SOLAR SPECTRUM FORMATION: EXAMPLES

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The clickers below link to specific pages in this pdf file. It is a snapshot selection from my example displays made on October 4 2016 by retaining only those that concern the ALC7 model atmosphere and non-equilibrium Hα formation. Many are hyperlinked in my publication *"Solar Hα features with hot onsets III. Long fibrils in Lyα and with ALMA"* accepted for Astronomy & Astrophysics on that date (DOI http://dx.doi.org/10.1051/0004-6361/201629238).

My current collection of lecture displays resides at:
http://www.staff.science.uu.nl/~rutte101/Lectures.html

ALC7 model: model hydrogen versus FCHHT-B strong lines

explanation of line plots: pops plot BSJ plot profile plot

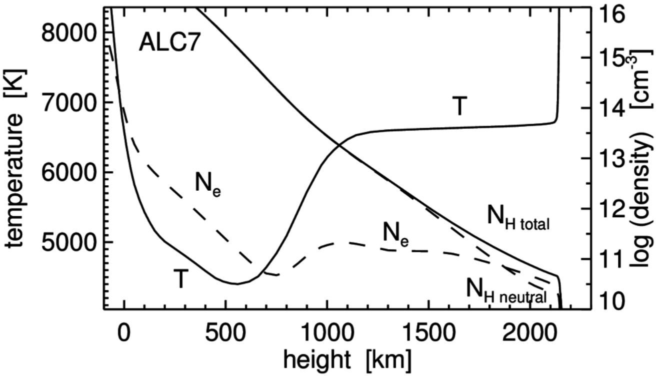
lines from ALC7: Mg I 4571 Fe I 6302 Mg I b$_2$ Na I D$_1$ Ba II 4554 Ca II 8542 Å Ca II K Mg II k Lyα Hα Hα S

dynamic chromosphere: non-E Hα aureole boosting Hα extinction

hidden clickers: title = previous page top-left = start top-right = thumbnails

2 ALC7 ATMOSPHERE

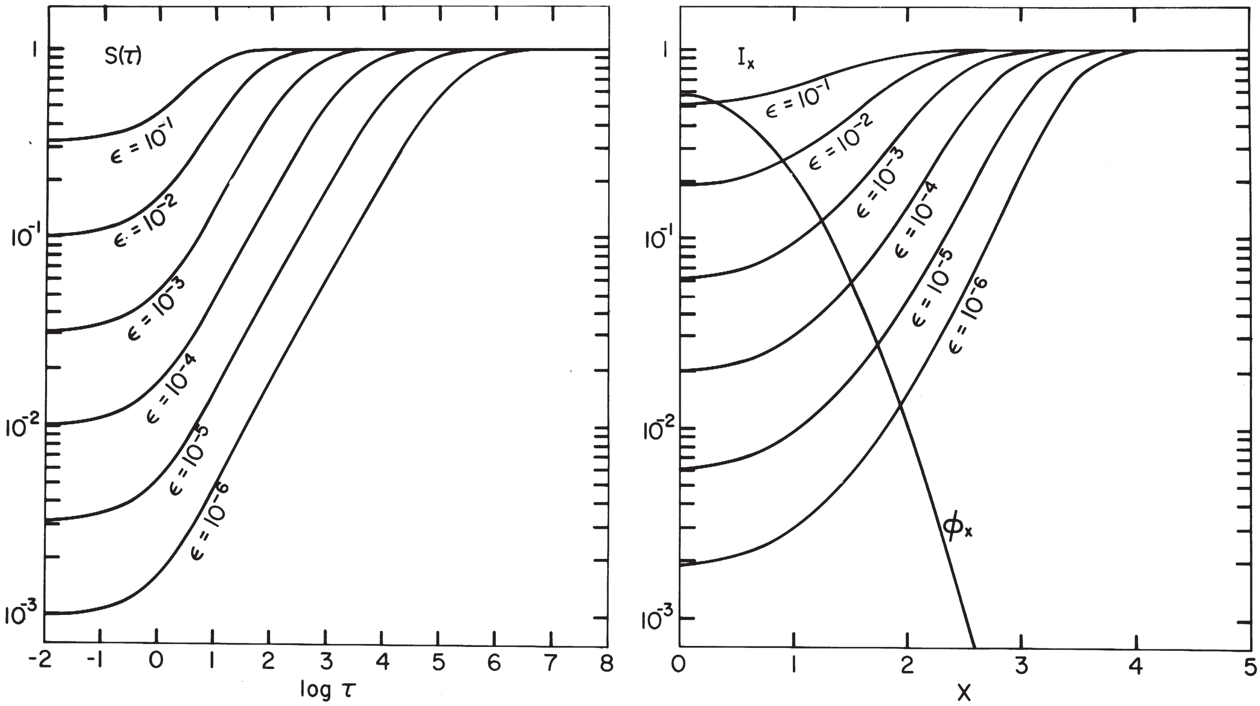
Avrett & Loeser *2008ApJS..175..229A*



- 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 presssure 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-$N_{\rm e}$ chromosphere
  – mimics Avrett's (1965) isothermal constant-ε two-level-atom scattering atmosphere

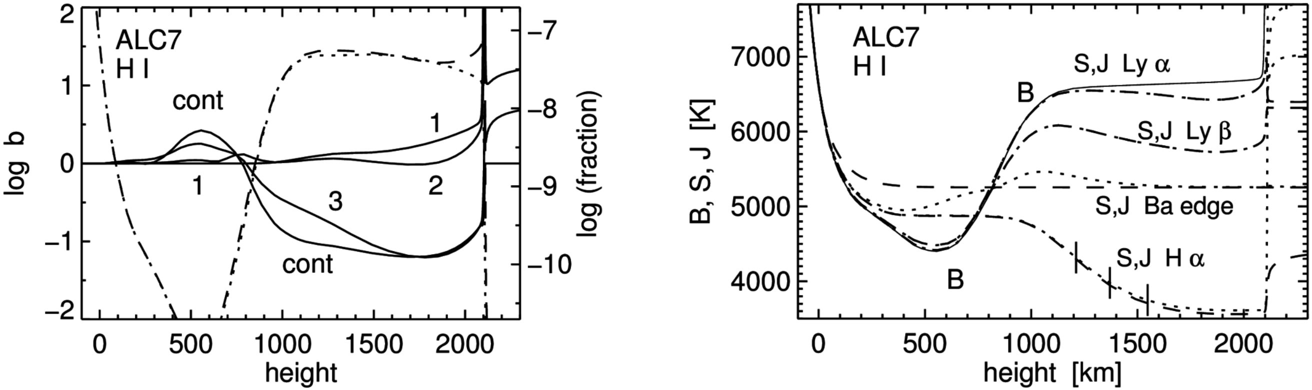
3 CRD RESONANT SCATTERING IN AN ISOTHERMAL ATMOSPHERE

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 $\sqrt{\varepsilon}$ law and thermalization at $\Lambda \approx 1/\varepsilon$.
- right: corresponding emergent line profiles and Gaussian extinction profile shape ϕ (only the righthand halves; $x = \Delta\lambda/\Delta\lambda_{\mathrm{D}}$)

4 HYDROGEN LINES IN THE ALC7 ATMOSPHERE



Hα: chromosphere is back-scattering attenuator for radiation from deep photosphere; outward S decline as in isothermal constant-ε two-level-atom atmosphere

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

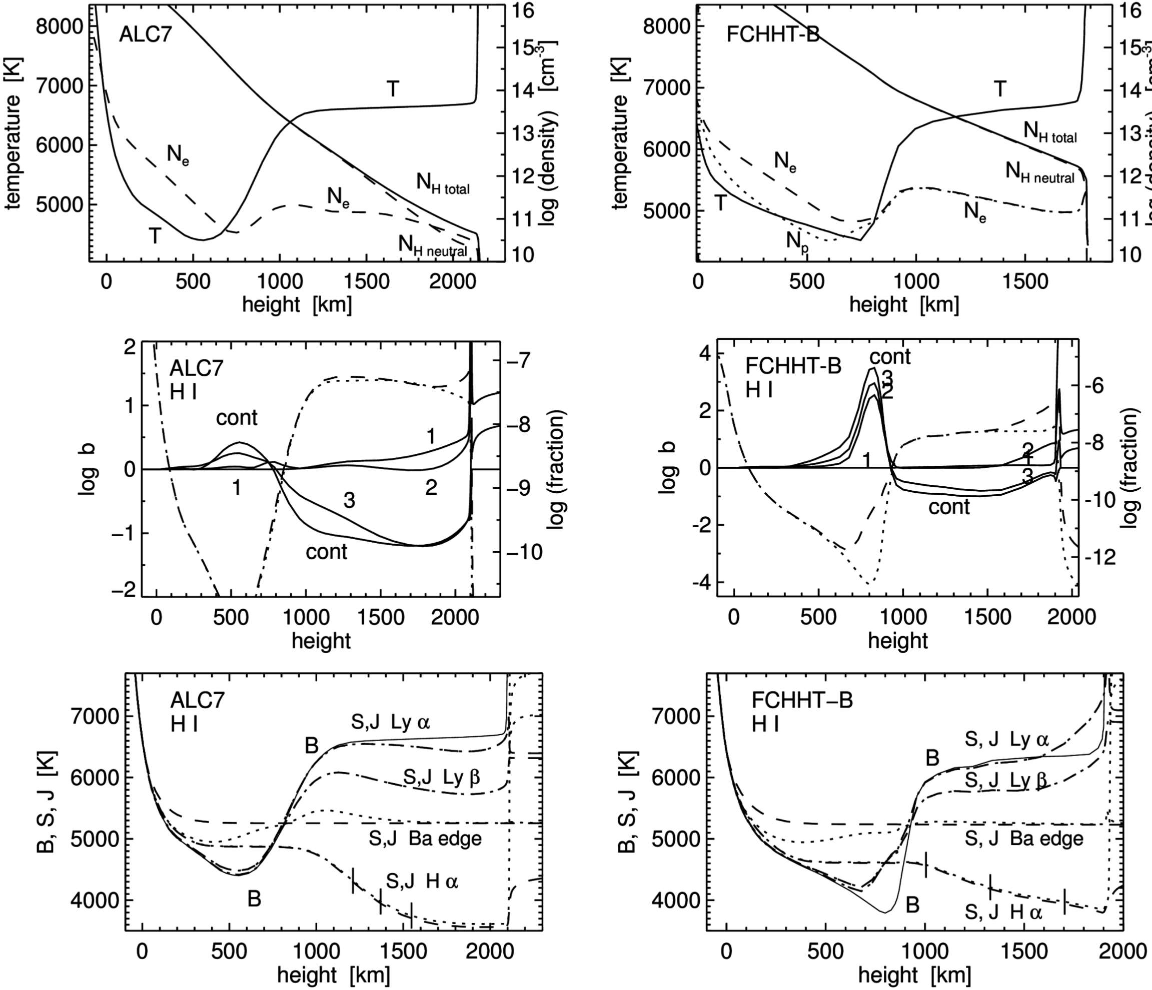
Lyβ: scattering as Lyα, shares photon losses in Hα (Hα ticks $\tau = 3, 1, 0.3$) (same $S/B \approx b_3/b_l$ since $b_2 \approx b_1$ but offsets differ in temperature representation)

$n = 1$: 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 Lyα thermalization (dotted fraction curve = $n_2^{\mathrm{LTE}}/N_{\mathrm{Htot}}$ $\approx$ dashed curve = actual n_2/N_{Htot})

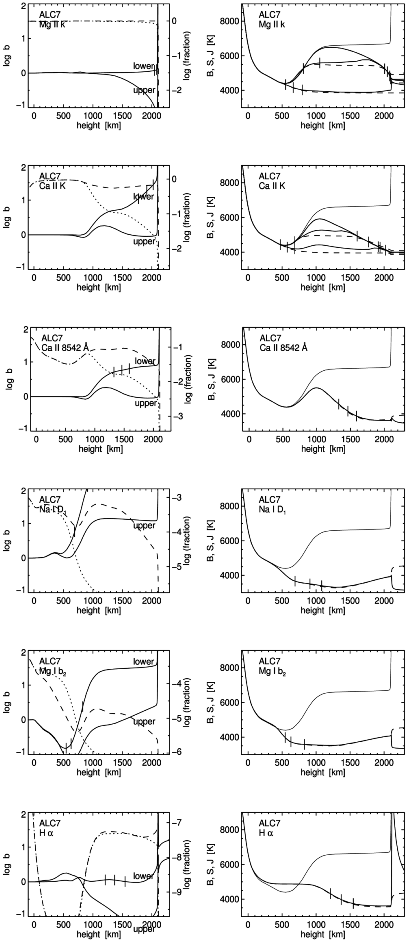
ionization: b_{cont}/b_2 defined by SE balancing of $B(T_{\mathrm{rad}}^{\mathrm{Bacont}})/B(T_{\mathrm{e}})$ ionization driving and recombination driving by Balmer and higher line photon losses. The H I top ($n \geq 2$) represents a 3.4 eV alkali atom with ground-state population set by Lyα.

5 EXPLAIN EVERYTHING – INCLUDING SIMILARITIES AND DIFFERENCES



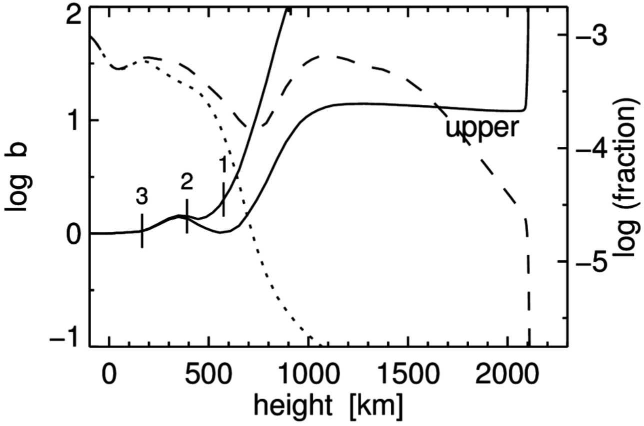
6 STRONG LINES IN ALC7

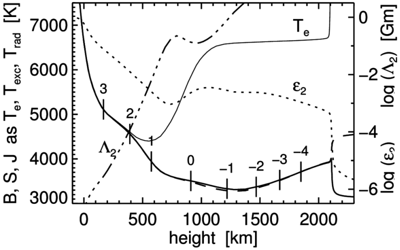
Avrett & Loeser *2008ApJS..175..229A* *Rutten* *2016A&A...590A.124R*

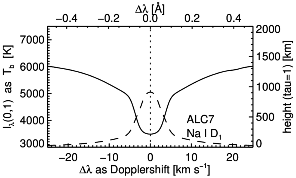


- *Mg II k*
  - extinction LTE, source function 2-level scattering
  - high peaks, low PRD dips, low wings
- *Ca II K*
  - lower abundance and ionization, underionization
  - small peaks and PRD dips
- *Ca II 8542*
  - as Ca II K with Boltzmann lowering and sensitivity
  - similar source function sampling as Hα
- *Na I D$_1$*
  - photospheric scattering, suction and underionization
  - no sensitivity to temperature rise
- *Mg I b$_2$*
  - as Na I D$_1$ but photospheric overionization
  - no sensitivity to temperature rise
- *Hα*
  - chromospheric scattering of photospheric photons
  - chromospheric extinction LTE from Lyα box-up

7 LINES FROM THE ALC7 ATMOSPHERE: POPULATIONS PLOT (Na I D$_1$)



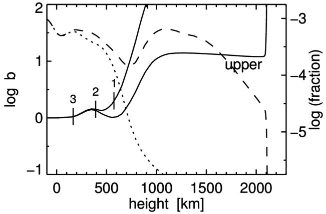


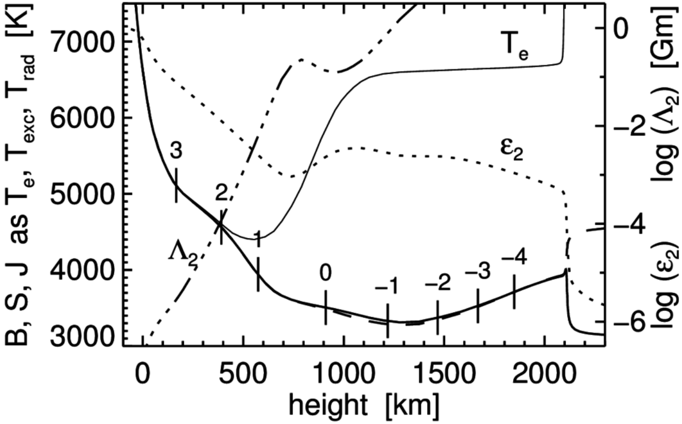


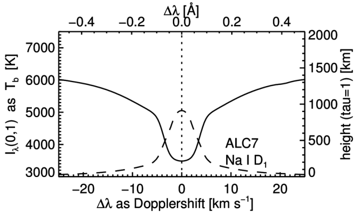
$b_i \equiv n_i/n_i^{\rm LTE}$ $\quad$ $\alpha^l \approx b_l\,\alpha^{\rm LTE}$ $\quad$ $S^l \approx (b_u/b_l)B$ $\quad$ $\varepsilon \approx \varepsilon_2 = \alpha^{\rm a}/(\alpha^{\rm s}+\alpha^{\rm a})$ $\quad$ $S^l \approx (1-\varepsilon_2)\,\overline{J} + \varepsilon_2\,B$

- *solid*: population departure coefficients for Na I D$_1$. 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 $n_l^{\rm LTE}/N_{\rm elem}$ per Saha-Boltzmann. Scale at right. Na I is a minority species. Initial decrease from increasing ionization at decreasing $N_{\rm e}$, slight hump from less ionization at lower temperature, steep decline at increasing T and decreasing $N_{\rm e}$ (Saha).
- *dashed*: fractional population $n_l/N_{\rm elem}$ in NLTE. Line-center optical depth $\tau_\lambda = -\int(\alpha^l+\alpha^c)\,{\rm d}h$ has $\alpha^l >> \alpha^c$ and $\alpha^l_\lambda \sim n_l = (n_l/N_{\rm elem})A_{\rm elem}N_{\rm Htot}$. Divergence from LTE curve corresponds to departure of b_l from unity. The steep b_l increase compensates the steep $n_l^{\rm LTE}$ decrease.

8 LINES FROM THE ALC7 ATMOSPHERE: B S J PLOT (Na I D_1)



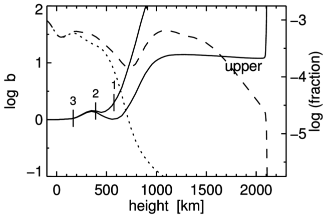


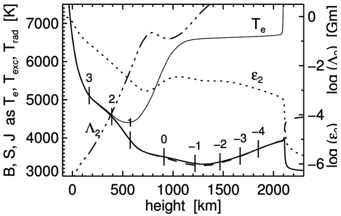


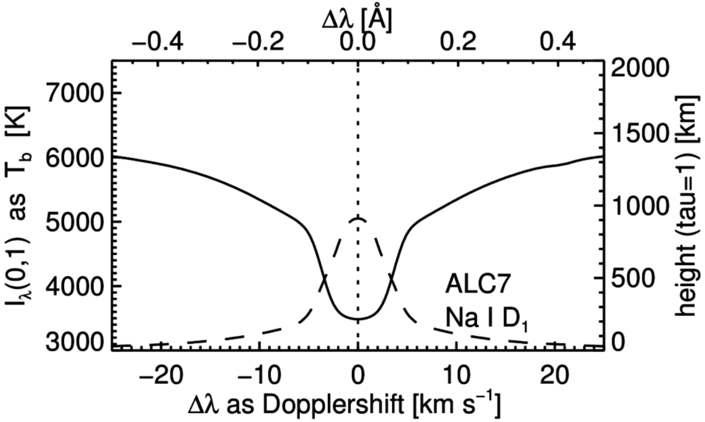
$S^l \approx (b_u/b_l)B$ $\quad\quad$ $\varepsilon \approx \varepsilon_2 \equiv \alpha^{\rm a}/(\alpha^{\rm s}+\alpha^{\rm a})$ $\quad\quad$ $S^l \approx (1-\varepsilon_2)\,\overline{J} + \varepsilon_2\, B$ $\quad\quad$ $\Lambda_2 \approx \sqrt{\pi}/(\alpha_0\, \varepsilon_2)$

- *thin solid*: B_{λ_0} as temperature $T_{\rm e}$ to remove Planck function variation with wavelength for comparison with other lines. The ALC7 atmosphere has a near-isothermal chromosphere.
- *thick solid*: Na I D_1 S^l as formal excitation temperature $T_{\rm exc}$. 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 $\overline{J}$ as formal radiation temperature $T_{\rm rad}$.
- *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.

9 LINES FROM THE ALC7 ATMOSPHERE: PROFILE PLOT (Na I D$_1$)







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

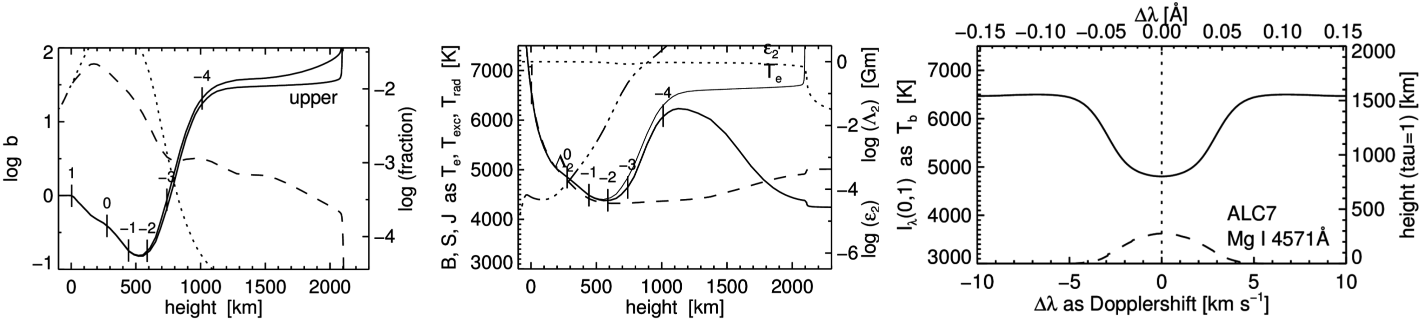
- *solid*: emergent intensity in the radial direction, represented as formal brightness temperature for comparison with other lines and the Eddington-Barbier estimate (BSJ plot, temperature axes match in the coming line-formation displays). Similarly, the bottom scale for wavelength separation from line 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 D$_1$) with frequency-independent line source functions (and $\overline{J}$ 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.

10 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.

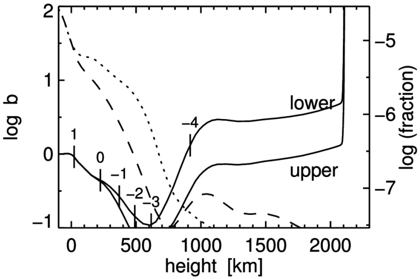
- this pattern is common to all lines of minority neutrals with ultraviolet ionization wavelenghs, including the electron donors (Mg I, Fe I, Si I, Al I).

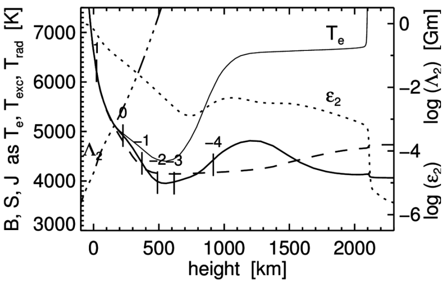
- source function unusually close to LTE because this is a “forbidden” intersystem line with small $A_{ul} = 2.7\,10^2\,\mathrm{s}^{-1}$, dominated by collisions $(\varepsilon \approx 1)$ with $b_u \approx b_l,\; S^l \approx B$ to large heights.

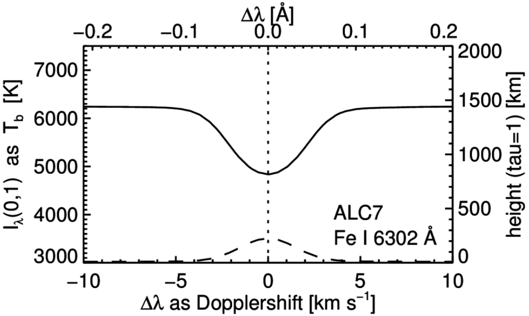
- yet fairly strong because its lower level is the Mg I ground state

- usefulness: photospheric thermometer but requires ultraviolet NLTE for optical depth

11 Fe I 6301.5 Å FROM THE ALC7 ATMOSPHERE



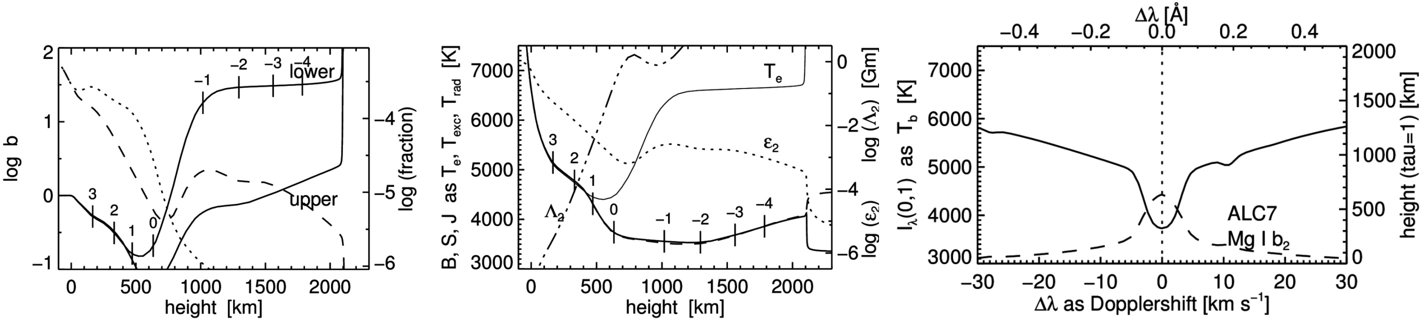




standard polarimetry line

- 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 $S^{\rm UV} \approx \overline{J}^{\rm UV}$ 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 $J^{\rm UV}$
- usefulness: differential line-pair polarimetry with its twin Fe I 6302.5 Å

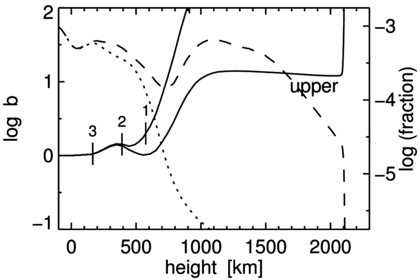
12 Mg I b$_2$ 5173 Å FROM THE ALC7 ATMOSPHERE

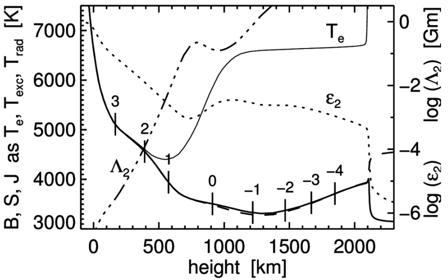


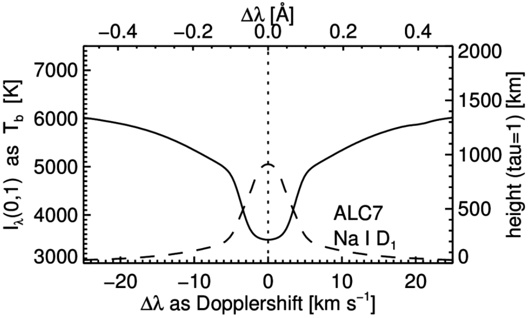
diagnostic of upper photosphere

- 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 $\varepsilon \approx 10^{-3}$
- similar to Na I D$_1$
- usefulness: as Na I D$_1$ but wider core = less asymmetry from reversed granulation

13 Na I D$_1$ 5896 Å FROM THE ALC7 ATMOSPHERE



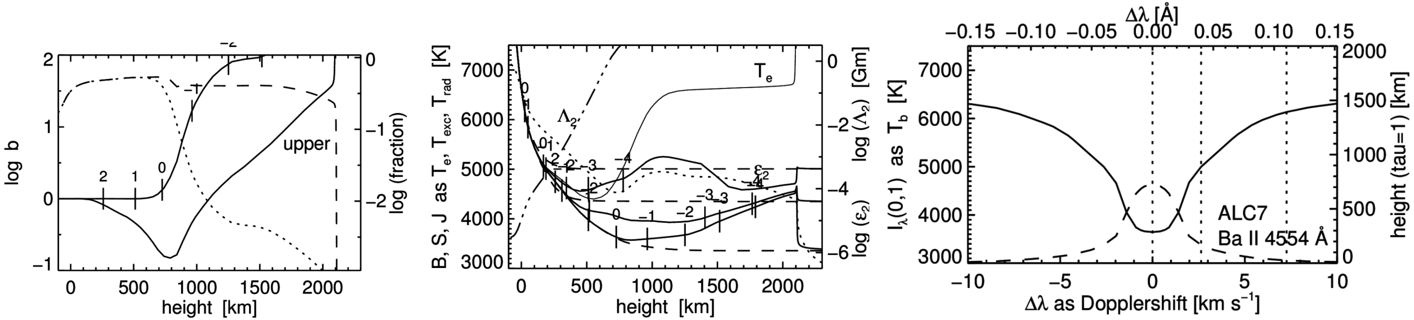




Na I D$_1$: darkest solar line in optical spectrum = textbook example of two-level scattering

- photon suction offsets ultraviolet overionization across the photosphere
- ultraviolet underionization offsets Saha depletion above 700 km
- 2-level CRD scattering with $\varepsilon \approx 10^{-3}$ and $S \approx \overline{J} << B$ 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$_1$ Dopplergrams indicate deeply-located shocks in fluxtubes

14 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 Lyα)

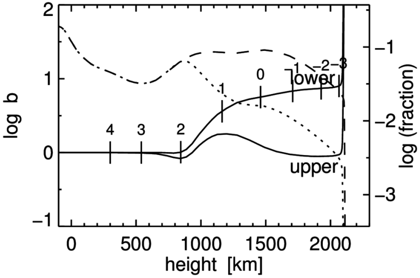
- steep b_l increase above 800 km from underionization offsets Saha depletion

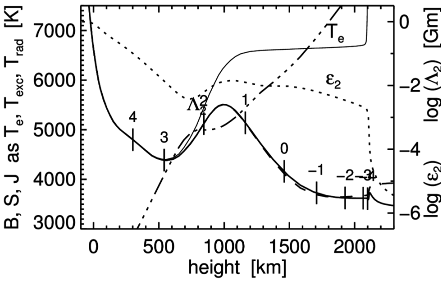
- resonance line with Grotrian diagram similar to Ca II K. PRD scattering source function with $\varepsilon \approx 10^{-4}$, therefore different monochromatic S_λ and J_λ curves for line center, inner wings, outer wings

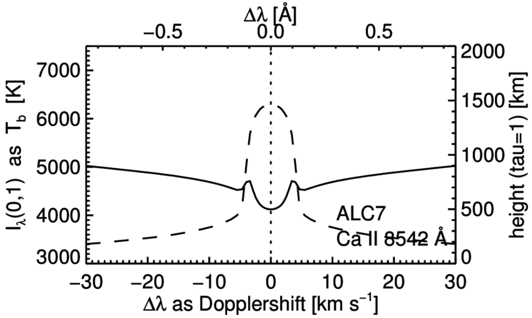
- S^l split in upper photosphere produces emission wings at the limb
  (my 1976 eclipse-expedition PhD thesis)

- usefulness: non-thermal Doppler sensitivity from large mass ($\sqrt{m_{\rm Ba}/m_{\rm H}} = 11.7$)
  intricate near-limb Hanle profile from hyperfine structure

15 Ca II 8542 Å FROM THE ALC7 ATMOSPHERE



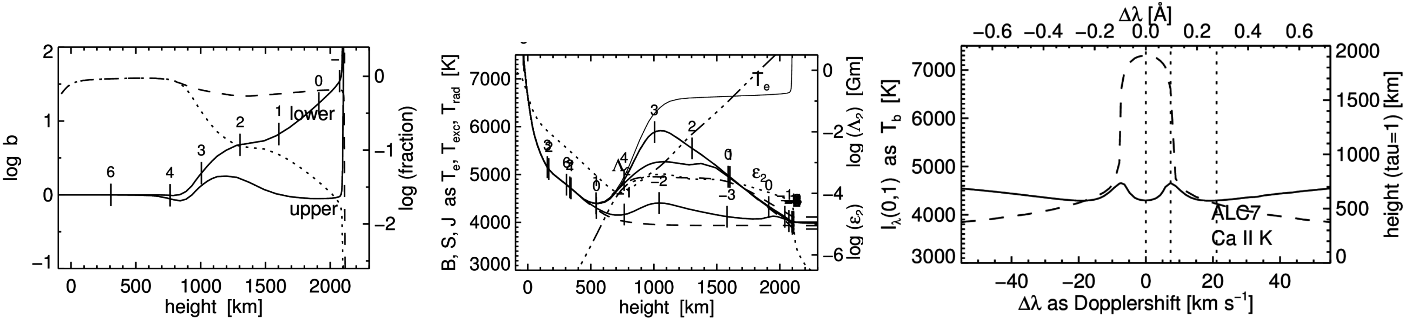




cleanest chromospheric diagnostic in the near infared

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

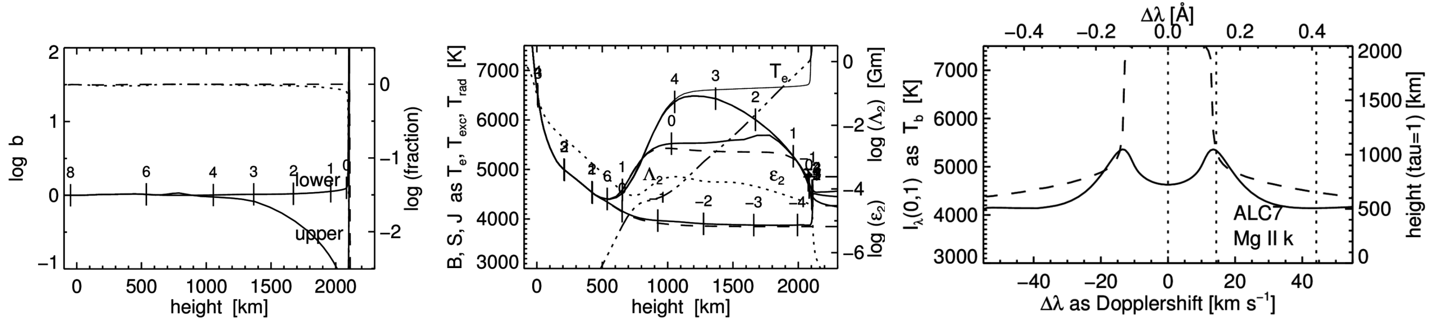
16 Ca II K 3934 Å FROM THE ALC7 ATMOSPHERE



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 $\varepsilon \approx 10^{-4}$ (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)

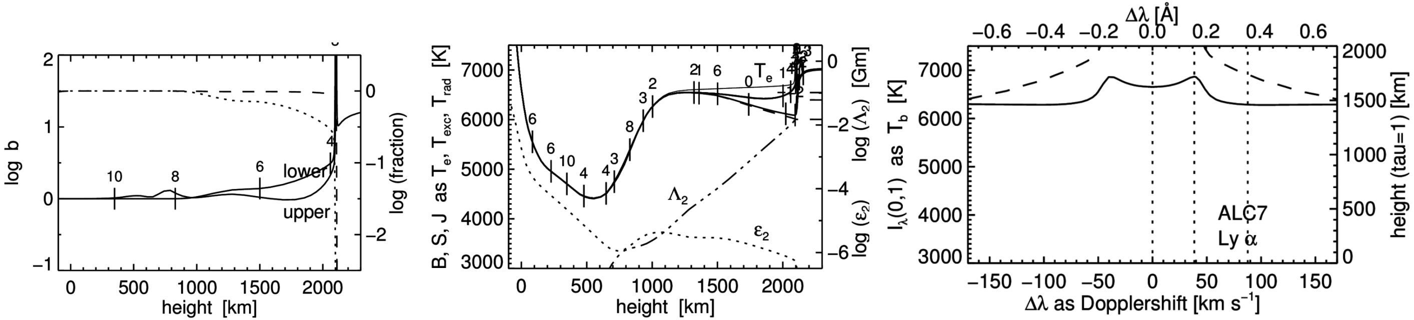
17 Mg II k 2796 Å IN THE ALC7 CHROMOSPHERE



cleanest PRD line and yet larger extincton 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 $\varepsilon \approx 10^{-4}$ (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)

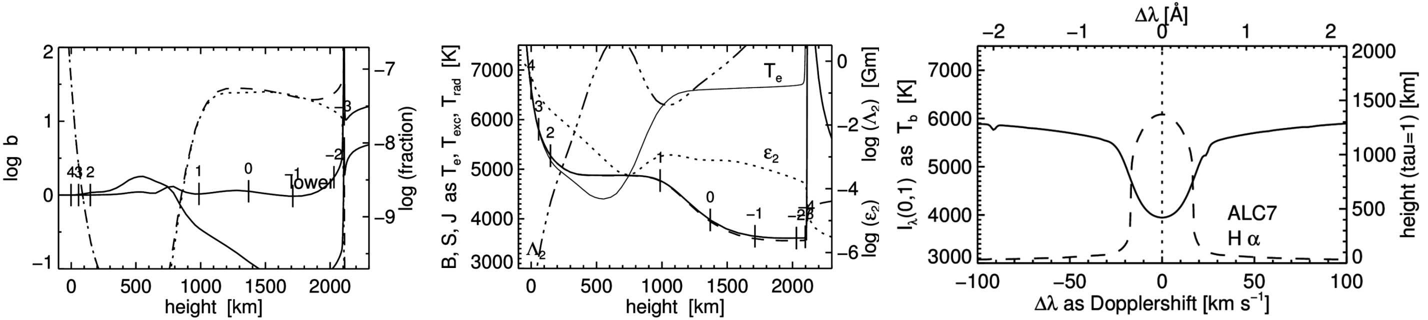
18 Lyα 1216 Å IN THE ALC7 CHROMOSPHERE



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 $\varepsilon \approx 10^{-6}$ (split between profile center, peaks, dips)
- Λ goes from $\propto 1/\varepsilon$ towards $\propto 1/\varepsilon^2$ with density from Stark wing development (not shown)
- radiation lock-in from large extinction produces radiative balance $n_u(A_{ul} + B_{ul}\overline{J}) = n_l B_{lu} \overline{J}$
- local thermalization from small Λ produces $\overline{S} \approx B$ throughout ALC7 chromosphere; $b_u \approx b_l \approx 1$ implies LTE extinction for Hα where it escapes
- usefulness: premier diagnostic but needs space; slitless imaging spectrometry difficult

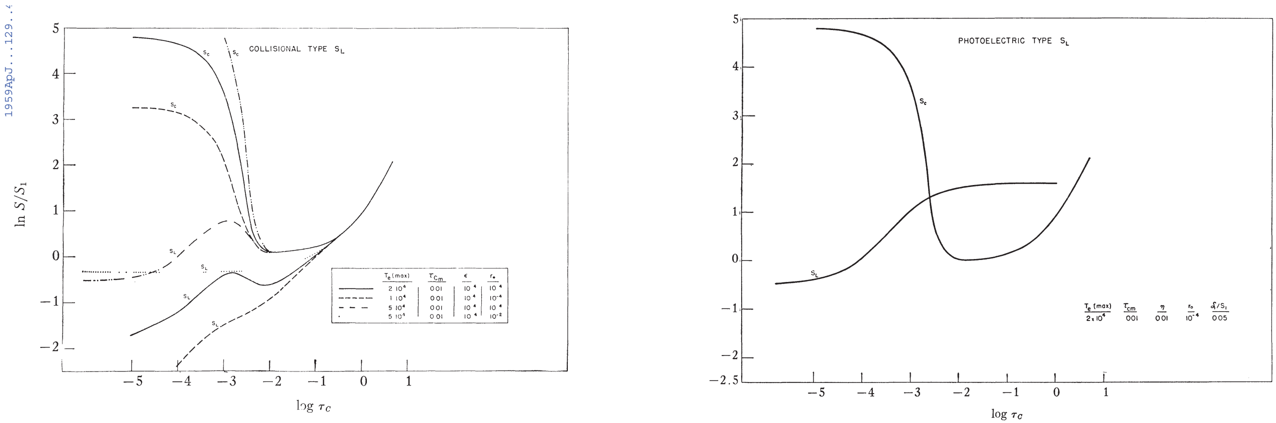
19 Hα 6563 Å FROM THE ALC7 ATMOSPHERE



Hα: extraordinary from high excitation energy, huge element abundance, on top of Lyα

- lower-level fractional population varies $10^{-10} - 10^{-7}$ due to 10 eV in Boltzmann
- extinction coefficient near-LTE up to 2000 km by Lyα thermalization
- S^l $\approx$ two-level scattering below transition region (few detours, not “photoelectric”)
- 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 $\sim \sqrt{2kT/m_{\rm H} + v^2_{\rm micro}}$
- extended wings from linear Stark effect in deep photosphere (Holtsmark distribution)
- usefulness: prominences, flares, Ellermans, dynamic fibrils, spicules-II, . . . = non-E

CANONICAL CHROMOSPHERIC LINE FORMATION



- CRD line source function including detour paths:

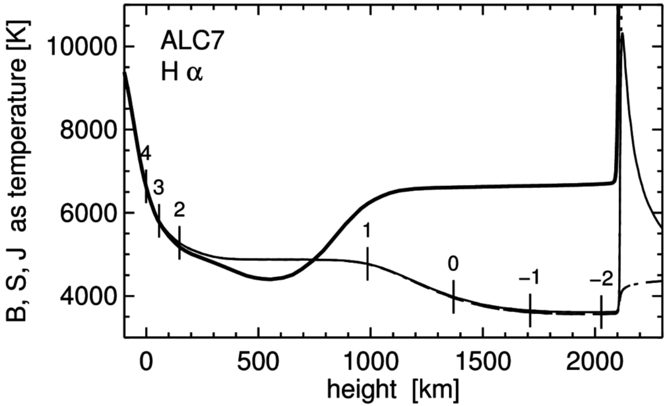
$$
\begin{aligned}
S^l_{\nu_0} &= \frac{\overline{J}_{\nu_0} + \varepsilon'_{\nu_0} B_{\nu_0}(T) + \eta'_{\nu_0} B_{\nu_0}(T_\mathrm{d})}{1 + \varepsilon'_{\nu_0} + \eta'_{\nu_0}} \\
&= (1 - \varepsilon_{\nu_0} - \eta_{\nu_0})\,\overline{J}_{\nu_0} + \varepsilon_{\nu_0} B_{\nu_0}(T) + \eta_{\nu_0} B_{\nu_0}(T_\mathrm{d})
\end{aligned}
$$

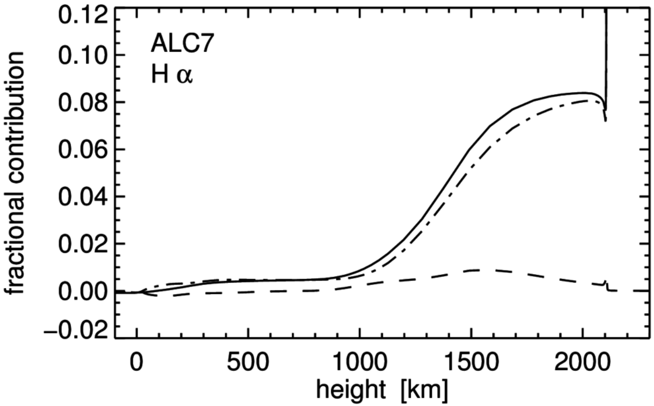
- ε = upper-lower collisional destruction fraction of total extinction
  η = detour-path extinction fraction of total extinction
  ε', η' = idem as ratio to scattering extinction
  $\overline{J}$ = profile-averaged angle-averaged intensity
  T_d = formal detour excitation temperature: $(g_u\, D_{ul})/(g_l\,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

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

21 Hα SOURCE FUNCTION IN THE ALC7 CHROMOSPHERE

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





- $S^l_{\nu_0} = (1-\varepsilon_{\nu_0}-\eta_{\nu_0})\,\overline{J}_{\nu_0} + \varepsilon_{\nu_0} B_{\nu_0}(T) + \eta_{\nu_0} B_{\nu_0}(T_\mathrm{d}) = \overline{J}_{\nu_0} + \varepsilon_{\nu_0}[B_{\nu_0}(T) - \overline{J}_{\nu_0}] + \eta_{\nu_0}[B_{\nu_0}(T_\mathrm{d}) - \overline{J}_{\nu_0}]$

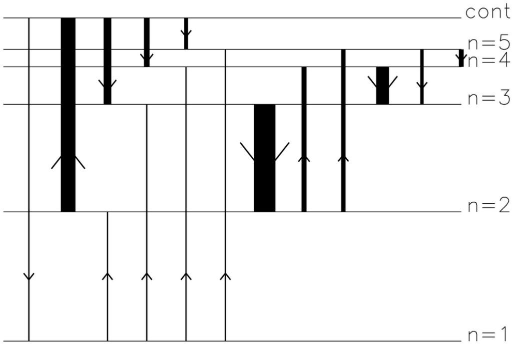
  The detour part $\eta_{\nu_0}[B_{\nu_0}(T_\mathrm{d}) - \overline{J}_{\nu_0}]/S^l_{\nu_0}$ exceeds the collision part $\varepsilon_{\nu_0}[B_{\nu_0}(T) - \overline{J}_{\nu_0}]/S^l_{\nu_0}$. However, their sum $[S^l_{\nu_0} - \overline{J}_{\nu_0}]/S^l_{\nu_0}$ (solid) reaches only a few percent so $S^l_{\nu_0} \approx \overline{J}_{\nu_0}$. Across the ALC7 chromosphere Hα is a scattering line, not "photoelectrically controlled".

- The Hα 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 $\overline{J}_{\nu_0} \approx B_{\nu_0}(T)$. The granulation pattern has larger contrast than the fibril pattern but is washed out in the scattering across the gap.

- The ALC7 Hα core formation is well described by the Eddington-Barbier approximation for an irradiated finite isothermal scattering atmosphere.

22 NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

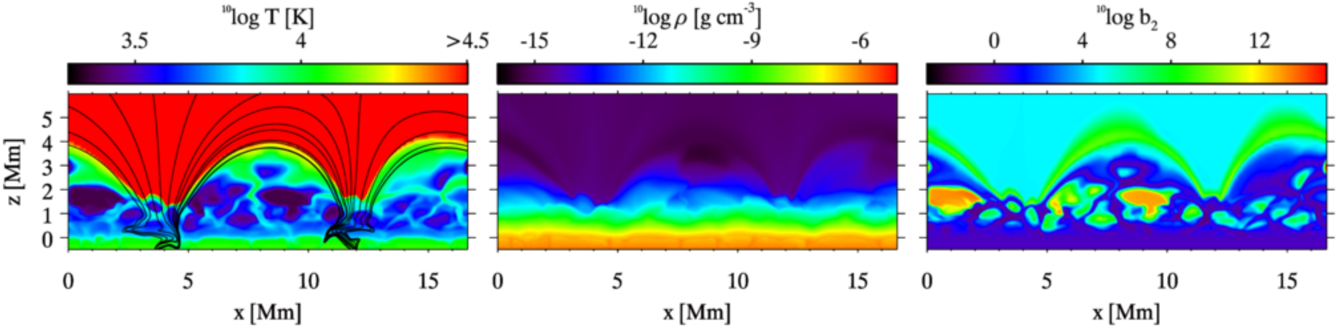
Carlsson & Stein *2002ApJ...572..626C*

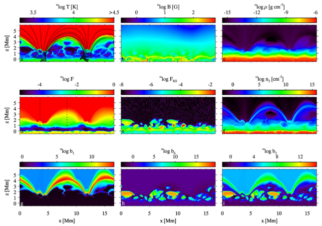


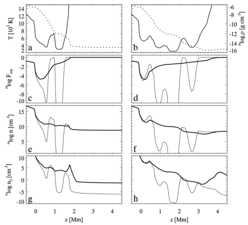
- RADYN code: 1D(t) hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed subphotosphere piston drives acoustic waves up that shock near $h = 1000$ km
- Lyα scatters in radiative balance and controls $n = 2$. Within shocks $S \approx J$ saturates to B from radiation lock-in (increased ε from partial hydrogen ionization) so that $b_2 \approx 1$
- collisional Lyα 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 $n = 2$ in the 3.4 eV alkali-like hydrogen top is an instantaneous statistical-equilibrium balance driven by Balmer continuum $J \neq B$ and photon losses in Balmer and higher lines, with $b_{\rm cont}/b_2 \approx 10^{-1}$ in hot and $\approx 10^{+3}$ in cool gas, adding to the retarded b_2
- between shocks hydrogen remains hugely overionized versus SE and LTE predictions

NON-E HYDROGEN IONIZATION IN 2D MHD SHOCKS

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



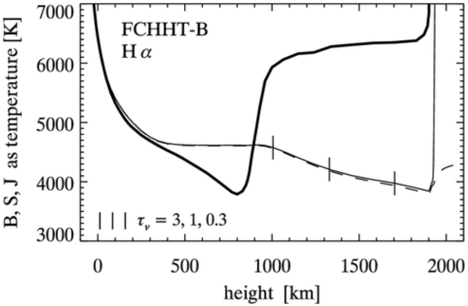


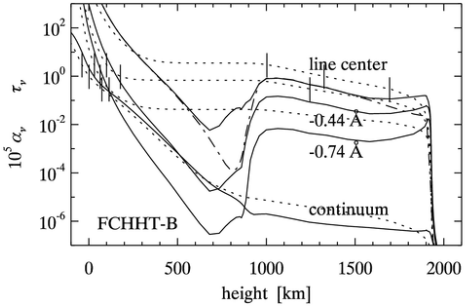


- in shocks Lyα has $S \approx B$ from high T (fast balancing) and N_e (10% H ionization)
- retarded collisional balancing in Lyα: n_2 hangs near high shock value $n_2 \approx n_2^{\rm LTE}$
- gigantic post-shock $n = 2$ overpopulations versus LTE (“S-B underestimates”)
- yet larger post-shock overionization from hydrogen-top Balmer balancing
- approximation: Lyman lines in radiative balance $\Rightarrow$ green arches artifacts

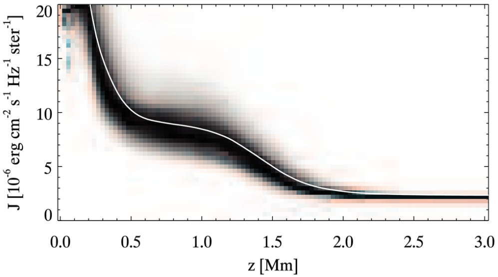
24 Hα IN BIFROST

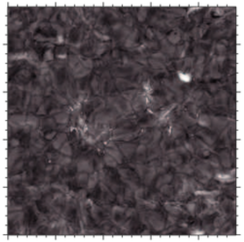
1D plane-parallel: Rutten & Uitenbroek 2012A&A...540A..86R





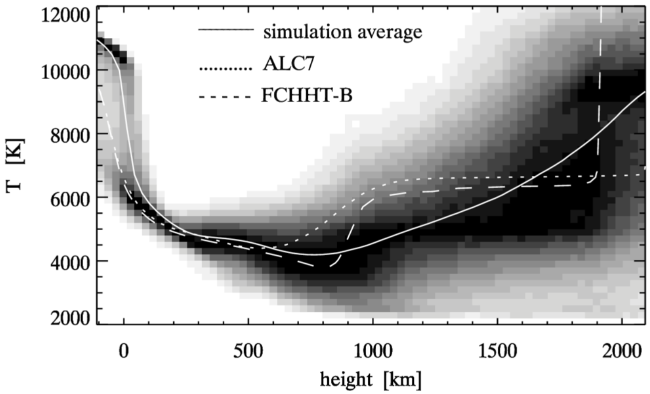
3D non-E MHD snapshot: Leenaarts et al. 2012ApJ...749..136L

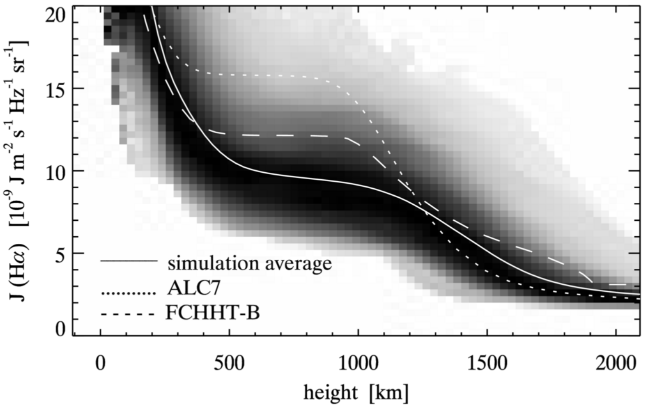




- Hα is a pure scattering line with $S \approx J$ and a deep opacity dip in the upper photosphere
- 3D scattering across the opacity gap enhances fibril visibility
- core darkness measures density, core width measures temperature
- caveat: BIFROST snapshot, no non-E line synthesis $\Rightarrow$ Hα severely underestimated

25 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*

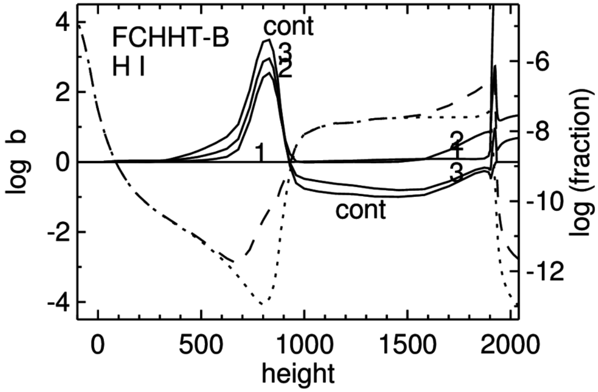
- ALC7 = UV fit: 1D static, no $\vec{B}$, HE + microturbulence, SE populations
  Avrett & Loeser *2008ApJS..175..229A*

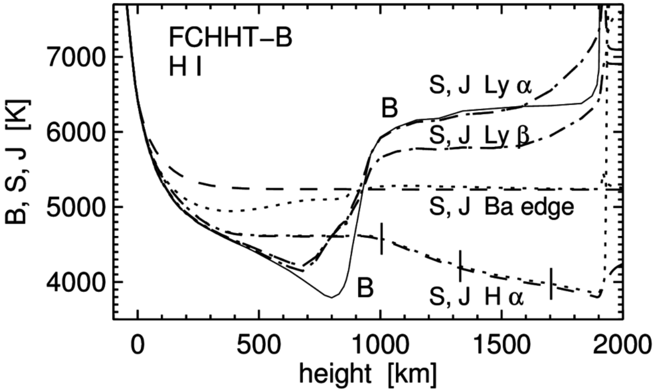
- FCHHT-B = UV fit: 1D static, no $\vec{B}$, HE + imposed acceleration, SE populations
  Fontenla, Curdt, Haberreiter, Harder & Tian *2009ApJ...707..482F*

The T and $J_\nu(\mathrm{H}\alpha)$ 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.

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

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

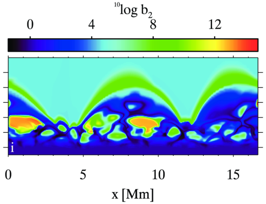
ionization: also b_2-boosted, with additional b_{cont}/b_2 offset defined by the Balmer continuum

Lyβ: b_3 between b_2 and b_{cont} and sharing Hα photon losses

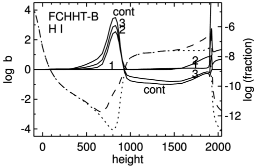
Hα: the FCHHT-B chromosphere is a back-scattering attenuator just as in the ALC7 atmosphere. The b_2 peak from Lyα irradiation does not affect Hα because even with this boost the Hα extinction in the temperature miminum remains negligible.

A hot feature embedded in cooler gas has a similar Lyα scattering aureole enhancing H ionization and Hα extinction around it. A temporary hot disturbance leaves such spread-out boost behind (a wake when moving).

27 Hα EXTINCTION RECIPE



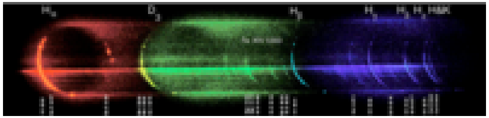
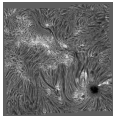
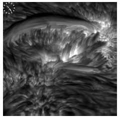
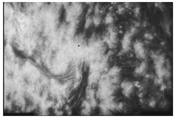
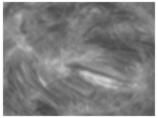
- *retarded Lyα balancing: extinction memory of hot moments*
  - $n_2 \approx n_2^{\rm LTE}$ in hot shocks from fast Lyα balancing and increased ε
  - n_2 decays slowly, tracking high shock values
  - gigantic b_2 in post-shock cooling clouds until next shock



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

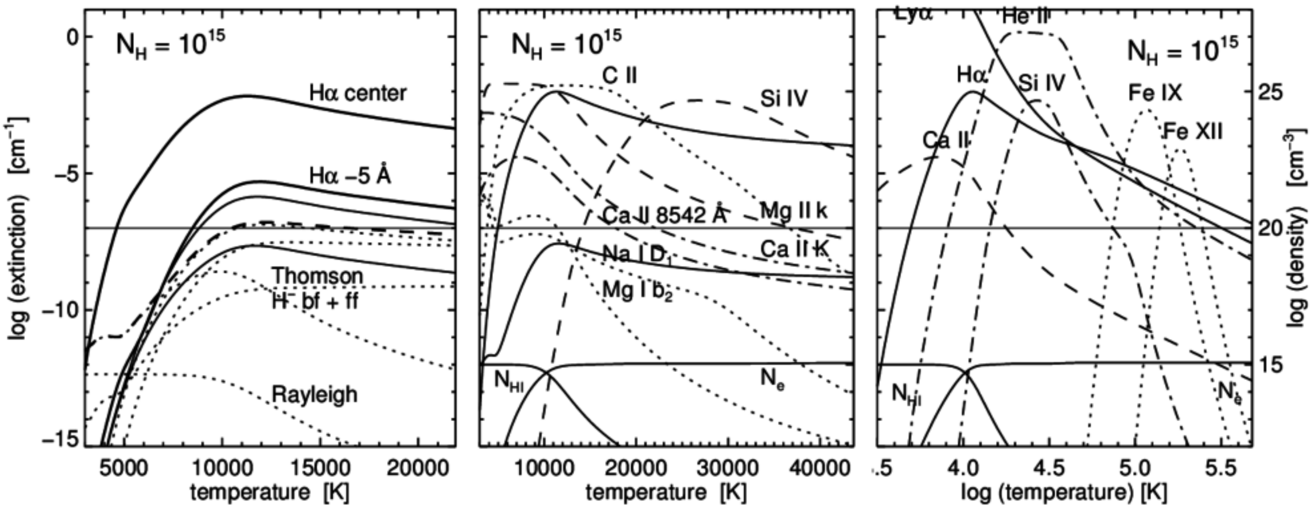
- *Hα extinction recipe*
  - find hottest instance nearby (∼300 km) and in recent past (∼minutes)
  - compute Saha-Boltzmann fractional n = 2 population then and there
  - use this extinction value in cooler gas around it and afterwards

  - small hot features leave wider Hα marks (as the grin of the Cheshire cat)
  - fast small hot features leave wider Hα trails (as contrails from jet engines)

Hα HOT-ONSET EXTINCTION

Rutten 2016A&A...590A.124R *Rutten & Rouppe van der Voort* 2016arXiv160907616R



- bachelor exercise “Cecilia Payne”: compute N_e and κ^LTE for given N_H
- line at $\log(\alpha) = -7$: $\tau = 1$ across 100-km slab
- Hα moustaches beyond continuum: linear Stark + Holtsmark
- photosphere: Hα much weaker than Ca II H & K, Lyα mm photon paths
- chromosphere: H$\alpha \approx$ Ca II 8542 Å, opposite temperature sensitivity
- clapotispheric shocks: H$\alpha \sim$ Ca II H & K and remembers that
- outburst onsets: extraordinary Hα opacity, competing with (E)UV lines