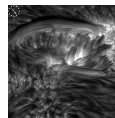
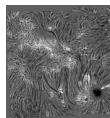
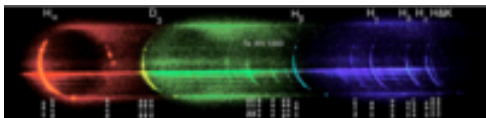
- *retarded Ly α balancing: extinction memory of hot moments*
 - $n_2 \approx n_2^{\text{LTE}}$ in hot shocks from fast Ly α balancing and increased ϵ
 - n_2 decays slowly, tracking high shock values
 - gigantic b_2 in post-shock cooling clouds until next shock



- *Ly α scattering: aureole boosting*
 - Ly α scattering defines $S_{\text{Ly}} \approx J_{\text{Ly}}$ with radiative balance
 - hot features in cool gas have Ly α scattering aureoles
 - H I top ($n \geq 2$ including n_{ion}) boosted in aureoles

- *H α extinction recipe*

- find hottest instance nearby (~ 300 km) and in recent past (\sim minutes)
- compute Saha-Boltzmann fractional $n = 2$ population then and there
- use this extinction value in cooler gas around it and afterwards
- small hot features leave wider H α marks (as the grin of the Cheshire cat)
- fast small hot features leave wider H α trails (as contrails from jet engines)

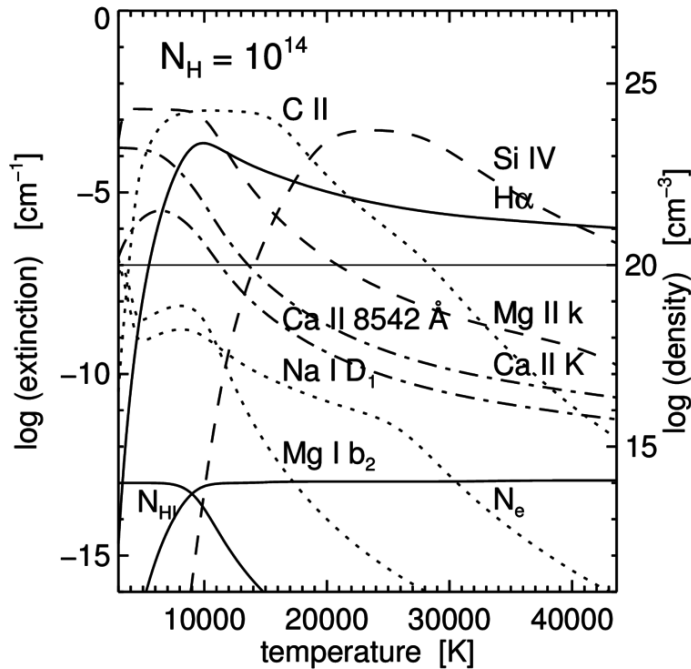


SAHA-BOLTZMANN FOR CHROMOSPHERIC LINES

Rutten 2016A&A...590A.124R

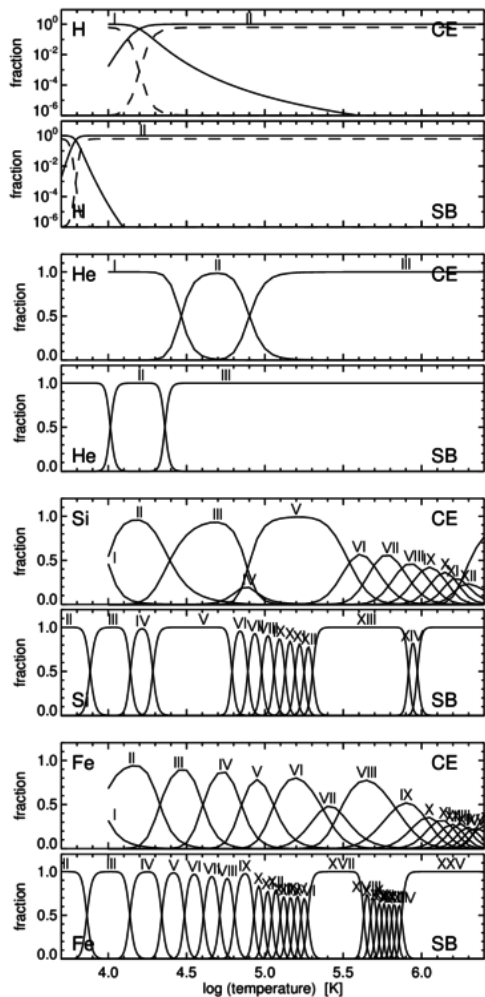
Bachelor exercise “Cecilia Payne”: compute N_e and κ^{LTE} for given $N_{\text{H_total}}$

“I taught making Saha-Boltzmann graphs to hundreds of students at Utrecht and elsewhere with a lab exercise “Cecilia Payne” (available on my website). It uses a fictitious and unpronounceable didactic element called “Schadeenium” after Utrecht astrophysicist Aert Schadee (1936–1999), who invented it for teaching in the 1970s.”



CORONAL EQUILIBRIUM VERSUS SAHA-BOLTZMANN IONIZATION

Rutten + Rouppe van der Voort 2017A&A...597A.138R
 “Carole Jordan versus Cecilia Payne”



- **CE**
 - up: collisional excitation/ionization
 - down: radiative deexcitation/recombination
 - NB: dielectronic recombination
- **SB**
 - up: collisional excitation/ionization
 - down: collisional deexcitation/recombination
- $N_e = 10^{14}$ (other densities)
 - SB: N_e affects ionization, not excitation
 - CE: N_e affects excitation, not ionization
 - smaller N_e : SB peaks steepen and shift left
- **hydrogen**
 - long H I tail from no H III (log scales)
 - still competitive at $10^{-5} \approx$ others
- **Mg III, C V, Si V, Si XIII, Fe XVII, Fe XXV**
 - wide hump from closed shell (atom configs)
 - extra recombination radiation into previous ion

ELLERMAN BURSTS OVERVIEW

SOLAR HYDROGEN "BOMBS"¹

by FRANCISQ ELLERMAN

Visual and photographic observations of a solar phenomenon which had previously escaped our attention have been carried on at Lick Observatory during the past two years.

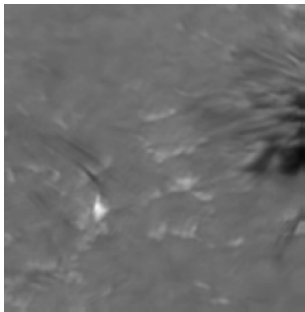
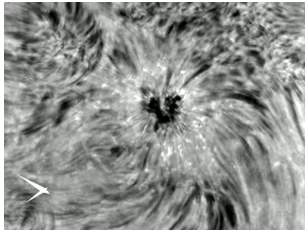
On September 21, 1915, while the writer was observing the H α line for reversals and distortions in an active spot-group, there suddenly appeared a very brilliant and very narrow band extending four or five angstroms on either side of the line, but not crossing it. In a couple of minutes it faded away and was not seen again. A month later, on October 21, more observations were recorded and a spectrum was secured.

On the first occasion the appearance was so extraordinary that it seemed hardly real; after the second observation, however, the existence of such phenomena as part of the solar activity seemed established, and a search has been made for them whenever conditions of seeing and other work have permitted.

There are two conditions essential for observation—good seeing and a large solar image—on the area of the phenomenon, even with the 16-inch image of the sun at the 150-foot tower telescope, is so small that only with difficulty is the point of disturbance kept on the slit.

The appearance of the phenomenon indicates something in the nature of an explosion, in which hydrogen seems to be the only element playing a part. The duration is only a few minutes—from one to three on the average, and from five to ten minutes rarely. This sudden performance suggested the name of hydrogen "bomb," which we have adopted to designate it.

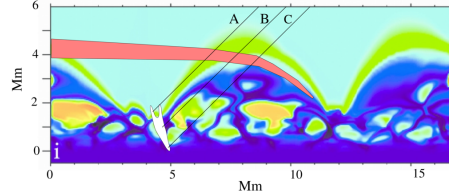
In the *Astronomical Journal*, Jan. 28, 1920, Dr. Walter M. Mitchell gives an account of solar observations made at Harvard College Observatory, together with a drawing which illustrates the appearance of H α in the spectrum of a "bomb," and from his



- Mount Wilson: solar hydrogen bombs
Ellerman 1917ApJ...46..298E ADS citation history (100=100?)
 - sudden brightenings in H α wings
 - not in line core, only in Balmer and Ca II lines
 - between spots in complex emerging active regions
- DOT: pseudo Ellerman bombs
Leenaarts et al. 2006A&A...449.1209L *2006A&A...452L..15L*
Rutten et al. 2013JPhCS.440a2007R
 - magnetic concentrations in sunspot moat
 - Spruit hole radiation plus small collisional damping
 - H α blue-wing BPs better than G-band BPs
- SST: true Ellerman bombs
Watanabe et al. 2011ApJ...736...71W
 - photospheric jets in rapid succession along network
 - shielded in H α core by overlying fibrils
 - photospheric strong-field reconnection?
- interpretation: *reconnection per cartoon*

ELLERMAN BOMB VISIBILITIES

Rutten 2016A&A...590A.124R



- *observations*

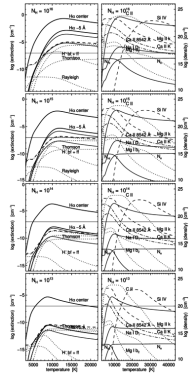
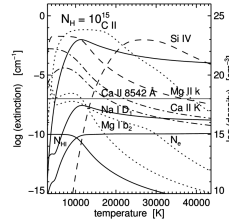
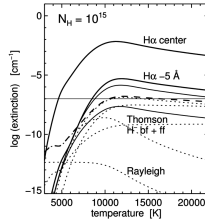
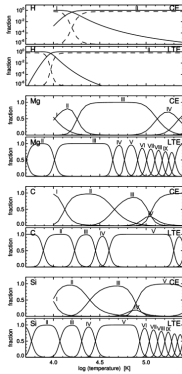
- Ellerman bomb: $H\alpha$ moustaches below core fibrils [example] [movie]
- also bright but different in Ca II 8542 Å [example]
- also bright but diffuse in AIA 1700 and 1600 Å [example]
- not in optical continuum nor Fe I, Na I D, Mg I b lines [example]
- also bright in IRIS C II and Si IV lines [example]
- hot FAF-like aftermaths with cool blends [example] [EBs vs FAFs]

- *visibility recipes*

- Balmer in hot and dense onsets: Saha-Boltzmann extinction
- cooling aftermaths: long Balmer memory of large onset extinction
- $H\alpha$ wings: electron broadening (Stark + Holtsmark)
- transition-region lines: at large N_e extinction closer to SB than CE
- “cool” blends: surrounding cool clapotisphere in slanted viewing (above)
- diffuse bright feet in 1700 Å: surround irradiation by EB + bound-free scattering

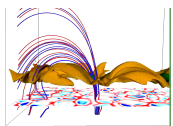
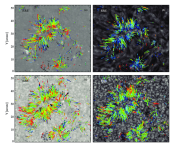
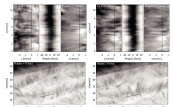
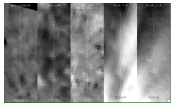
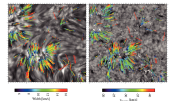
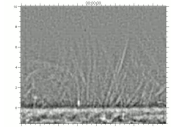
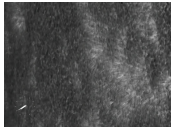
ELLERMAN BOMBS PER LTE

Rutten 2016A&A...590A.124R



- $H\alpha$
 - extraordinary hot-gas opacity (large abundance, large excitation energy, no HIII)
 - extraordinary wide wings at large H ionization (Stark + Holtsmark)
 - extraordinary memory for hot past
- *ultraviolet Balmer continuum*
 - same hot-gas opacity and memory as $H\alpha$
 - fibrils transparent so no Stark moustaches needed
 - shielding by surrounding photosphere, but scatter-through in Mg I and Fe I edges
- *other lines*
 - Na I D and Mg I b absent above 10 000 K
 - Si IV absent below 20 000 K but may have hot-past memory in cooling gas
 - EB bottoms shielded by adjacent or overlying cooler gas, except $H\alpha$ and Si IV

STRAWs / SPICULES-II / RBEs / RREs



- *observations*

- “straws”, DOT Ca II H
Rutten 2006ASPC..354..276R
- “spicules-II”, Hinode Ca II H
De Pontieu et al. 2007Sci...318.1574D
- “rapid blue excursions”, SST H α
Roupe van der Voort et al. 2009ApJ...705..272R
- “coronal heating events”, Hinode H α + SDO EUV
De Pontieu et al. 2011Sci...331...55D
- “torsion-swaying jets”, SST H α + Ca II 8542 Å
De Pontieu et al. 2012ApJ...752L..12D
- “rapid red excursions”, SST H α
Sekse et al. 2013ApJ...769...44S

- *simulation: Martínez-Sykora et al. 2011ApJ...736....9M*

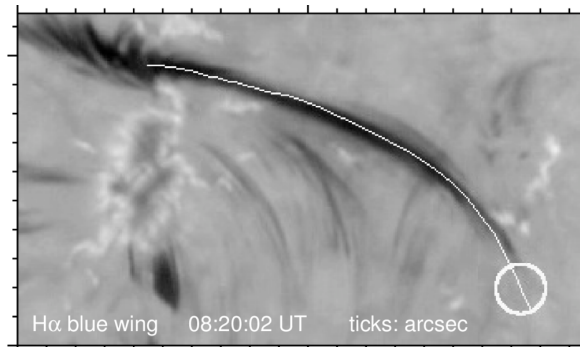
- feature called a spicule-II but questionable
- no others in simulations so far
- driver unknown (Pereira et al. 2012ApJ...759...18P)

- *upshot: ubiquitous small magnetic heating events possibly important in*

- quiet-sun (also unipolar) coronal heating
- fast solar wind driving
- solar wind element segregation

LONG FIBRILS AS CONTRAILS

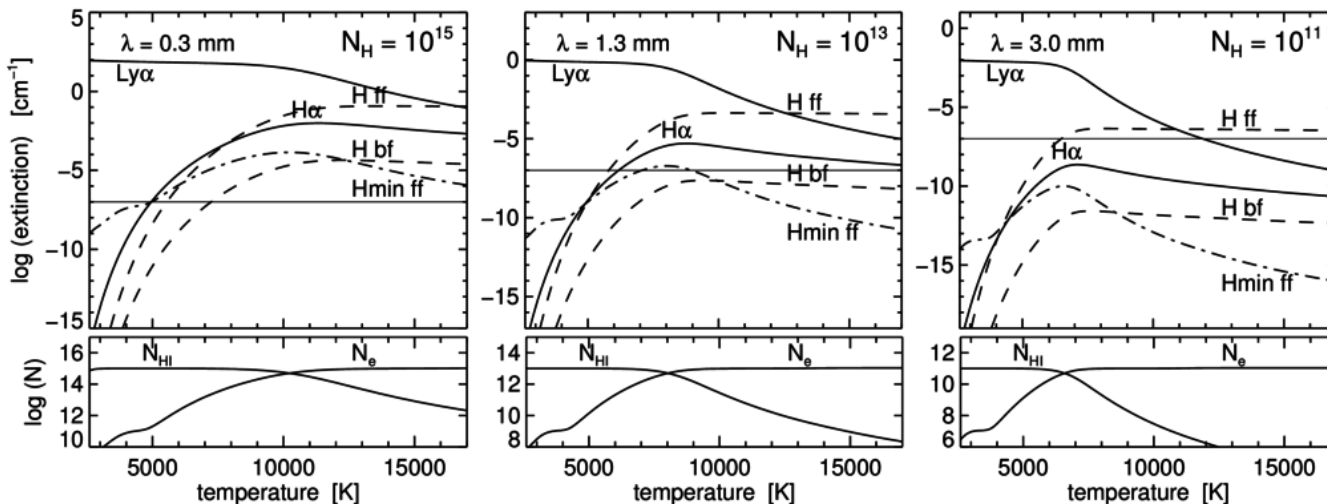
Rutten & Rouppe van der Voort 2017A&A...597A.138R



- $H\alpha$ blue wing: fantail with slender extending dark thread = wide blueshifted core
- visible in IRIS 1400 Å (Si IV), AIA 304, 171, 193 Å, not in Ca II 8542 Å = hot
- three-four minutes later dark $H\alpha$ core fibril = non-E H recombination
- large non-E $H\alpha$ opacity in cooling post-hot-disturbance gas
- fibril \sim contrail: not representing cool present but much hotter precursor past
- line-tying by precursor H ionization: contrail maps preceding field topography

SAHA-BOLTZMANN HYDROGEN EXTINCTION AT ALMA WAVELENGTHS

Rutten 2017A&A...598A..89R 2017IAUS..327....1R (tutorial)

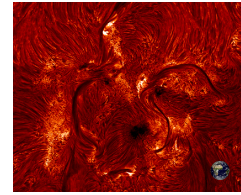


- LTE extinction: Ly α H α H I continua H⁻ ff continuum 8542 other lines
- H α at high T: LTE extinction from $n_2 \approx n_2^{\text{LTE}}$ enforced by enclosed Ly α
- H ionization: $n = 2$ population fixed by (actually non-E) Ly α ; hydrogen top has additional NLTE-SE balancing between Balmer continuum and Balmer lines
- Balmer continuum $T_{\text{rad}} \approx 5250 \text{ K}$: overionization below, underionization above \Rightarrow de-steepening of these LTE H ff Boltzmann increases around 5250 K pivot
- $\alpha_{\nu}^{\text{ff}} \sim \lambda^2 N_e N_{\text{ion}} T^{-3/2}$ (RTSA Eq. 2.79) gives steep H ff increase between ALMA bands
- features with non-E post-hot H α extinction have larger to very much larger H ff extinction

PREDICTIONS FOR SOLAR ALMA



2017A&A...598A..89R



1. ALMA sun mostly covered by long fibrils (unlike simulated suns)
2. similar to $H\alpha$, good dark–dark correspondence, more opaque at longer ALMA wavelengths, less lateral contrast (no Dopplershifts)
3. temperatures: above 10 000 K in heating events propagating outward from activity, around 7000 K in initial fibrils, cooling down to 5000 K in long contrail fibrils (or less)
4. heating events best detectable with ALMA (if sufficient resolution)
5. if so, darker aureoles vanishing above 15 000 K ($Ly\alpha$ scattering)
6. small precursors produce 0.2–0.5 arcsec $H\alpha$ and ALMA contrail widths ($Ly\alpha$ scattering)
7. precursors better field mappers than subsequent contrail fibrils (H ionization)
8. internetwork shocks only in quietest areas, with 4000 K cooling clouds (COMosphere)
9. no Ellerman bombs (hidden by fibrils)
10. flaring active-region fibrils poke through (@ measure reconnection temperature)
11. off-limb spicules-II more opaque than in $H\alpha$ and Ca II H
12. coronal rain much more opaque than in $H\alpha$

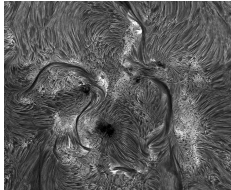
SOLAR RYDBERG LINES WITH ALMA?

Rutten 2017IAUS..327....1R

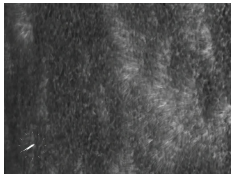
- “linear thermometer”
 - H^- free-free + H I free-free: $S \equiv B$
 - thick feature: $T_b = T(\tau_\nu = 1)$
 - thin feature: cloud contribution $\Delta T_b = \tau T$
- solar Rydberg lines so far
 - in μm range Mg I stronger than H I
 - prediction H I α lines $n = 4 - 18$
 - H I 19α , 21α observed at limb
- H I Rydberg lines with ALMA?
 - candidate: H I 30α in Band 6 (1.3 mm)
 - much stronger than above predictions from large post-hot non-E extinction?
 - if so, unblendedly present since Mg I etc are not non-E boosted?
 - on disk as $T(\tau_\mu = 1)$ emission at steep $T(\tau)$ gradient
 - at limb as τT extension
 - Zeeman in I and Stokes: super-sensitive chromospheric magnetometer?

NON-EQUILIBRIUM CHROMOSPHERE

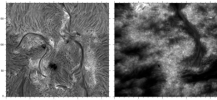
chromosphere potpourri



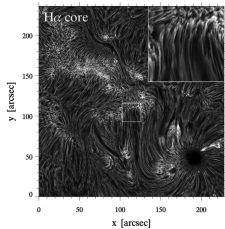
- $H\alpha$ chromosphere = *past defined by Ly α*
 - long fibrils = post-hot cooling clouds
 - long-fibril contrast = different histories and Dopplershifts
 - long-fibril widths = Ly α scattering (0.2–0.5 arcsec)



- $Ca II$ H & K chromosphere = *present defined by temperature*
 - thin fibrils = horizontally launched heating events
 - thin-fibril widths = heating-event widths + scattering halo
 - @ corresponding IRIS Si IV, AIA EUV, ALMA mm features?

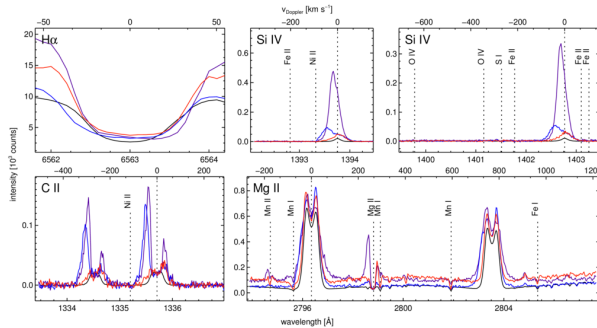


- $H\alpha$ versus Ly α = *past versus present*
 - Ly α grains = heating events
 - Ly α short fibrils and comet heads = initial tracks
 - @ Ly α , ALMA heating-event imaging spectroscopy?



- $H\alpha$ versus $Ca II$ 8542 Å versus $He I$ D₃ versus $He II$ 304 = *idem*
 - $Ca II$ instantaneous = short fibrils
 - $He I$ D₃ ~ $He II$ 304 = post-hot irradiated cooling gas?
 - @ time-delay image correlations

IRIS DIAGNOSTICS OVERVIEW



- *Si IV 1400 Å lines*
 - peak ratio 2: feature (not “lines”) optically thin
 - if so: faithful Doppler mapping (e.g., EB bimodal jets)
 - gas temperature: 90 kK for CE, 20 kK for SB (ALMA at ratio \Rightarrow 1?)
- *Mg II h & k lines*
 - enormous SB opacity
 - strong PRD scatterers
 - SB opacity sampling classical chromosphere top to bottom
- *Mg II triplet lines*
 - bright suggests steep deep temperature rise
 - bright suggests (non-E?) recombination from wide Mg III reservoir
 - Mn I blend = photospheric gas along line of sight

IRIS DIAGNOSTICS

- *Mg II h & k*
 - Leenaarts et al. 2013ApJ...772...89L
 - Leenaarts et al. 2013ApJ...772...90L
 - Pereira et al. 2013ApJ...778..143
 - Carlsson et al. 2015ApJ...809L..30C
- *other lines*
 - Mg II triplet Pereira et al. 2015ApJ...806...14P
 - C II doublet Rathore et al. 2015ApJ...811...80R
 - C II doublet Rathore et al. 2015ApJ...811...81R
 - C II doublet Rathore et al. 2015ApJ...814...70R
 - O I 1355.6 Å Lin et al. 2015ApJ...813...34L

SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten

<https://webspacescience.uu.nl/~rutte101>

thin: cloud modeling corona chromosphere Rydberg per ALMA?

thick: UV line flip VAL3C temperature VAL3C spectrum Kurucz stars

photospheric lines: inversions bright points reversed granulation Na I D1 MGs
limb emission lines

continua from VAL3C: Avrett models versus 3D MHD VAL3C continua
VALII budget hydrogen budget all

lines from ALC7: model optical spectrum ultraviolet depletion hydrogen
strong lines plot formats pops plot BSJ plot profile plot Mg I 4571
Fe I 6302 Mg I b₂ Na I D₁ Ba II 4554 Ca II 8542 Å Ca II K Mg II k
Ly α H α H β He I 584 He I 10830 canonical H α Na I D₁-Mg I b₂
Ly α -H α H α -Ca II 8542 Å Ca II K-Mg II k versus FCHHT-B ALC7-FALC
FALC-FALP ALC7-FALP

detour lines: pumping suction

Oslo-simulated dynamic atmosphere: 1D RADYN 3D Bifrost Bifrost line synthesis

LA-conjectured PSBE atmosphere: non-E H α aureole boosting H α extinction
CE-SB EBs spicules-II contrail ALMA non-E chromosphere?

IRIS diagnostics: overview diagnostics

SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten
<https://webpage.science.uu.nl/~rutten01/>

title: cloud modeling corona chromosphere Rybberg per ALMA?

click: UV line flip VAL3C temperature VAL3C spectrum Kurucz stars

photopheric lines: inversions bright points reversed granulation Na I D1 M3s limb emission lines

continua from VAL3C: Arnett models versus 3D MHD VAL3C continua
 WOLF: budget hydrogen budget all

lines from ALIC7: model optical spectrum ultraviolet depletion hydrogen strong lines plot forms poor plot BSJ plot profile plot Mg 4471 Fe I 5022 Mg I b Na I D Bal 4554 Ca I 8542 A Ca I K Mg 1 a Lyv H α H β H γ H δ H ϵ H ζ H η I 10330 canonical H α Na I D α -Mg I b Lyv α -H α Ca I 8542 A Ca I K-Mg 1 a versus FCHHTB ALIC7-FALC FALC-FALP ALIC7-FALP

detector lines: pumping suction

Old-omitted dynam atmosphere: ID RADYN 3D Bilrost Bilrost line synthesis

L-constructed PRB atmosphere: non E H α source boosting H α extinction
 CE-5B EBV spectra H central ALMA non E chromosphere?

ISIS diagnostics: overview diagnostics

1

CLOUD MODELING

review: Zaitsev 2007ASPC...368...2177

Formal solution for line of sight (LOS) through irradiated cloud

$$I_{\lambda} = I_0(R) e^{-\tau_{\lambda}} + \int_{\lambda_0}^{\lambda} S_{\lambda}(L) e^{-\tau_{\lambda}(\lambda_0, L)} dL$$

Homogeneous cloud, Gaussian broadening, parameters $f_{\lambda}(\Delta\lambda)$, S_{λ} , τ_{λ} , LOS z

$$f_{\lambda}(\Delta\lambda) = f_{\lambda}(\Delta\lambda) e^{-i(\Delta\lambda)^2 + S} [1 - e^{-i(\Delta\lambda)^2}]$$

$$\tau_{\lambda}(\Delta\lambda) = \tau_{\lambda} e^{-i(\Delta\lambda)^2 + S}$$

$$S(\Delta\lambda) = \frac{S}{\Delta\lambda} \left(1 - e^{-i(\Delta\lambda)^2 + S} \right)$$

Refinements: Voigt, γ -dependent S , wavelength-dependent S (for PFD with $S = i\Gamma$)

Interpretation: $S = (T/\mu)$
 = Sokolov 1985Sb, 3-367b; Giovannelli NLTE hydrogen ionization tables
 = Moloney Horas et al. 1999A&A...345...616M: "inversion" from many model profiles

Problems: impinging profile, sideways invasion, multi-thread

2

H α CLOUD MODELING

Rutten & Lites/Book 2015M&A...540A...86R

Ha H α formation: the Kurucz and FCHHT B models both reproduce observed H α cloud modeling: $I_{\lambda} = I_0(R) e^{-\tau_{\lambda}} + \int_{\lambda_0}^{\lambda} S_{\lambda}(L) e^{-\tau_{\lambda}(\lambda_0, L)} dL$

new recipe: for the impinging profile $I_{\lambda}(R)$ take the outward r profile in a RE model at the depth r_{in} , which equals the cloud thickness r_{in} (dotted profiles)

3

SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten
<https://webpage.science.uu.nl/~rutten01/>

title: cloud modeling corona chromosphere Rybberg per ALMA?

click: UV line flip VAL3C temperature VAL3C spectrum Kurucz stars

photopheric lines: inversions bright points reversed granulation Na I D1 M3s limb emission lines

continua from VAL3C: Arnett models versus 3D MHD VAL3C continua
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detector lines: pumping suction

Old-omitted dynam atmosphere: ID RADYN 3D Bilrost Bilrost line synthesis

L-constructed PRB atmosphere: non E H α source boosting H α extinction
 CE-5B EBV spectra H central ALMA non E chromosphere?

ISIS diagnostics: overview diagnostics

4

SOLAR ECLIPSE VISIBILITY

H.C. van de Hulst

• dusty sky has 0.1–0.01% of the solar brightness (10^{-3} – 10^{-4}), brighter closer to Sun

• "coronal" blue sky (Rayleigh scattering) is one millionth (10^{-6}), less than the coronal brightness

• during totality the sky brightness is only one billionth (10^{-9}), less than the coronal brightness

• "K" = continuum component, "E" = Fraunhofer component, "E" = emission-line component

• a earthshine (10^{-10}) = see-moon brightness from full-earth-with-spot irradiation

5

CORONAL WHITE LIGHT

• Walter Grotrian (Potsdam, 1931)
 while = Thomson scattering of photospheric photons by free electrons weak = low electron density selection cross section only 10^{-18} cm²
 absence of photospheric Fraunhofer lines = washed out by large Doppler shifts required electron speeds 4000 km/s [= if motions thermal: 1 million degrees T]

• linear polarization from right angle scattering

• line structure major variations in electron density dictated by magnetic fields

• the F component further out results from photon scattering by slower-moving interplanetary dust particles; its spectrum shows the photospheric Fraunhofer lines

Appreciate that during totality you are illuminated by normal photospheric light — but only if 10^{-9} fraction bounced around the moon, without Fraunhofer lines, and polarized too!

6

WHITE LIGHT CORONA

M. Sliv "The Sun", Section 9.1.3

Grotrian (1931): Thomson scattering 8000 km s⁻¹ electrons

$$\rho = n^2 = n^2$$

$$I(r) = 2 \int_{\lambda_0}^{\lambda} f_{\lambda}(\Delta\lambda) d\lambda = 2 \int_{\lambda_0}^{\lambda} \frac{dI_{\lambda}}{d\lambda} d\lambda = 2 \int_{\lambda_0}^{\lambda} I_{\lambda}(\theta, \lambda) d\lambda$$

n , from inverse Abel transform = isotropically scattered irradiation

$$f_{\lambda}(\theta) = \frac{1}{\pi} \int_{\lambda_0}^{\lambda} \frac{df_{\lambda}/d\lambda}{\sqrt{\lambda^2 - \lambda_0^2}} d\lambda = \sigma_{\lambda} N_{\lambda} \int_{\lambda_0}^{\lambda} I_{\lambda}(\theta, \lambda) d\lambda$$

7

"CORONUM" LINES

M. Sliv "The Sun", Section 9.1.3 <http://lasersstars.org/spectra/Coronium.html>

Grotrian (1930); Edén (1942): forbidden lines high ionization stages (Sliv, Table 9.2 p. 398)

name	wavelength	identification	$\Delta\lambda_{\text{D}}$	λ_{D}	λ_{D}	previous ton.
green line	530.29 nm	[Fe XIV]	0.051 nm	29 km/s	60 s ⁻¹	Fe XII 355 eV
yellow line	565.45 nm	[Ca XIV]	0.087	46	95	Ca XIV 800
red line	637.45 nm	[Fe XI]	0.049	23	69	Fe X 235

Coronal sky at Dome C

8

EUV CORONA

If equilibria: collisional ionization = radiative recombination = only $f(T, n_e)$, not $f(T, N_e)$


If equilibria: collisional excitation = radiative deexcitation = $f(T, N_e)$

$$n_e N_e = n_e N_e \int_{\lambda_0}^{\lambda} \sigma_{\lambda} f_{\lambda}(\Delta\lambda) d\lambda = n_e N_e \sum_{\lambda} \int_{\lambda_0}^{\lambda} A_{\lambda} n_e N_e d\lambda = \int_{\lambda_0}^{\lambda} N^2 \left(\frac{dI_{\lambda}}{d\lambda} \right) d\lambda = E_{\text{EM}}$$

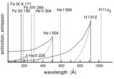
9

BRIGHT AND DARK IN EUV IMAGES

Rutter 1988ASPC...184...187R



- iron lines
 - Fe IX K (71 Å) about 1.0 MK
 - Fe XII Fe IXA (102 Å) about 1.5 MK
 - Fe XIV 284 Å about 2 MK
- bright
 - collision up, radiation down
 - thermal photon creation, NLTE equilibrium
 - one line: selected loop + spacial lines in burst
- dark
 - lack of emissivity ("volume blocking"?) or
 - bound free scattering
 - scattering: radiation up, re-radiation at bound-free threshold → black in narrow passband
 - scattering agents: H, He, H₂



10

SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten
<https://web.archive.org/web/2011/07/20141011>

thin: cloud modeling corona chromosphere Rytberg per ALMA?
 thick: UV line flip VALSC temperature VALSC spectrum Kuncic stars

photospheric lines: inversions bright points reversed granulation Na I D1 Mg b limb emission lines

continuum from VALSC: Arvid models versus 3D MHD VALSC budget hydrogen budget all

lines from ALCT: model optical spectrum ultraviolet depletion hydrogen strong lines pilot format: RSD profile Mg I 4481 Fe I 5302 Mg II h Na I D₁ Ba II 4554 Ca II H&K Mg II k Li I H_α H_β Na I 8204 Na I 8190 coronated Fe I Na I D₂ Mg II₂ Ly-He₂ H_α-Ca II 8542 A Ca II H+Mg k versus FHFTB ALCT-FALC-FALC-FALC ALCT-FALC

action lines: pumping excitation

photo-ionized dynamic atmosphere: 1D RADYN 3D Bifrost Bilrost line synthesis


1-A-constructed FUSE atmosphere: none H₂ auroral boosting H₂ extinction CE-SB EBs spicules-II central ALMA none H chromosphere?

DESI diagnostic: overview diagnostics

11

NORMAN LOCKYER

wikipedia



Dr Joseph Norman Lockyer, FRS (17 May 1836 – 16 August 1920), known simply as Norman Lockyer, was an English scientist and astronomer. Along with the French scientist Pierre Janssen he is credited with discovering the gas helium.

In 1885 he became the world's first professor of astronomical physics at the Royal College of Science, South Kensington, now part of Imperial College. At the college, the Solar Physics Observatory was built for him and there he directed research until 1913.

To facilitate the transmission of ideas between scientific disciplines, Lockyer established the general science journal Nature in 1869. He remained its editor until shortly before his death.

12

CHROMOSPHERE AND HELIUM NAMING

Abstract of Norman Lockyer's paper read Nov. 26, 1868. *Philos. Royal Society of London*, 17, 171-182. 1868:ISSN: 0030-131X. courtesy Kevin Reardon, 8 cities (P. RR)

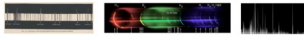
Details are given of the observations made by the new instrument, which was received immediately on the 16th of October. These observations include the discovery, and exact determination of the lines, of the prominence-spectrum on the 20th of October, and of the fact that the prominence are surely local aggregations of a gaseous medium which entirely envelopes the sun. The term Chromosphere is suggested for this envelope, in order to distinguish it from the cool absorbing atmosphere on the one hand, and from the white-light-giving photosphere on the other. The possibility of relations in the thickness of this envelope is suggested, and the phenomena presented by the star in Corona are referred to.

Two of the lines correspond with Fraunhofer's C and F₁; another line B' or B'' (cf. Kirchhoff's analysis) from D' reveals E. There is another bright line, which occasionally makes its appearance near C, but slightly less refrangible than that line. It is remarked that the line near D' has no corresponding line ordinarily visible in the solar spectrum. The author has

Fraunhofer's "C" is H_α, "F" is H_β. The non-Fraunhofer line near "D" (Na I D₁, Na I D₂) by which Lockyer proposed a new element "helios" as He I D₁. The occasional "less refrangible" (redward) line near He I 6678 Å.

13

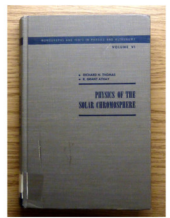
SOLAR FLASH SPECTRUM



- chromosphere naming → definition (Lockyer 1868 outside eclipse)
 - strong: H_β Balmer line, He I D, Ca II H&K
 - weaker: Mg I b, Na I D, Sr I B II
- chromosphere research → flash spectrometry
 - Merrill thesis → 1880-1888 Compt. Rend. 100, 17... 184 (332pp on ADS)
 - Thomas & Athay book → 1962 HAO 1961pubs...A (422 pp, not on ADS)
 - Dunn et al. → 1962 HAO 1966pubs...15-2130 (275pp on ADS, RR digitized)
- chromosphere → origins
 - flash spectrum ≠ reversed disk spectrum
 - both hot (He I D) and cool (Na I D₁ & D₂) lines
 - spatial extent exceeds radiative-equilibrium scale height

14

ECLIPSE WISDOM



15

ANNOTATION IN SACRAMENTO PEAK OBSERVATORY LIBRARY COPY

attention reader

See De Jager's comments on this book in 2. *Astrophysik* v. 55: p. 16 (1922)

(rotliche Umgebung!)

16

De Jager's review (1962ZA...55...66T + 1962ZA...55...70W)

Besprechungen

TANAKA, R. N., und B. G. ARAKI: *Physics of the Solar Chromosphere*. X + 412 Seiten. Interscience Publishers, Inc., New York 1961. Geb. \$ 8.50.

Das Titel des Buches verspricht mehr, als der Inhalt gibt. Jeder, der schon einmal durch ein He-Filter oder durch ein Spektrohelioskop die heissere Struktur der Chromosphärenoberfläche gesehen oder das Profil der Sonnenrande beobachtet hat, wird – sobald er den Titel „Physik der Chromosphäre“ liest – an eine Erklärung der Dynamik dieser Gassebene denken. Es wird ein Problem der Schall-, Stoß- und Gravitationswellen und an die Dispersion von deren Energie denken. Vollständig wird er sich freuen, was Autoren von der Größe haben, die Magnetfelder und magnetohydrodynamische Wellen spielen und in welchem Maße von ihnen die verschiedenen Strukturen der ruhigen low-gestörten Gebiete dieser markantesten Teile der Sonne bestimmt werden. Von allem dem wird er aber in diesem Buche nichts finden: Die leitendsten Probleme werden kaum erwähnt, geringfügige dem besprochen, und so weiter... für papage more

Uplrot: the book treats the derivation of a model atmosphere from the spectrograms taken by the 1962 HAO eclipse expedition but ignores the inhomogeneity and dynamics of the chromosphere such as sound, shock, gravity and MHD waves, as well as magnetic fields.

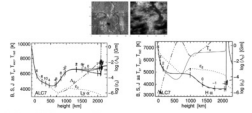
17

CHROMOSPHERE POTPOURRI

- line formation theory
 - flash spectrum @ Harvard, Boulder → Mihalas (1970, 1978): summary
 - static 1D "standard" models: VALSC, micro-Avrett, hydrogen exam
 - none-E: detailed balancing 1D Radyn, 2D Stagger, 3D Bifrost
- chromosphere diagnostics
 - Na I D₁, Mg I b, Ly-He₂ H_α-Ca II 8542 A Ca II H+K Mg II k & Sr II r or He I 6678
- chromospheric & coronal heating ingredients
 - gravity waves
 - acoustic waves
 - Alfvén waves
 - reconnection
- fine structure
 - sketches: Noyes 1979 Gabriel 1976 Rutten 1989 Wedemeyer 2016 Rutten 2016
 - observed and explained: Ca II gran. dynamic fibrils
 - observed but not explained: strand/spicules IRRES/IRFE long H₂ fibrils
 - fibril field alignment for NLFFF: yes partly only at launch?

18

Ly α and H α

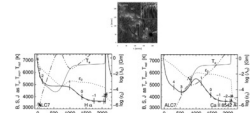


• both: heavy NLTE scatterers with $\beta > 1$
 • Ly α : based in by enormous extinction \rightarrow radiative detailed balance: $S = J$ in shock (vs. NLCT chromospheric collisional thermalization: $\lambda_{\alpha} \approx \lambda_{\gamma}$) in cool gas surrounding hot structures $\lambda_{\alpha} \gg \lambda_{\gamma}$ from Ly α around scattering in post-hot cool gas slow $\beta > 1$ thermalization with $\lambda_{\alpha} \gg \lambda_{\gamma}$ density of hot post

• H α : photos created in granulation scatter: SD across upper photosphere opacity gap and through chromosphere in shock etc. Boltzmann extinction λ_{α} in post-hot cool gas $\lambda_{\alpha} \gg \lambda_{\gamma}$ extinction memory of hot post Ly α source: heating events bright down-broast, cooling contrasts dark from scattering H α source: RBE/RRE heating events, cooling contrasts dark from non-E opacity

28 (info)

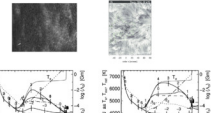
H α and Ca II 8542 Å



• both: heavy NLTE scatterers with $\beta > 1$ sampled at similar $r = 1$ heights
 • both: Saha-Boltzmann of large extinction in shock and NLCT
 • core width: both decrease away from network \rightarrow decreasing temperature
 • H α fibrils extend further, contradicting: Saha Boltzmann extinction sensitivities
 fibril opacity in Ca II 8542 Å instantaneous, in H post-hot non-E?

29 (info)

Ca II H & K and Mg II h & k

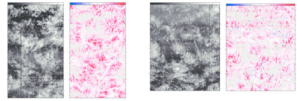


• both: heavy NLTE scatterers with PRD source function splits
 • both: near-Saha Boltzmann extinction everywhere, abundance ratio 18
 • both: absence of non-E sensitivities = instantaneous chromosphere
 • both: slender fibrils emanating from network, in Ca II H & K better at narrower bandwidth, in Mg II k best in λ_{α} peak separation
 slender fibrils = propagating heating events?

30 (info)

CLOSED AND OPEN QUET-SUN INTERNETWORK IN SHV

Peter et al. in preparation

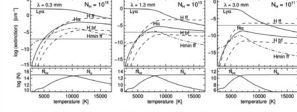


• thin to thick (ratio < 2) line formation
 • Gaussian fits
 • widths in non-thermal widths
 reddish fibrils away from network = recombining H α canopy?
 roundish coronal-hole blueshifts in network \rightarrow down-broast heating events?

31 (info)

SAHA-BOLTZMANN HYDROGEN EXTINCTION AT ALMA WAVELENGTHS

Rutten 2017A&A...598A-899 2017SOLIS...327...19 (tutorial)



• LTE extinction: Ly α H α H I continua H I continuum 8542 other lines
 • H α at high T: LTE extinction from ν_{ul} initiated by enclosed Ly α
 • H ionization: $n = 2$ population lived by (actually non-E) Ly α : hydrogen top has additional NLTE-SE balancing between Balmer continuum and Balmer lines
 • Balmer continuum: $T_e = 15200$ K: ionization below, underionization above = de-sloping of these LTE H I H Boltzmann increases around 5250 K pivot
 • $n_{\alpha}^{\alpha} = \lambda_{\alpha}^{\alpha} N_{\alpha} T^{-1/2}$ (RTSA Eq. 2.79) gives steep H I increase between ALMA bands
 • features with non-E post-hot H α extinction have larger to very much larger H I extinction

32 (info)

SOLAR RYDBERG LINES WITH ALMA?

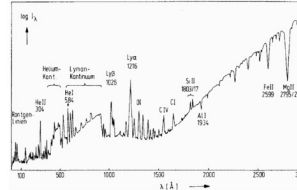
Rutten 2017A&S...327...19

• "linear thermometer"
 - H free-free + H I free-free: $S = B$
 - thick feature: $S = 2T_e - 1$
 - thin feature: cloud contribution $\Delta T_e = T$
 • solar Rydberg lines so far
 - in ppt range Mg I stronger than H I
 - prediction H I = lines $n = 4 - 14$
 - H I λ_{α} is observed at 60p
 • H I Rydberg lines with ALMA?
 - candidate: H I 30 μ in Band 6 (1.3 mm)
 - much stronger than above predictions from large post-hot non-E extinction?
 - if so, underbelly present since Mg I etc are non-E boosted?
 - on disk as $T_e = 11$ emission at steep T_e gradient
 - at limb as ~ 7 extension
 - Zeeman τ and Stokes: super-sensitive chromospheric magnetometer?

33 (info)

SOLAR ULTRAVIOLET SPECTRUM

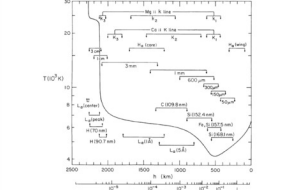
Scheffe & Elsässer, courtesy Karin Muglach



34 (info)

VALBIC MODEL

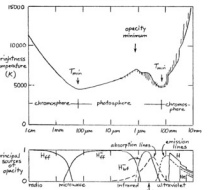
Vernazza, Arrett, Losser 1981ApJS...45-639V



35 (info)

VALBIC SPECTRUM FORMATION

Arrett 1980A&S...138...3A



36 (info)

KURCZ STARS

Kurucz ATLAS program = LTE-RE-HE 1976AJS...40...TK
<https://webphoto.phisoc.nyu.edu/~r1014101/>

- color $M_V = M_V$
- $(\lambda) = 1.8 \mu\text{m}^{-1}$; $\lambda = 555 \text{ nm} = E(BV) \text{ color } V$
- Balmer edge at $\lambda = 1.74 \mu\text{m}^{-1}$
- Paschen edge at $\lambda = 1.22 \mu\text{m}^{-1}$

37

NLTE MASKING

Rutten & Koster 1996AAS...115...104R

- VALIC = LITES steeper decline than HOLMUL = BELLEA
- ultraviolet by scattering causes Fe I underpockets
- strong line to scattering causes Fe I source function deficits
- ultraviolet to pumping causes Fe I source function excesses
- empirical LTE line depth fitting la Höweger:
 - quality deficient Fe I cores suggest too small height
 - scattering Fe I cores suggest too low temperature
 - pumped Fe I cores suggest too high temperature

40

SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten
<https://webphoto.phisoc.nyu.edu/~r1014101/>

thick: cloud modeling corona chromosphere Rydberg per ALMA?

thick: UV line flip VAL3C temperature VAL3C spectrum Kurucz stars

photopheric lines: inversions bright points reversed granulation Na I D1 Mg3 limb emission lines

continua from VAL3C: Avest models versus 3D MHD VAL3C continua VAL3 budget hydrogen budget all

lines from ALG7: model optical spectrum ultraviolet depletion hydrogen strong lines spot forms RSJ/LRI profile plots Na I 8571 Fe I 6302 Mg II k Na I D Ba II 4554 Ca II 8542 A Ca II K Mg II k Li I H α H β Na I 7894 H I 10950 coronal H α Na I D (Mg II)₂ Ly α -H α H α -Ca II 8542 A Ca II K-Mg II k versus FCHHT B ALG7-FALC FALC-FALP ALG7-FALP

active lines: pumping suction

3D-simulated dynamic atmosphere: 1D RADYN 3D Bifrost Bilrost line synthesis

LA-coupleded PSBE atmosphere: non-E H α aureole boosting H α extinction CE-SB EBS spicules-II central ALMA non-E chromosphere?

ERS diagnostic: overview diagnostics

43

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38

MILNE-EDDINGTON APPROXIMATION IN A MURAM SIMULATION

Vlas et al. 2005MNRAS...359...391V

- representative weak-Fe I line with excitation energy 0.3, 3, and 6 eV; transition probability scaled to obtain the same emergent line strength
- dotted curve: line center τ_{50} (normalization)
- solid curve: continuum $\tau_{50} = 1$; modulation represents line-core Doppler brightening. The line vanishes from ionization within a magnetic concentration at $\tau_{50} \approx 0.6$ km
- left panel: increasing Fe I ionization and corresponding τ_{50} increase at larger depth cause very steep gradients in normalized populations $\rightarrow v_{th} \approx v_{ph}$
- other panels: increasing compression from Boltzmann excitation factor
- upshot: Milne-Eddington approximation better at higher excitation

41

FLUX TUBES

- 1970s: Utrecht fluxtube paradigm
 - magnetostatic equilibrium; flaring
 - evacuation; Wilson depression
 - thin tube: hot walls bright; brighter limbbeards
- 1980s: Zürich unsharp 1.5D models
 - McMath-Pierce FTS Fe I Fe II Stokes V'
 - assume magnetostatic geometry
 - spatially-averaged LTE Stokes profile fitting
 - flatter than-RE temperature gradient
- 1990s+: sharp observations and simulations
 - enhanced contrast in G band, strong line wings
 - rapid morphology change, much vorticity
 - near limb faculae: see-through into granules

44

THE MOST SUCCESSFUL INVERSION EVER

Höweger 1967ZA...65...365H [243 class]; Höweger & Müller 1976SoPh...39...194 (over 800 cites)

- PHD thesis: empirical LTE fit of the optical continuum and the depths of 900 lines
- very similar to subsequent 'theoretical' radiative-atom models
- HOLMUL = update (fitting Balmer H lines) preferred in all pre-AGKand abundance determinations because it has no chromosphere - but also no granulation
- [...] Among the problems that need further study are deviations from LTE. Unfortunately, these are easily arising in the computer if important collisional processes are neglected, or if radiative rates are not realistic; in cool stars, collisional excitation for hydrogen atoms is generally neglected. However, in the Sun, hydrogen atoms outnumber the free electrons by a factor of 10000. The UV radiation field is complicated by a vast number of absorption lines...

39

ULTRAVIOLET DEPLETION IN THE ALG7 ATMOSPHERE

- minority atoms: photopheric extinction depletion by ultraviolet bound-free scattering
- ultraviolet bound-free edges produce scattering continua
- $J = 2$ from:
 - τ_{50} gradient defined by radiative equilibrium for the optical
 - τ_{50} steeper in the ultraviolet due to Wien nonlinearity
 - λ operator gives $\tau_{50} > 2$ for steep τ_{50}
 - deep escape from small H I H α extinction
- τ_{50} for electron donors Mg I, Fe I, Si I and Al I imply λ population decrease across photopheric because $\tau_{50} \approx 1$
- their photopheric lines have increasing extinction deficits compared to LTE
- τ_{50} for H I shows similar behavior for the tip of the hydrogen atom starting at $m=2$

42

1970s magnetostatic fluxtubes

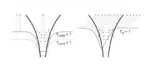
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Kees Zwaan & Hans Rosenberg Zwaan 1976SoPh...60...213Z
 Spruit 1976SoPh...30...209S
 Rutten 1996ASPC...184...181

45

46

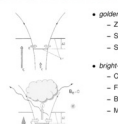
MAGNETIC BRIGHT POINTS



- high-resolution observation
 - Berger et al. 2004AA...428...6138I: G-band bright points as ribbons and flowers
- high-resolution simulation
 - Keller et al. 2004ApJ...607L...59C: continuum faculae simulation
 - Carlsson et al. 2004ApJ...616L...1237C: G-band faculae simulation
- bright points in $H\alpha$
 - DOT $H\alpha$ movie 2004-10-06
 - Leenaars et al. 2006AA...449...1026I: bright points in $H\alpha$
 - Leenaars et al. 2006AA...452L...15C: comparison of bright point diagnostics
- less bright points in "normal" lines
 - Vlas et al. 2009AA...499...2011I: only MnI lines are not locked up by granulation

47

MODELING NETWORK/PLAGE MAGNETISM FOR SPECTRAL IRRADIANCE



- golden age of fluxtube modeling = hole in surface
 - Zwaan – Spruit: idealized magnetostatic fluxtubes
 - Stenflo – Solanki – Keller: unresolved FT3 polynometry
 - Steiner – Keller – Carlsson: realistic MHD simulations
- bright point enhancements = hole deepening
 - FeI G-band, CN 3883 band: dissociation
 - FeI line gaps: ionization
 - Bannister line wings: small collision broadening
 - MnI line cores: large hyperfine broadening
- dark age of ID irradiance modeling = down the rabbit hole
 - "chromospheric cloud" = "photosphere heating"
 - PALF = FALC ledge \Rightarrow SATIRE (ADS N9B H13)
 - 1000Å – 7000Å [SST CHROMAG Ca II κ wing scales]
- coming age of simulation irradiance modeling = of age
 - 1D = 3D abundances ("pre-pool Asplund")
 - first step: MURM with LTE
 - to do: 3D/3D MHD with NLTE, line face, H NSE?

48

SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten
<https://web.archive.org/web/2011/01/rutten101>

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Fe I 6302 Mg I b Na I D Ba II 8542 Ca II 8542 Ca II K Mg I λ Ly- α H α He I 504 He I 5052 coronal line Na I D Mg I b Ly- α H α Ca II 8542 Ca II K-Mg I κ versus FCHHT ALCT-FALC FALC-FALP ALCT-FALP

dotter lines: pumping fraction

Obs-imulated dynamic atmosphere: 1D RADYN 3D Bifrost Bifrost line synthesis

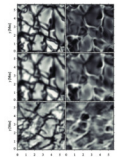
L α -corrected FSI α atmosphere: non-E $H\alpha$ aureole boosting $H\alpha$ extinction
CE-SE EBs spicules- β central ALMA non-E chromosphere?

IRN diagnostics: overview diagnostics

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REVERSED GRANULATION OBSERVATION & SIMULATION

Leenaars & Wedemeyer-Schnitzler 2005AA...431...387I

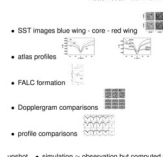


- observation similar to simulation so phenomenon "explained"
- no magnetism since pure hydro simulation (CO 2 BOLD)
- internal gravity waves?

50

OBSERVATION & SIMULATION OF Na I D $_1$, Mg I b, Ca II 8542 Å

Rutten et al. 2011AA...531A...17R



- SST images blue wing - red wing
- FALC formation
- Dopplergram comparisons
- profile comparisons

spot:

- simulation = observation but computed Ca II 8542 Å is much too narrow
- difference in showing reversed granulation is set by reversed intensity-Doppler shift correlation sampled differently by different iron-wing steepness
- Na I D, Dopplergrams are upper-photosphere kilogauss magnetograms

51

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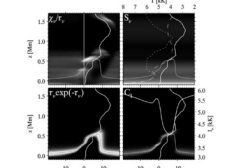
L α -corrected FSI α atmosphere: non-E $H\alpha$ aureole boosting $H\alpha$ extinction
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IRN diagnostics: overview diagnostics

52

Na I D $_1$ IN A MAGNETIC CENTENION

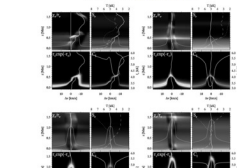
Leenaars et al. 2010ApJ...709...1362I



53

FORMATION BREAKDOWNS Na I D $_1$ & Ca II 8542 Å

Leenaars et al. 2010ApJ...709...1362I



54

STAGGERMULTI2D Na I D $_1$ DOPPLERGRAMS AS UNSIGNED MAGNETOGRAMS

Rutten et al. 2011AA...531A...17R

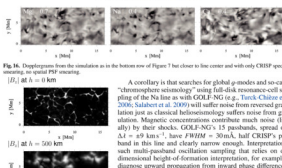
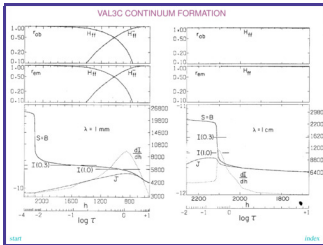


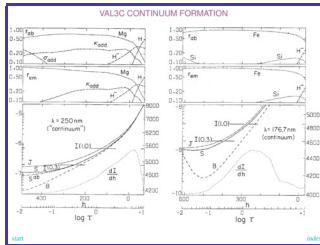
Fig. 16. Dopplergrams from the simulation as in the bottom row of Figure 7 that cluster in the center and with CRISP around centering, no real PV forming.
[Rutten et al. 2011]

A conrarily it was searched for global g -modes and so-called "chromospheric seismology" using full-disk resonance-cell sampling of the Na line as with COKE-NC (e.g., Truscott et al. 2006; Solanki et al. 2007) will suffer noise from reversed granulation just as classical helioseismology suffers noise from granulation. Magnetic concentrations contribute much noise (filterability by their shocks: COKE-NC: 15 pixels/beam, versus over $\Delta \lambda = 49$ km s^{-1} , have FWHM = 30mÅ, half CRISP's resolution in line face and clearly worse enough. Interpretation of such multi-pixelated oscillation sampling that relies on one-dimensional height-of-oscillation interpretation, for example to diagnose internal propagation from mixed-phase diagnostics, is likely to fail since the Dopplergrams signals are better described as shifted or varying spectra in carrying height at which the varying Doppler shifts act as shutters obscuring the inner line wings.

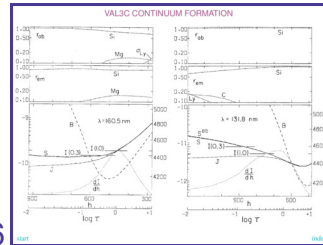
64



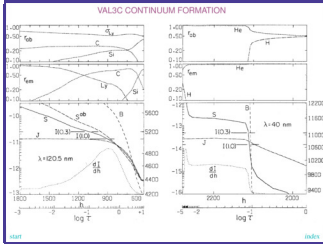
65



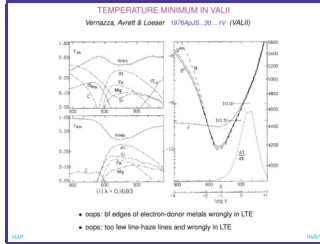
66



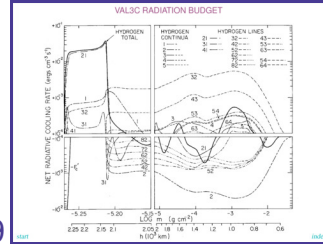
67



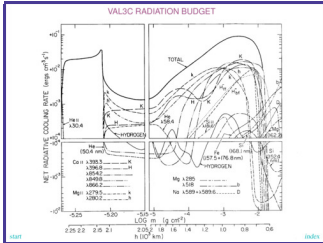
68



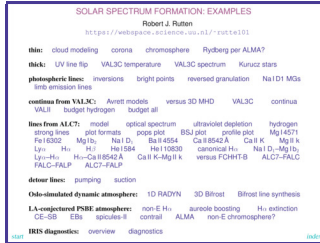
69



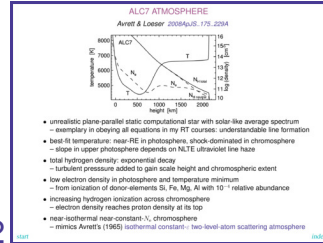
70



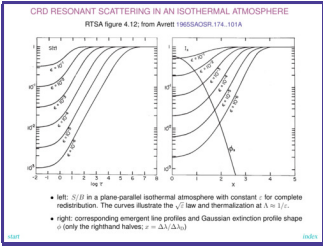
71



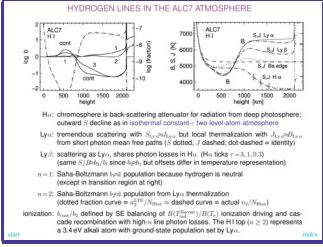
72



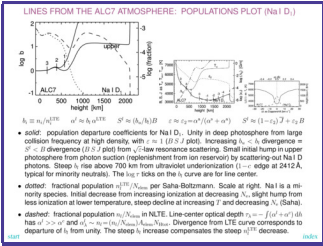
- unrealistic plane parallel static computational star with solar like average spectrum
- elementary in obeying all equations in my PT courses; underradiative line formation
- best fit temperature: near-RE in photosphere, shock dominated in chromosphere
- slope in upper photosphere depends on ALCT ultraviolet line haze
- total hydrogen density: exponential decay
 - turbulent pressure added to gain scale height and chromospheric extent
- low electron density in photosphere and temperature minimum
 - from ionization of donor elements Si, Fe, Mg, Al with 10^{-4} relative abundance
- increasing hydrogen ionization across chromosphere
 - electron density reaches proton density at its top
- near-isothermal near-constant- n_e chromosphere
 - mimics Auer & Loser (1965) isothermal constant- n_e two-level atom scattering atmosphere



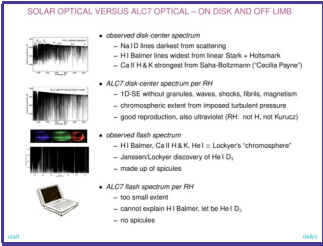
73



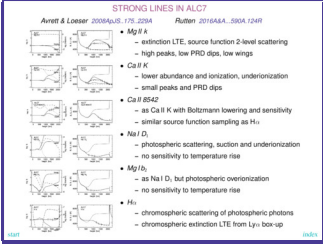
76



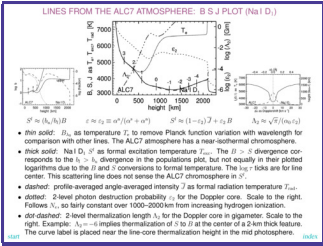
79



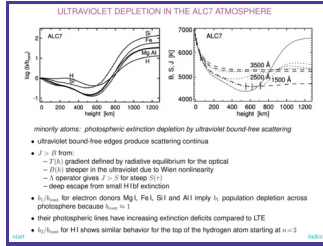
74



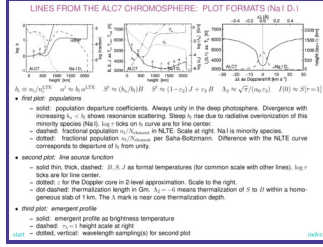
77



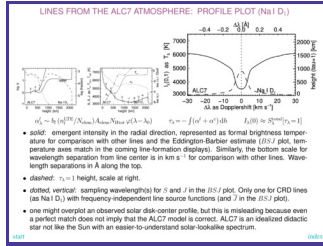
80



75

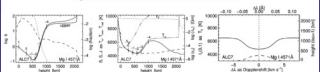


78



81

Mg I 4571 Å FROM THE ALC7 ATMOSPHERE



unique photospheric line with LTE source function

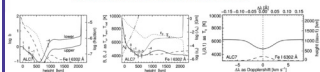
- extinction severely cut at LTE. Deep I_0 dip across the ALC7 photosphere from overionization by deeply absorbing bound-free scattering ultraviolet radiation, including edges of Mg I itself at 2512 and 7621 Å. Corresponding steep I_0 rise above 700 km from ultraviolet underionization where the temperature increases in excess of the ultraviolet radiation temperature.
- this pattern is common to all lines of trivalent materials with ultraviolet ionization wavelengths, including the electron donors (Mg, Fe, Si, Al, Ti).
- source function unusually close to LTE because this is a "forbidden" intersystem line with small $A_{ul} \approx 2.1 \times 10^{-11} s^{-1}$, dominated by collisions ($S \approx 1$) with $n_e \approx 10^{16} cm^{-3}$ to large heights.
- yet fairly strong because its lower level is the Mg I ground state
- usefulness: photospheric thermometer but requires ultraviolet NLTE for optical depth

82

best

best

Fe I 6301.5 Å FROM THE ALC7 ATMOSPHERE



standard polarimetry line

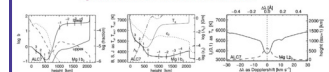
- severe extinction NLTE across the photosphere due to ultraviolet bound-free scattering overionization and affecting the I_0 scaling (in curves)
- minor σ^2 NLTE from resonance scattering in the upper photosphere ($S < 1$) split
- "inversion" codes (numerical best fit iterations) sometimes include σ^2 NLTE but usually not extinction NLTE, ignoring that bound-free scattering with $\sigma^2 \approx \sigma^1$ depends on 2D temperature gradients in deeper layers and makes I_0 (hence σ^1 and σ^2) non-local both in space and wavelength
- problem: the enormous density of NLTE lines ("haze") in the ultraviolet affecting J^1
- usefulness: differential line pair polarimetry with its twin Fe I 6302.5 Å

83

best

best

Mg Ib, 5173 Å FROM THE ALC7 ATMOSPHERE



diagnostic of upper photosphere

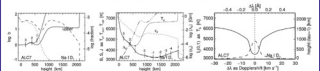
- large NLTE n_e depletion from ultraviolet bound-free scattering across the photosphere overionization and affecting the I_0 scaling (in curves)
- large NLTE n_e increase from ultraviolet scattering offsets Saha decline in chromosphere
- CRD scattering source function with $n \approx 10^{17}$
- similar to Na I D,
- usefulness: as Na I D, but wider core = less asymmetry from reversed granulation

84

best

best

Na I D, 5896 Å FROM THE ALC7 ATMOSPHERE



Na I D lines: darkest lines in optical spectrum = textbook example of two-level scattering

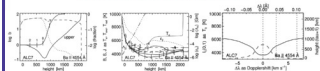
- photon suction offsets ultraviolet overionization across the photosphere
- ultraviolet underionization offsets Saha depletion above 700 km
- 2-level CRD scattering with $n \approx 10^{17}$ and $S < 1$ in the ALC7 chromosphere
- thermalization in mid photosphere: core intensity does not sense ALC7 chromosphere, observed photons are created near the thermalization depth (height of λ_c label), observed intensity variation preferentially encodes temperature variation there
- fast scattering near $n = 1$: Doppler and Stokes inner-wing encoding occurs around 500 km
- usefulness: sharp Na I D Dopplergrams indicate deeply located shocks in flares/bursts

85

best

best

Ba II 4554 Å FROM THE ALC7 ATMOSPHERE



widest PRD line, best velocity diagnostic, good Hare diagnostic

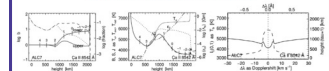
- extinction LTE up to line core formation height thanks to photon losses offsetting overionization (edge at 542.0 visible λ_{ul})
- steep I_0 increase above 800 km from underionization offsets Saha depletion
- resonance line with Zeeman diagram similar to Ca II K, PRD scattering source function with $n \approx 10^{17}$, therefore different monochromatic, and J_1 curves for line center, inner wing, outer wing
- σ^2 split in upper photosphere produces emission wings at the limb (my 1978 eclipse-expansion PRD thesis)
- usefulness: non thermal Doppler sensitivity from large mass ($\lambda_{ul}/\lambda_{obs} = 1.17$) intricate near-limb Ba II profile from hyperfine structure

86

best

best

Ca II 8542 Å FROM THE ALC7 ATMOSPHERE



clearest chromospheric diagnostic in the near infrared

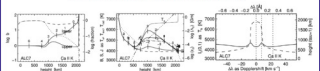
- extinction: I_0 boost from its own photon losses compensates Saha depletion
- CRD scattering source function with $n \approx 10^{17}$
- core formation spans lower ALC7 chromosphere
- best optical line for photospheric magnetometry
- usefulness: at longer wavelengths non-diffraction but less seeing = prime DOST line

87

best

best

Ca II K 8500 Å FROM THE ALC7 ATMOSPHERE



largest extinction in the optical spectrum

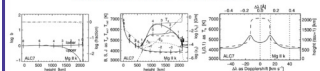
- extinction: successive I_0 boosts from photon losses in infrared triplet and H&K compensation Saha depletion
- PRD scattering source function with $n \approx 10^{17}$ (split between profile center, peaks, dips)
- core formation spans the ALC7 chromosphere
- narrowness of the Doppler core upsets filter imaging so far
- Sunrise-to-Sun best so far: high hopes for SST/CHROMS
- usefulness: best optical chromosphere diagnostic but challenging (bandwidth, S/N)

88

best

best

Mg II k 2796 Å IN THE ALC7 CHROMOSPHERE



clearest PRD line and yet larger extinction than Ca II K

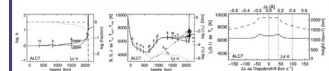
- LTE lower-level population and extinction because of all Mg sites in the Mg II ground state
- PRD scattering source function with $n \approx 10^{17}$ (split between profile center, peaks, dips)
- textbook scattering decline
- similar to Ca II K but with 18% larger abundance and with much darker wings
- usefulness: key diagnostic but requires space platform slitless imaging spectrometry very difficult combine with "triplet" doublet between h & k (recombination indicator)

89

best

best

Ly α 1216 Å IN THE ALC7 CHROMOSPHERE



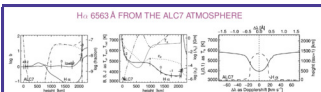
champion: largest extinction and most scattering of all lines

- lower-level population fraction $n \approx 1$: all hydrogen in ground state
- overpopulation of the ground state towards the transition region from photon losses in wings with slight scattering drops $S = J < 1$
- enormous line-center extinction across the ALC7 chromosphere
- PRD scattering source function with $n \approx 10^{17}$ (split between profile center, peaks, dips)
- goes from $n \approx 1$ (inwards $\propto 1/r^2$) with density from Stark wing development (not shown)
- radiation lock-in from large extinction produces radiative balance $n_e(\lambda_{ul} + R_{u,l}) = n_e R_{l,u}$
- local thermalization from small λ_{ul} produces $S \approx 1$ throughout ALC7 chromosphere;
- $\lambda_{ul} \approx \lambda_{obs}$ implies LTE extinction for n_e where k escapes
- usefulness: premier diagnostic but needs space slitless imaging spectrometry difficult

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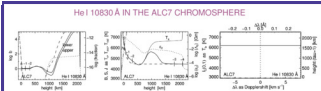
best

best



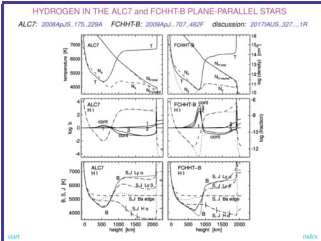
- H I:** extraordinary from high excitation energy, huge element abundance, on top of Ly α
- lower-level fractional population varies as n_e^{-1} (due to 10 eV vs Boltzmann)
 - extinction coefficient near-LTE up to 2000 km by Ly α thermalization
 - S' = two-level scattering below transition region (not 'photobalistic') just like Ca II 8542 Å
 - upper photosphere transparent: core shows fibrils, wings show granulation
 - Edgington-Barber $\tau_{0.5} = 1$ in chromosphere, but photon creation in deep photosphere
 - large J across T min from backscattering: ALC7 chromosphere = scattering attenuator
 - wide line core from small atomic mass in Doppler broadening $\sim \sqrt{2} \Delta T / v_{\text{th}}$
 - extended wings from linear Stark effect in deep photosphere (Hotzmark distribution)
 - usefulness: prominences, flares, Elements, dynamic fibrils, spicules II, ... = non E

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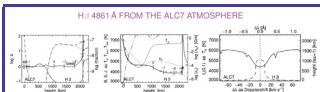


- not of interest in ALC7**
- high excitation line supposedly obtaining visibility from coronal irradiation – not in ALC7
 - minute fractional population from large Boltzmann factor
 - upper-level $i_{0.5}$ set by He I 584 Å plus collisional coupling $2p^2 P \rightarrow 2p^1 P$ with large He I 584 Å down-radiation from transition region into chromosphere
 - total source function is $1 + \tau_{0.5}$ source function until Thomson scattering takes over
 - nothing in the ALC7 spectrum

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- H I:** analog to H α at $S \sim 4$, smaller oscillator strength and in the blue
- same large Boltzmann sensitivity and Ly α lower-level control as H α
 - in comparison with H α (dark with previous):
 - same $i_{0.5}$, steeper $i_{0.1}$ decay
 - similar scattering
 - less steep S' decay from shorter wavelength
 - smaller chromosphere thickness from smaller g'
 - narrower core and $r = 1$ peak
 - RH-computed profile has less deep wings than observed atlas profile (not shown) because RH does not use the Hotzmark distribution for linear Stark broadening by charged particles (less steep wing drop than Voigt function)
 - usefulness: differences against H α

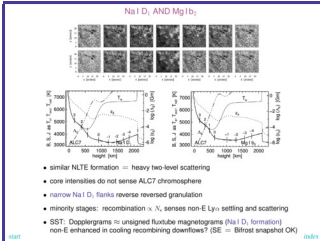
92

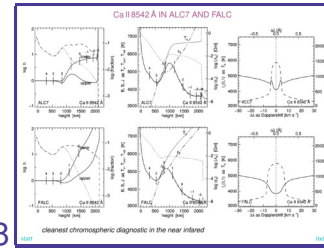
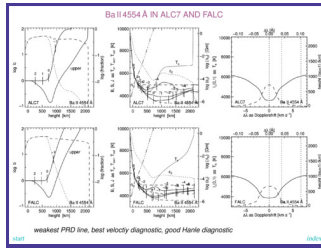
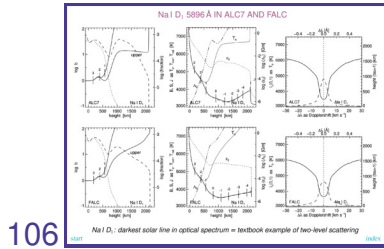
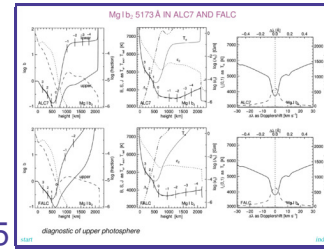
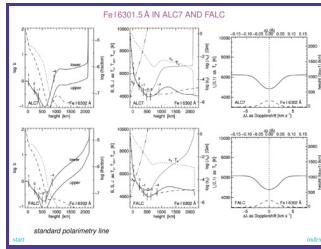
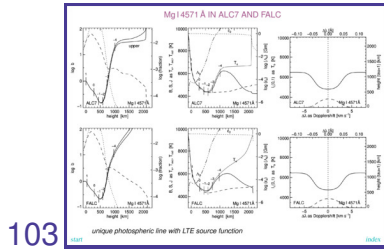
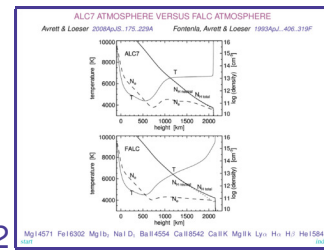
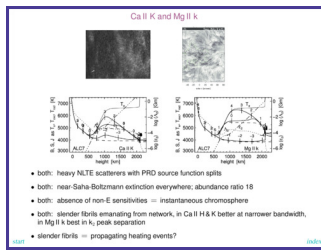
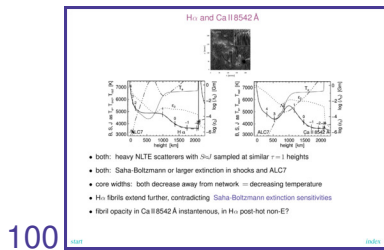


- CRD line source function including detour paths:

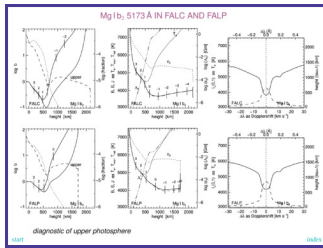
$$S'_e = \frac{J_{e,0} + c_e R_{e,0}(T_e) + c_e R_{e,1}(T_e)}{1 + c_e} = (1 - \tau_{e,0} - \tau_{e,1}) J_{e,0} + c_e R_{e,0}(T_e) + c_e R_{e,1}(T_e)$$
- c_e = upper lower collisional destruction fraction of total extinction = detour path extinction fraction of total extinction
- $\tau_{e,0}$ = $\tau_{e,1}$ as ratio to scattering extinction
- $J_{e,0}$ = profile averaged angle-averaged intensity
- T_e = formal detour excitation temperature, $i_{e,0}(T_e)/i_{e,1}(T_e) = \exp(h\nu_e/kT_e)$
- line source function split (Thomas 1957ApJ...125..260T):
 - 'collision type' (H & K) or 'photobalistic type' (B, Balmer continuum feeding)

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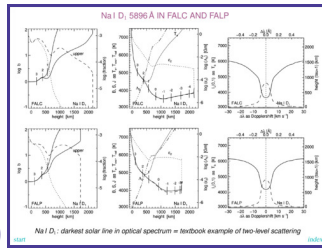




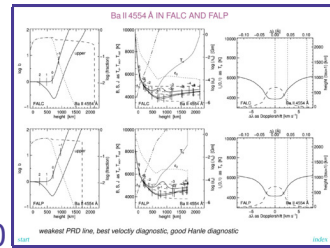
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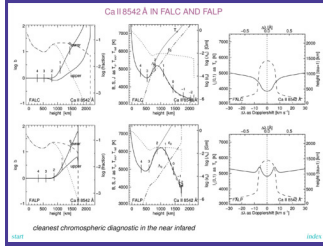
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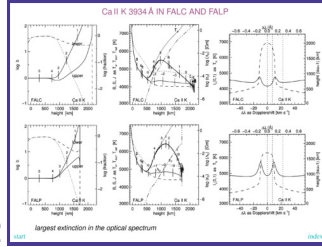
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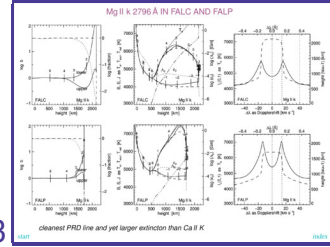
121



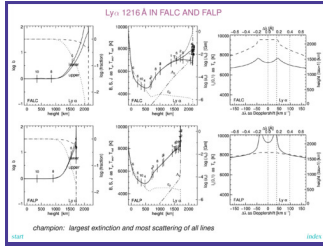
122



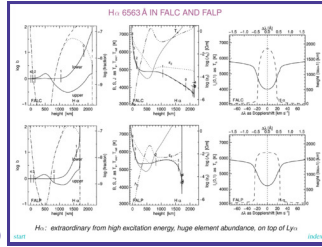
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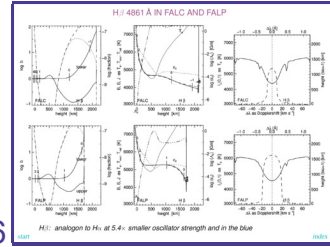
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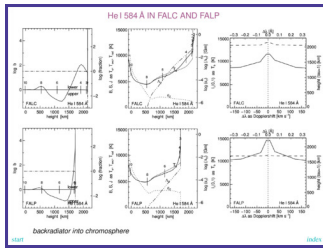
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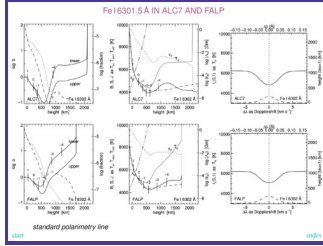
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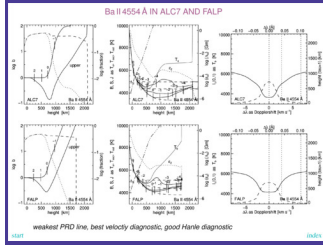
127



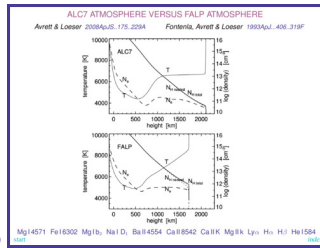
130



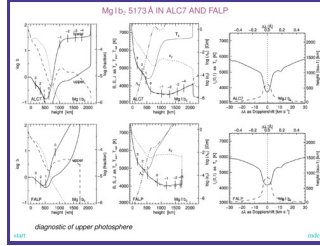
133



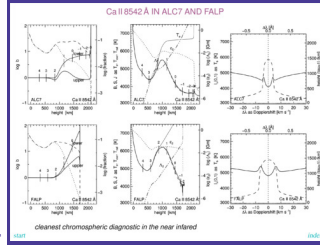
128



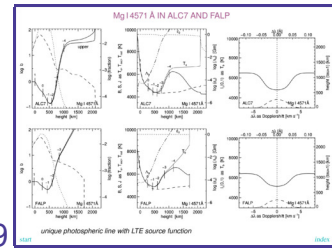
131



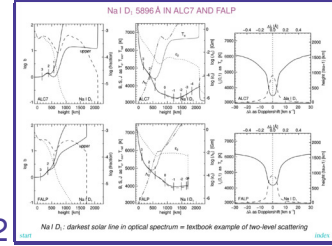
134



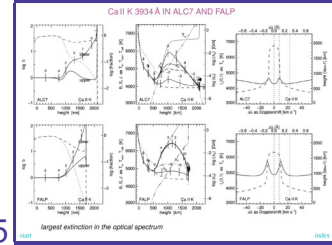
129



132

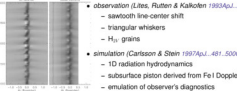


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INTERNETWORK H₃ — ACOUSTIC SHOCKS

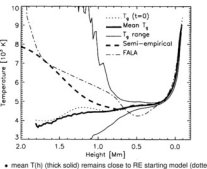
- Ca II K₁ grana (Ruten & Ulmerbrock 1995ApJ...134...159)
 - extended and correlated literature (600 references)
 - most likely non-magnetic phenomenon
 - most likely acoustic shocks
 - wave interference reminiscent of "diapirs"
- observation (Lites, Ruten & Kalkofen 1993ApJ...414...348J)
 - sawtooth line-center shift
 - transverse velocities
 - H₃ grana
- simulation (Carlson & Stein 1997ApJ...481...500C)
 - 1D radiation hydrodynamics
 - subsurface convection from FeI Doppler
 - simulation of observer's diagnostics
- analysis
 - source function breakdown
 - dynamical chromosphere



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SHOCK-RIDDEN COOL LOWER CHROMOSPHERE

Carlson & Stein 1995ApJ...440L...29C



- mean T_{th} (thick solid) remains close to RE starting model (dotted)
- bandwidth of fluctuations (thin solid) varies large above 1000 km
- fit of the mean ultraviolet intensities needs a temperature rise (dashed)

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BIFROST

- heritage
 - Nordlund & Stein 3D HD — granulation
 - Carlson & Stein 1D HD RADYN — Ca II H₃ shocks
 - Nordlund et al. 3D MHD Stagger — MGS, internetwork
- code
 - Gudkosen et al. 2011AA...531A1545 Bifrost description
 - Carlson & Lennarts 2012AA...539A...39C coding - heating approximations
 - Lennarts et al. 2012AA...543A106L fast range-dependent PRD
 - Martinez-Sykora et al. 2012ApJ...773...161M ambipolar diffusion
 - Perez et al. 2013AA...556A119P 3D simulation better than standard 1D models
 - Orlun et al. 2013ApJ...146...700 non-E 3D solver
 - Gidding et al. 2014ApJ...794...300 non-E H₃ ionization
 - Carlson et al. 2014AA...569A...4C publicly available snapshot
 - Shafranovskii & Lennarts 2014AA...570A...46F PRD in 3D simulations
 - Martinez-Sykora et al. 2015ApJ...817...394 3D C2500 tomography
 - Lennarts 2015AA...60506666 tracer particles — Langrangian flow lines
- warnings
 - no Iy — RT no. N₃ boosting from Iy₃ surround scattering around hot structures
 - 3D RT may be needed (MALTRO of Lennarts & Carlson 2016ApJ...815...873)
 - beyond columnwise (RH 3D of Perez & Ulmerbrock 2015AA...174A...3F)
 - non-RT may be needed beyond snapshot wave SE, especially N. H₃

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CLAPTOSPHERE

Ruten 1995ApJ...L151R "The internetwork chromosphere is inherently a claptosphere"

"The extensive literature on the Ca II H₃ grana and related cell-interior phenomena leads us to the conclusion that bright cell areas are of hydro-magnetic origin. Due to conditions that are present all over the solar surface but which produce grana only at places and moments set by the pattern interference of waves oscillating in the K layer and the evanescent wave trains of the μ-mode oscillation deeper down. They remind us of what is called "diapirs" on sea charts for areas where wave interference produces waterpuffs on the ocean (Dowd 1981)"

Ruten & Ulmerbrock 1995ApJ...134...159

"When the crests of such waves coincide, their amplitudes combine, creating high standing waves, much stronger than traveling waves. This phenomenon is called "diapirs". Of the northern tip of New Zealand, where major wave patterns collide in deep water, diapirs is regularly seen. The prevailing waves formed here have so much vertical power that they can throw a laden kayak clear out of the water."

Dowd 1981 (not on ADS)

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SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten
<https://webpage.colledd.edu/rlr1/rutten101>

thin: code modeling corona chromosphere Rytberg per ALMA2

thick: UV line fit VALSC temperature VALSC spectrum Kurucz stars

photospheric lines: inversions bright points reversed granulation Na I D1 MGS 816 emission lines

continua from VALSC: Arctis models versus 3D MHD VALSC continua
VALB budget hydrogen budget all

lines from ALCT: model optical spectrum ultraviolet depletion hydrogen strong lines granularities non-PRD 850 grana ambipolar diffusion Mg I 4781 Fe I 6302 Mg II b Na I D Ba II 8542 Ca II 8542 A Ca II K Mg II h Ly_α H_α H_β He I 5844 He I 6680 coronal He I Na I D 7670 Ly-He H₃-Ca II 8542 A Ca II K-Mg II h versus FCHRT B ALCT-FALC FALC-FALP ALCT-FALP

detour lines: pumping suction

Ohmic-insulated dynamic atmosphere: 1D RADYN 3D Bifrost Bifrost line synthesis

L₃-corrected FSRB atmosphere: non-E H₃ aureole boosting H₃ extinction CE-S EBS spicules-I code ALMA non-E chromosphere?

IRIS diagnostics: overview diagnostics

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BIFROST ANALYSES 1

Hyatt et al. 2013AA...517A...48H solar-type stars

Martinez-Sykora et al. 2014ApJ...792...44M EUV line asymmetries

Lennarts et al. 2014ApJ...748...136R 3D H₃ formation

Stepán et al. 2015ApJ...798...433 Ly_α H_α

de la Cruz Rodriguez et al. 2015AA...543A...34C Ca II 8542 A inversion test

Orlun et al. 2015ApJ...787...430 non-E in CIV ratios

Martinez-Sykora et al. 2015ApJ...771...66M Ca II H₃ and H₃ from a spicule-I

Lennarts et al. 2015ApJ...772...896 Mg II h k for IRIS I

Lennarts et al. 2015ApJ...772...896 Mg II h k for IRIS II

Perez et al. 2015ApJ...781...143 Mg II h k for IRIS

Hansen & Archontis 2015ApJ...786L...2A reconnecting strong field simulation

Orlun et al. 2015ApJ...802...362 optically thin emission lines

Lennarts et al. 2015ApJ...802...364 H₃ H₃ versus field

Stepán et al. 2015ApJ...803...655 scattering polarization Ly_α

Perez et al. 2015ApJ...806...14F Mg II triplet formation

Carlson et al. 2015ApJ...806...302 Mg II h from pluge

Hansen et al. 2015ApJ...811...506H heating from footpoint tracing

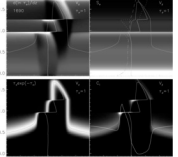
Rathore et al. 2015ApJ...811...506H heating from footpoint tracing

Guerrero et al. 2015ApJ...813...810 quiet Sun heating events

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SHOCK GRAIN DIAGNOSIS

Carlson & Stein 1997ApJ...481...500C

$$L(\mu) = \int_{\tau_{500}}^{\tau_{\infty}} S_{\nu} e^{-\tau_{\nu}} d\tau_{\nu} = \int_{\tau_{500}}^{\tau_{\infty}} S_{\nu} e^{-\tau_{\nu}} \frac{d\tau_{\nu}}{d\tau_{500}} d\tau_{500}$$


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BIFROST SOLAR ANALOG STAR

- Bifrost: a Modular Python/C++ Framework for Development of High-Throughput Data Analysis Pipelines 2017IAA...3200000C
- Vertical crustal motion observed in the BIFROST project 2013Sci...35...4263
- BIFROST project: 3-D crustal deformation rates derived from GPS confirm post-glacial rebound in Fennoscandia 2017EPAS...53...7053
- SPACE 2013-2015 ASSARD Balloon and BIFROST Parabolic Fit: Latest Developments in Hands-On Space Education Projects for Secondary School Students 2015ESAEP726...630C
- BIFROST: conference held in Boston (not on ADS)
- Bifrost: computational star in Cadizcosmo, comparability like the Sun in its spectral characteristics and likewise non-plane-parallel, inconstant, and inconsistent, with the virtue of allowing much spatio-temporal fine structure similar to solar fine structure:
 - granules and Intergranules
 - acoustic box modes similar to solar μ-mode interference patterns
 - non-diagnosed internal gravity waves
 - claptospheric internetwork shocks
 - magnetic reconnection concentrations
 - dynamic fibrils
 - filament reconnection bursts
 - foot locking: spicules-I, long fibrils, μ₃ peak separation S/W in UV bursts, more?
- Bifrost analogs in chromosphere-formation stage: COSOLB MURAM Marcha

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BIFROST ANALYSES 2

Martinez-Sykora et al. 2014ApJ...817...48H non-E Si IV CIV ratios

Gidding et al. 2014ApJ...817...155D non-E He ionization

Nóbrega-Siverio et al. 2014ApJ...822...189 2D H₃ grana

Kato et al. 2014ApJ...827...7K waves from magnetic pumping

de la Cruz Rodriguez et al. 2014ApJ...830...302 Mg II h k & Mg II triplet inversions

Schmitt-DuPoncel 2014ApJ...831...1605 IRIS CIV CIV internetwork versus IRIS

Lennarts et al. 2014AA...556A119P spatial structure in He I 10850

Schmitt & De Pontieu 2014ApJ...831...1585 TR emission from internetwork

Martinez-Sykora et al. 2014ApJ...831L...114 2.5D ambipolar magnetizing fibrils field

Faschauer et al. 2014ApJ...832...38F Ly-He NLPF on Bifrost snapshot

Gidding et al. 2014AA...567A1005 He resonance lines

Kanella & Gudkosen 2014AA...603A...83K detect reconnection sites and current sheets

Hansen et al. 2017AA...603A1030 small-scale heating events

Martinez-Sykora et al. 2017So...3661008I spicules from ambipolar diffusion

Guerrero et al. 2017ApJ...839...229J generation of bombs and nanoflare flares

Nóbrega-Siverio et al. 2017ApJ...850...153N 2D non-E Si IV surges

Roupe van der Voort et al. 2017ApJ...851L...19I plasmoids in UV burst reconnection

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BIFROST ANALYSES 3

Bjergen et al. 2018AA...611A...62B **Ca II H&K insufficient peak separation**
 Liu et al. 2018arXiv180902071 **automatic self detection**
 Høegberg-Sørensen et al. 2018ApJ...858...101 **2D non-E-SW CV images**
 Martínez-Sykora et al. 2018arXiv180504479v1 **ion-neutral 2D spicules II**

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DETAILED BALANCING

Hydrogen ionization/recombination rate
 imitates throughout the solar-like shocked F-dyn atmosphere. The time-scale for settling to equilibrium at the local temperature is very long, 10–150 min. In the chromosphere but much shorter, only anions, in shocks in which hydrogen partially ionizes.
 Carlsson & Stein 2003ApJ...572...626C

net radiative and collisional downward rates (Wien approximation)
 $n_e n_p - n_i n_H = \frac{h\nu}{h\nu - E_{12}} k_{12} n_e n_p - \frac{h\nu}{h\nu - E_{21}} k_{21} n_i n_H$ zero for $S = J$, no heating/cooling
 $n_e n_p - n_i n_H = n_e n_p \left(\frac{h\nu}{h\nu - E_{12}} - \frac{h\nu}{h\nu - E_{21}} \right) = h\nu^2 C_{12}^{\text{net}} \left(\frac{1}{k} - \frac{1}{k'} \right)$ zero for $n_e = n_i$, LTE S'

dipole approximation for atom collisions (van Regemorter 1962)
 $C_{12} = 2M \left(\frac{h\nu}{kT} \right)^{1/2} T^{-1/2} N_e N_i$
 Einstein relation
 $C_{21} = C_{12} \frac{g_1}{g_2} e^{-E_{12}/kT}$
 C_{12} is not very temperature sensitive (only collision will do); C_{21} has Boltzmann sensitivity

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OSLO SIMULATION VERSUS 1D STANDARD MODELS

simulation - state of the art: 2000, β , non-HE, SE populations but NE for H
 Leenarts, Carlsson & Røpke van der Voort 2012ApJ...749...136L
 more complex non-E formation than HE, not only He I 584 acting as Ly α but ionization/recombination not limited to the atom top as for H (smooth Balmer continuum driven from below) but emitting hot and structured irradiation from above
 see Brüst He papers and more to come
 to-do for 2018 = 150 years after Lockyer: explain He I D δ in flash spectrum long dark H α -like He I 304 filter also: neutral optical contacts?

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RECENT DEVELOPMENTS IN PRD LINE SYNTHESIS

- RH code: Ulmerick 2007ApJ...557...389J
 - Rybicki & Hummer: not $N(S)$ but $\langle S \rangle$ iteration; preconditioning
 - overlapping lines
 - 1D, 2D, 3D, spherical versions
- RH 1.5D: Pineda & Ulmerick 2016MNRAS...454A...3P
 - 1.5D = column-by-column
 - massively parallel
 - also molecular lines (but Kurucz lines in LTE)
- angle-dependent redistribution: Leenarts et al. 2010A&A...543A...106L
 - good summary PRD theory and equations
 - non-stationary atmosphere requires angle-dependent PRD
 - hybrid approximation: transform to gas parcel frame, assume angle-averaged PRD ($\mu = \text{angle dependent from deep isotropy}$), transport back
- ionized dilute PRD: Sakurovich & Leenarts 2017A&A...307A...46S
 - hybrid approximation for small memory
 - linear frequency interpolation for speed
 - 250–250–496 grid, 1024 CPUs, 2 days for Mg II k = double
- near 3D PRD with multigrid (Bjergén & Leenarts 2017A&A...388A...118B)

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NON-E HYDROGEN IONIZATION IN 2D MHD SHOCKS

Leenarts et al. 2017A&A...473...625L

- in shocks Ly α has $S(0) = \text{high } T$ (fast balancing) and N_e (10% H ionization)
- retarded collisional balancing in Ly α : n_2 hangs near high shock value $n_2 = n_1^{1/2}$
- significant post-shock $\alpha = 2$ overpopulations versus LTE ('S-B underestimates')
- yet large post-shock overionization from hydrogen ion Balmer balancing
- no Lyman-RT, green arches reflect, no lateral N_e boost from Ly α scattering

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He I and He II

optical He I lines: not in ALCT; no in atmosphere, nor in Moore-Menzel-Huggast
 more complex non-E formation than HE, not only He I 584 acting as Ly α but ionization/recombination not limited to the atom top as for H (smooth Balmer continuum driven from below) but emitting hot and structured irradiation from above
 see Brüst He papers and more to come
 to-do for 2018 = 150 years after Lockyer: explain He I D δ in flash spectrum long dark H α -like He I 304 filter also: neutral optical contacts?

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NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

Carlsson & Stein 2003ApJ...572...626C

- atom top = 3.4 eV alkali: NLTE SE ionization loop
 - driven by photon pumping Balmer continuum, scattering from deep, $n = 5000$ K, smooth
 - closure by photon losses in ∞ lines
- atom bottom actually up to 10 eV: non-E Ly α
 - tremendous scattering from small λ
 - tremendous opacity from huge H abundance
 - small structures already detailed radiative balance
 - non-E: fast settling at high T , slow at low T

- RADYN code: 1D0 hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed subphotospheric piston drives waves up; that shock near $\lambda = 1000$ km
- Ly α scatters in radiative balance and controls $\alpha = 2$. Within shocks $\alpha = J$ saturates to J from radiation lock-in (increased from partial hydrogen ionization) so that $n_2 = n_1$
- collisional Ly α balancing has Boltzmann temperature sensitivity: fast (seconds) in hot gas, slow (minutes) in cool gas, resulting in retardation: post-shock cooling gas maintains the high α shock value at increasing t , during minutes, up to huge overpopulation $n_2 = 10^{11}$
- ionization from $\alpha = 2$: instantaneous statistical equilibrium balance driven by Balmer continuum J and α and closed by cascade recombination with $n_{2, \text{stat}} = 10^{11}$ in hot and $n = 10^{10}$ in cool gas, the latter adding to much larger retained n_2
- between shock hydrogen remains hugely overionized versus SE and LTE predictions

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H α IN BIFROST

1D plane-parallel SE: Rutten & Leenarts 2012A&A...540A...891R

3D non-E MHD: Leenarts et al. 2012ApJ...746...156L

- H α is a pure scattering line with $S = J$ and a deep cavity dip in the upper photosphere
- $\alpha = 2$ scattering across the opacity gap enhances field visibility
- core darkness measures density, core width measures temperature
- cusps: Brüst snapshot, no non-E RT lacking spicules II, long filars

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HYDROGEN AUREOLE BOOSTING IN COOL GAS BESIDE HOT GAS

Forsner et al. 2009ApJ...707...482F, Rutten & Ulmerick 2008A&A...540A...891R, Rutten 2016A&A...388A...148R

FCHRT-B: steep β rises to chromosphere and corona emulate adjacent cool and hot footpoints
 Ly α scattering back-radiation boosts $n_2 = n_1$ and H α extinction $n_2 = n_1 n_2 / n_H$ towards hot feature value (left: dotted $n_2 = n_1$, dashed actual $n_2 = n_1 n_2 / n_H$)
 ionization: also β -boosted, with additional $n_{2, \text{stat}}$ off defined by the Balmer continuum
 Ly α : n_2 between n_1 and $n_{2, \text{stat}}$ and sharing H α photon losses

He: the FCHRT-B chromosphere is a back-scattering attenuator just as in the ALCT atmosphere. The n_2 peak from Ly α irradiation does not affect H α because even with the boost the He ionization in the temperature minimum remains negligible. A hot feature embedded in cooler gas has a similar Ly α scattering aureole enhancing H ionization and H α extinction around it. A temporary hot disturbance leaves such transient-out boost behind it (as when moving).

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H_α EXTINCTION RECIPE

- retarded Ly α balancing:** extinction memory of hot moments
 - $n_e n_H^{0.75}$ in hot shocks from fast Ly α balancing and increased n_e
 - n_e decays slowly, tracking high shock values
 - appears in post-shock cooling clouds until next shock
- Ly α scattering:** auroral boosting
 - Ly α scattering defines $N_{Ly\alpha}$ & $N_{H\alpha}$ with radiative balance
 - hot features in cool gas have Ly α scattering aureoles
 - H I top ($n \geq 2$ including $n_{H\alpha}$) boosted in aureoles
- H α extinction recipe**
 - = find hottest instance nearby (~300km) and in recent past (~minutes)
 - = compute Saha Boltzmann fractional $n = 2$ population then and there
 - = use this extinction value in cooler gas around it and afterwards
 - small hot features leave wider H α marks (as the grin of the Cheshire cat)
 - fast small hot features leave wider H α trails (see contrasts from jet engines)

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SAHA-BOLTZMANN FOR CHROMOSPHERIC LINES

Rutten 2016AAA.356A (2016)

Bachelor exercise "Coclea Pyraea" compares $N_{Ly\alpha}$ and $N_{H\alpha}$ for given $N_{H\alpha}$

7 taught making Saha-Boltzmann graphs to hundreds of students at Utrecht and elsewhere with a 30-minute "Coclea Pyraea" (available on my website). It uses a fictitious and unpronounceable eldorado element called "Schadenbaum" after Utrecht astronomer/astrophysicist Aert Schaeke (1836-1906), who invented it for teaching in the 1970s.

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CORONAL EQUILIBRIUM VERSUS SAHA-BOLTZMANN IONIZATION

Rutten & Rogge van der Voort 2017JAGL...587A (2017)
Coclea Unders versus Coclea Pyraea

- CE**
 - up: collisional excitation/ionization
 - down: radiative deexcitation/recombination
 - NB: electronic recombination
- SB**
 - up: collisional excitation/ionization
 - down: collisional deexcitation/ionization
 - $N_e = 10^{17}$ (other densities)
 - SB: N_e affects ionization, not excitation
 - CE: N_e affects excitation, not ionization
 - smaller N_e : SB peaks steeper and shift left
- hydrogen**
 - long H I tail from no H II (log scales)
 - SB competitive at 10^{-10} others
 - Mg II, C IV, Si IV, S XVI, Fe XVII, Fe XXV
 - wide hump from closed shell (atom config)
 - extra recombination radiation into previous ion

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ELLERMAN BURSTS OVERVIEW

- Mount Wilson:** solar hydrogen bombs
Ellerman 1917ApJ...46..268F 140c: photos history (1920-1937)
 - sudden brightenings in H α wings
 - not in line core, only in Balmer and Ca II lines
 - between spots in complex emerging active regions
- DOT:** pseudo Ellerman bombs
Leontaris et al. 2006A&A...448 (2006), 2006A&A...452L (2006)
Rutten et al. 2013LPJCS...3462007R
 - magnetic concentrations in sunspot moat
 - Spruit hole radiation plus small collisional damping
 - H α blue-wing BPs better than G-band BPs
- SST:** true Ellerman bombs
Watanabe et al. 2017ApJ...736..719W
 - photospheric jets in rapid succession along network
 - situated in H α core by overlying filaments
 - photospheric strong field reconectivity
- interpretation:** reconnection per carbon

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ELLERMAN BOMB VISIBILITIES

Rutten 2016AAA.356A (2016)

- observations**
 - Ellerman bombs: H α mousetails below core fibrils [example] [movie]
 - also bright but different in Ca II 8542 Å [example]
 - also bright but diffuse λ AIA 1700 and 1600 Å [example]
 - not in optical continuum nor Fe I, Na I D, Mg b lines [example]
 - also bright in IRIS C II and Si IV lines [example]
 - not F4E-like alternata with cool fibrils [example] [EUV vs F4E]
- visibility recipes**
 - Balmer in hot and dense areas: Saha Boltzmann extinction
 - cooling alternata: long Balmer memory of large onset extinction
 - H α wings: electron bremsstrahlung (Stark + Holtsmark)
 - transition-region lines: at large N_e extinction closer to SB than CE
 - "cool" blends: surrounding cool clotspheres in started viewing (ABE)
 - diffuse bright light in 1700 Å: surround radiation by EB + boost-free scattering

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ELLERMAN BOMBS PER LTE

Rutten 2016AAA.356A (2016)

- H α**
 - extraordinary hot gas opacity (large abundance, large excitation energy, no H II)
 - extraordinary wide wings at large ionization (Stark + Holtsmark)
 - extraordinary memory to hot past
- ultraviolet Balmer continuum**
 - same hot gas opacity and memory as H α
 - fibrils transparent so no Stark mousetails needed
 - spreading by surrounding photosphere, but scatter through in Mg I and Fe I edges
- other lines**
 - Na I D and Mg b absent above 10000 K
 - Si IV absent below 20000 K but may have hot past memory in cooling gas
 - EB bottoms shielded by adjacent or overlying cooler gas, except H α and Si IV

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STRAWS / SPLICULES II / RBES / RBES

- observations**
 - "braided" DOT Ca II H
 - Rutten 2005A&P...354..276R
 - "spicules II", H α H α Ca II H
 - De Pontieu et al. 2005So...218..194D
 - "rapid blue excursions", SST H α
 - Rogge van der Voort et al. 2010ApJ...705..272R
 - "coronal heating events", H α H α - SDO EUV
 - De Pontieu et al. 2012So...231...36D
 - "transient-heating jet", SST H α - Ca II 8542 Å
 - De Pontieu et al. 2012ApJ...726...12D
 - "rapid red excursions", SST H α
 - Sekse et al. 2013ApJ...769...44S
- simulation:** Martínez-Sykora et al. 2017ApJ...738...38M
 - = better causal spicule-like questionable
 - = no others in simulations so far
 - driver unknown (Pereira et al. 2013ApJ...759...18P)
- upshot:** ubiquitous small magnetic heating events possibly important in
 - = quiet Sun (blue wing) coronal heating
 - = fast solar wind driving
 - = solar wind element segregation

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LONG FIBRILS AS CONTRAILS

Rutten & Rogge van der Voort 2017JAGL...587A (2017)

- H α blue wing:** faint with slender extending dark thread - wide blueshifted core
- visible in IRIS 1400 Å (Si IV), AIA 304, 171, 193 Å, not in Ca II 8542 Å - hot**
- three-four minutes later dark H α core fibrils = non E H recombination**
- large non-E H α opacity in cooling post-hot-disturbance gas**
- H α - fibrils:** not representing cool present but much hotter processor past
- line-lying by precursor H α ionization:** central maps preceding field topology

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SAHA-BOLTZMANN HYDROGEN EXTINCTION AT ALMA WAVELENGTHS

Rutten 2017JAGL...588A (2017)
2017JAGL...587A (2017)

- LTE extinction:** Ly α H α H I continuum H α if continuum 8542 other lines
- H α at high T:** LTE extinction from $n=2$ H α attenuated by extended Ly α
- H α ionization:** $n = 2$ population fixed by (actually non-E) Ly α ; hydrogen top has additional NLTE SE balancing Balmer continuum and Balmer lines
- Balmer continuum $T_{\text{ion}} = 6250$ K:** overionization below, underionization above
 - = deionizing of these LTE H α Boltzmann increases around 5550 K pivot
- $N_{Ly\alpha} \sim N_e N_{H\alpha} T^{-1.1}$ (RTSA Eq. 2.7)** gives steep H α increase between ALMA bands
- features with non-E post-hot H α extinction have large to very much larger H α extinction**

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PREDICTIONS FOR SOLAR ALMA



2017ALM...386A...89R

- ALMA sun mostly covered by long fibrils (unlike simulated sun)
- similar to H α , good dark-dark correspondence, more opaque at longer ALMA wave-lengths, less lateral contrast (no Doppler shifts)
- temperature: above 10 000K in heating events propagating outward from activity; around 7000K in initial fibrils, cooling down to 5000K in long central fibrils (or less)
- heating events best detectable with ALMA (if sufficient resolution)
- if so, darker aureoles vanishing above 15 000K (Ly α scattering)
- small precursors produce 0.2–2.5 arcsec H α and ALMA central widths (Ly α scattering)
- precursors better field ruggers than subsequent central fibrils (if precursors)
- internetwork shocks only in quietest areas, with 4000K cooling clouds (COmosphere)
- no Eklerman bombs (hides fibrils)
- flaring active-region fibrils poke through (if measure reconnection temperature)
- off limb spicules II more opaque than in H α and Ca II H
- coronal rain much more opaque than in H α .

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SOLAR RYDBERG LINES WITH ALMA?


Rutten 2017AUS...327...1R

- "linear thermometer"
 - H α free-free + H I free-free: $S \propto B$
 - thick feature: $S \propto T^2 \propto n^2$
 - thin feature: cloud contribution $\Delta T_e \propto T_e^{-2}$
- solar Rydberg lines so far
 - n_1 jet range Mg I stronger than H I
 - prediction H I λ lines $n = 1 - 35$
 - H I λ n_2 is observed at limb
- H I Rydberg lines with ALMA?
 - candidates: H I 30 μ in Band 6 (1.3 mm)
 - much stronger than above predictions from large post-hot non-E extinction?
 - if so, unambiguously present since Mg I etc are not non-E boosted?
 - on disk as $T^2 \propto n^2$ emission at steep T^2 gradient
 - at limb as T^2 extension
 - Zeeman in J and Stokes: super-sensitive chromospheric magnetometer?

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NON-EQUILIBRIUM CHROMOSPHERE

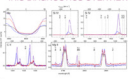
chromosphere popout



- H α chromosphere = past defined by Ly α
 - long fibrils = post-hot cooling clouds
 - long fibril contrast = different histories and Dopplershifts
 - long fibril width = Ly α scattering (0.2–0.5 arcsec)
- Ca II H&K chromosphere = present defined by temperature
 - thin fibrils = horizontally launched heating events
 - thin fibril width = heating event width + scattering halo
 - if corresponding IRIS Si IV, AIA EUV, ALMA mm features?
- H α versus Ly α = past versus present
 - Ly α grains = heating events
 - Ly α short fibrils and comet heads = initial tracks
 - if Ly α , ALMA heating event imaging spectroscopy?
- H α versus Ca II 8542 Å versus He I λ , versus He II λ 304 = idem
 - Ca II instantaneous = short fibrils
 - He I λ , He II 304 = post-hot irradiated cooling gas?
 - if time-delay image correlations

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IRIS DIAGNOSTICS OVERVIEW



- Si IV 1400 Å lines
 - peak ratio 2: feature (not 'lines') optically thin
 - if so: bathym Doppler mapping (e.g., EB bimodal jet)
 - gas temperature: 30kK for CE, 20kK for SB (ALMA at ratio ≈ 1.7)
- Mg II h&k lines
 - enormous SB opacity
 - strong PRD scatterers
 - SB opacity sampling classical chromosphere top to bottom
- Mg II triplet lines
 - bright suggests steep deep temperature rise
 - bright suggests (non-E?) recombination from wide Mg III reservoir
 - Min blend = photospheric gas along line of sight

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IRIS DIAGNOSTICS

- Mg II h&k
 - Leenaarts et al. 2013ApJ...772...896
 - Leenaarts et al. 2013ApJ...772...906
 - Pereira et al. 2013ApJ...778...143
 - Carlsson et al. 2015ApJ...809K...300
- other lines
 - Mg II triplet: Pereira et al. 2015ApJ...806...14P
 - C II doublet: Rathore et al. 2015ApJ...811...80R
 - C II doublet: Rathore et al. 2015ApJ...811...81R
 - C II doublet: Rathore et al. 2015ApJ...814...70R
 - O I 1355.6 Å: Lin et al. 2015ApJ...813...34L

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SOLAR SPECTRUM FORMATION: EXAMPLES

Robert J. Rutten
<https://web.archive.org/web/2016-01-17/rjrt1601>

thin: cloud modeling corona chromosphere Rydberg per ALMA?

thick: UV line flip VALSC temperature VALSC spectrum Kravtsov stars

photospheric flux: inversions bright points reversed granulation Na I D1 MGs
limb emission line

continua from VALSC: Aaret models versus 3D MHD VALSC continua
VALI budget hydrogen budget all

lines from ALCT: model optical spectrum ultraviolet depletion hydrogen
strong lines plot format (pop III) IRIS plot = profile plot
Fe I 6302 Mg II λ Na I D λ Ba II 4554 Ca II 8542 Å Ca II K Mg II k
Ly α H α H β He I 6684 He I 10830 canonical H α He I D λ Mg II λ
Ly α -H α H α -Ca II 8542 Å Ca II K-Mg II k ALCT-FALC
FALC-FALP ALCT-FALP


detour lines: pumping suction

Obs-simulated dynamic atmosphere: 1D RADYN 3D Bifrost 3D Bifrost line synthesis

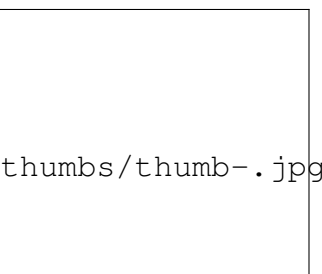
LA-conjectured PSBE atmosphere: non-E H α aureole boosting H α extinction
CE-SB EBs spicules II coronal ALMA non-E chromosphere?

IRIS diagnostics: overview diagnostics

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thumbs/thumb-.jpg



thumbs/thumb-.jpg