NON-EQUILIBRIUM SPECTRUM FORMATION AFFECTING SOLAR IRRADIANCE

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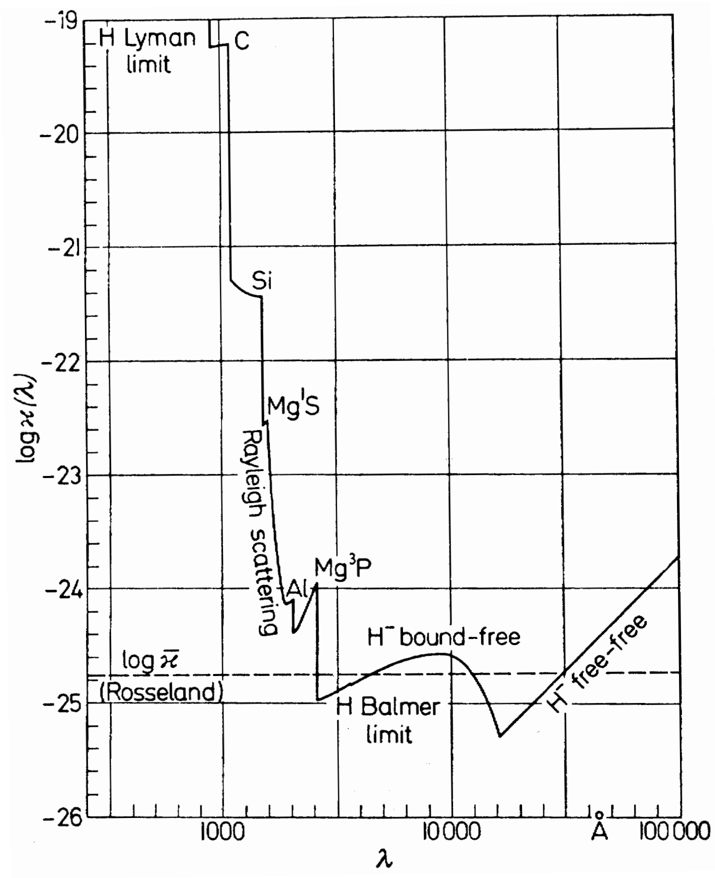
lecture displays `http://www.staff.science.uu.nl/~rutte101`

- *microcourse "solar spectrum formation"*
  - photonic processes
  - NLTE lines and contina
  - NSE
- *modeling "haze" lines*
  - methods
  - demo: FTS versus RH
- *modeling network / plage "fluxtubes"*
  - methods
  - demo: 1600 Å versus 1700 Å
- *to do for spectral irradiance modeling*
  - haze: define tractable recipe
  - fluxtubes: 3D(t) MHD with NLTE synthesis
  - caveat: hydrogen NSE

SOLAR ATMOSPHERE RADIATIVE PROCESSES

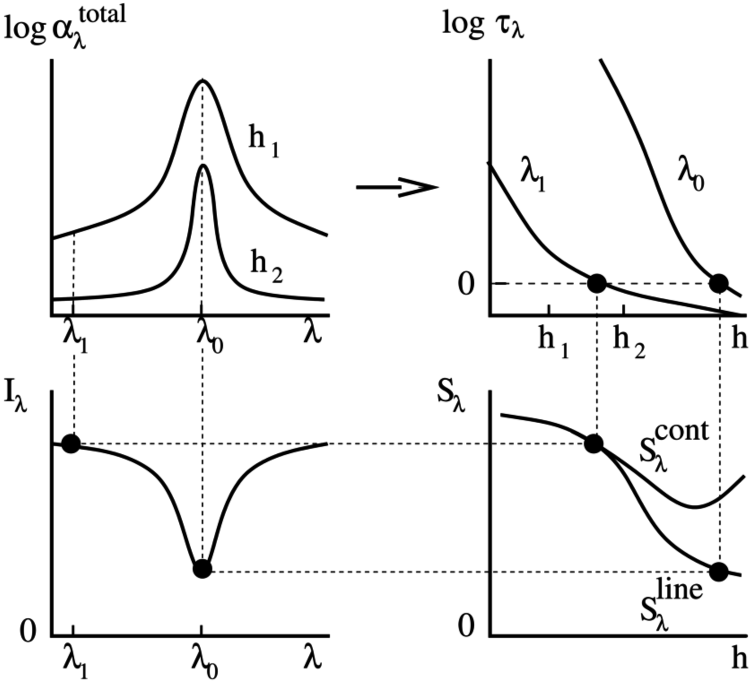
- *bound-bound* – κ_ν, S_ν: CE, LTE, NLTE, PRD, NSE?
  - neutral atom transitions
  - ion transitions
  - molecule transitions
- *bound-free* – same except always CRD
  - H^- optical, near-infrared
  - H I Balmer, Lyman; He I, He II
  - Fe I, Si I, Mg I, Al I $=$ electron donors
- *free-free* – $S_\nu = B_\nu$
  - H^- infrared, sub-mm
  - H I mm, radio
- *electron scattering* – $S_\nu = J_\nu$
  - Thomson scattering
  - Rayleigh scattering
- *collective* – p.m.
  - cyclotron, synchrotron radiation
  - plasma radiation



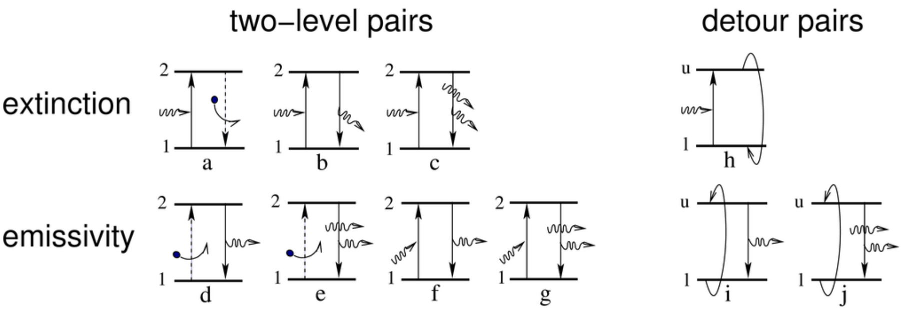
E. Böhm-Vitense

SCHEMATIC THICK SOLAR LINE FORMATION

- extinction: symmetric bb peak in α_λ becomes lower and narrower with height
- optical depth: $\tau_\lambda \equiv -\int (\alpha^l_\lambda + \alpha^c_\lambda)\,\mathrm{d}h$ increases roughly log-linear with geometrical depth
- source function: split line (bb) and continuum (bf, ff, electron scattering) processes
- intensity: Eddington-Barbier $I_\lambda \approx S_\lambda(\tau_\lambda\!=\!1)$ for $S^{\rm total}_\lambda = (\alpha^c_\lambda\, S^c_\lambda + \alpha^l_\lambda\, S^l_\lambda)/(\alpha^c_\lambda + \alpha^l_\lambda)$



LINE FORMATION AS SEEN BY THE ATOM



- *pair combinations*
  - beam of interest to the right
  - a / d + e = collisional destruction / creation of beam photons
  - b + h / f + i + j scattering & detour photons out / into beam (c, g cancel)

- *equilibria*
  - LTE: a + d + e dominate; bb Boltzmann $f(T)$, bf Saha $f(T,N_\mathrm{e})$
  - CE: d only; bb $f(T,N_\mathrm{e})$, bf $f(T)$
  - NLTE, NSE: scattering and/or detours important; bb and bf $f(T, N_e, , \overline{J}_{ul}, \overline{J}_{ij}, \overline{J}_{ic})\,[t]$

- *line extinction and line source function*
  - $\alpha^l = \alpha^\mathrm{a} + \alpha^\mathrm{s} + \alpha^\mathrm{d}$ absorption + scattering + detour extinction
  - $\varepsilon \equiv \alpha^\mathrm{a}/\alpha^l$ destruction probability $\eta \equiv \alpha^\mathrm{d}/\alpha^l$ detour probability
  - $S^l = (1-\varepsilon-\eta)\,\overline{J} \; + \; \varepsilon B(T) \; + \; \eta S^d$ $\overline{J}$: mean mean intensity S^d: all detours

KEY LINE FORMATION EQUATIONS

population departure coefficients

$$b_l = n_l / n_l^{\rm LTE} \qquad\qquad b_u = n_u / n_u^{\rm LTE}$$

Zwaan: $n^{\rm LTE} =$ Saha-Boltzmann fraction of $N_{\rm el}$ Harvard: n/n_c (main stages $\approx 1/b_c$)

general line extinction and line source function

$$\alpha_\lambda^l = \frac{\pi e^2}{m_e c}\,\frac{\lambda^2}{c}\,b_l\,\frac{n_l^{\rm LTE}}{N_{\rm el}}\,N_{\rm H}\,A_{\rm el}\,f_{lu}\,\varphi\left[1-\frac{b_u}{b_l}\,\frac{\chi}{\varphi}\,{\rm e}^{-hc/\lambda kT}\right] \qquad S_\lambda^l = \frac{2hc^2}{\lambda^5}\,\frac{\psi/\varphi}{\frac{b_l}{b_u}\,{\rm e}^{hc/\lambda kT}-\frac{\chi}{\varphi}}$$

CRD approximation: $\psi = \chi = \varphi$ Wien approximation: neglect stimulated parts

$$\alpha^l \approx b_l\ \alpha^{\rm LTE} \qquad\qquad S^l \approx (b_u/b_l)\ B(T)$$

PRD: Lyα, Mg II h & k, Ca II H & K, strong UV   Wien: up to Hα ($\lambda T = hc/k$ at 21 900 K)

probabilities per extinction of collisional photon destruction and of detour photon conversion

$$\varepsilon \equiv \frac{\alpha^{\rm a}}{\alpha^{\rm s}+\alpha^{\rm a}+\alpha^{\rm d}} \qquad\qquad \eta \equiv \frac{\alpha^{\rm d}}{\alpha^{\rm s}+\alpha^{\rm a}+\alpha^{\rm d}}$$

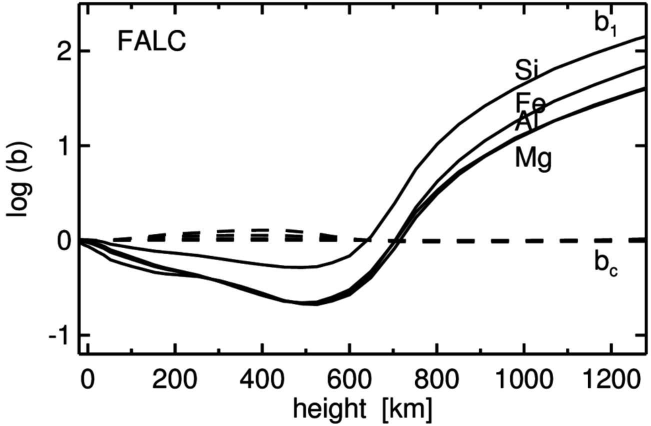
line source function (for CRD, monofrequent for PRD)

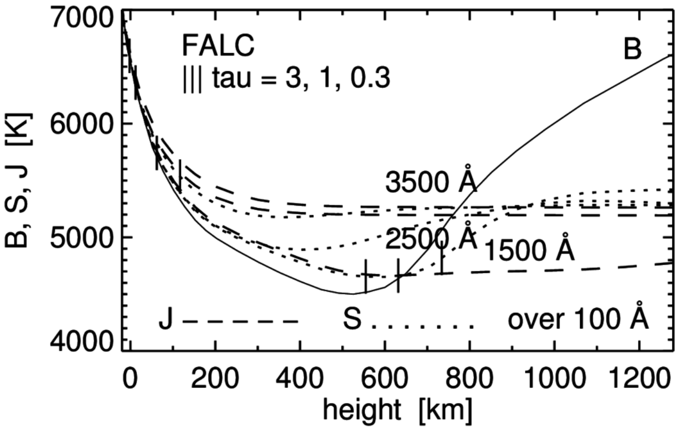
$$S^l = (1-\varepsilon-\eta)\,\overline{J} \;+\; \varepsilon B(T) \;+\; \eta S^{\rm d}$$

“source” $=$ local addition of new photons into beam per local extinction in terms of energy

$\overline{J} \equiv (1/4\pi) \iint I\varphi\,{\rm d}\Omega\,{\rm d}\lambda$ reservoir $\varepsilon\,B$ thermal creation $\eta\,S^{\rm d}$ detour production

NLTE IN ULTRAVIOLET CONTINUA





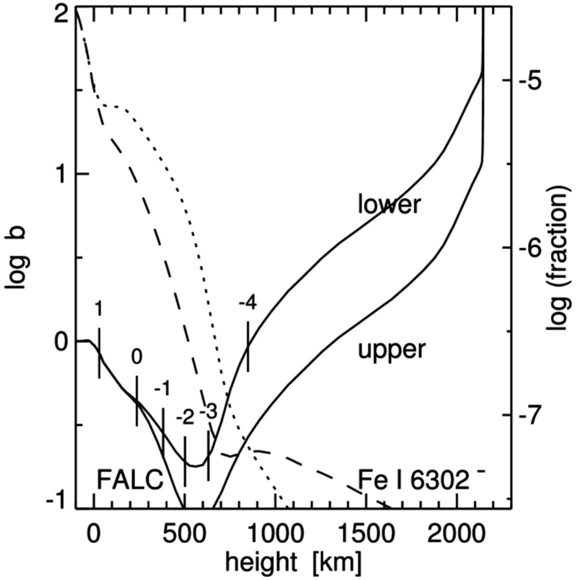
- ultraviolet bound-free edges produce scattering continua with $S \approx J > B$ from:
  - upper-photosphere $T(h)$ gradient defined by radiative equilibrium for the bulk $\approx$ optical (all quiet 1D models $\approx$ RE model, e.g., Kurucz)
  - deep thermalization depth; above it $S \approx (1-\alpha)\overline{J} + \alpha B$ as in two-level scattering
  - Λ operator (wide averager of S into J) produces larger $J > S$ excess for steeper $S(\tau)$
  - $B(h)$ steeper at depth following $T(h)$ and in ultraviolet from Wien nonlinearity

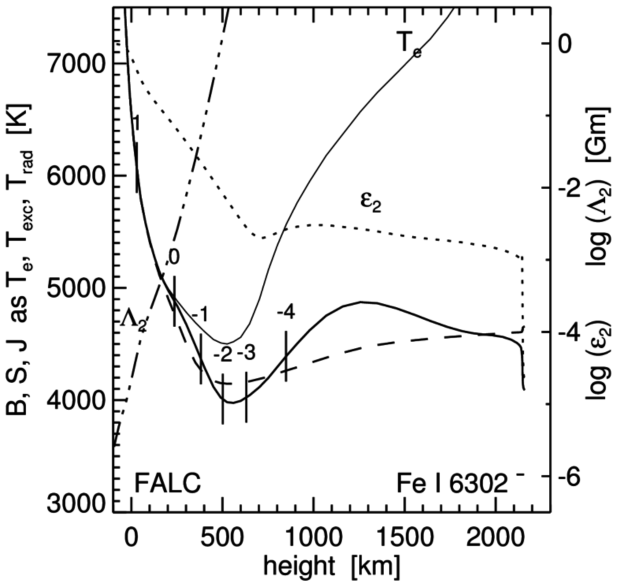
- corresponding b_1/b_c ratios for main edge providers (Mg I, Fe I, Si I, Al I) show increasing neutral-stage population depletion across photosphere and steep boost in chromosphere because $b_c \approx 1$ (ions contain most of $A_{\rm el}$)

- lines of Mg I, Fe I, Si I, Al I tend to have:
  - outward increasing NLTE extinction deficits in photospheric temperature declines
  - outward increasing NLTE extinction excesses in chromospheric temperature rises

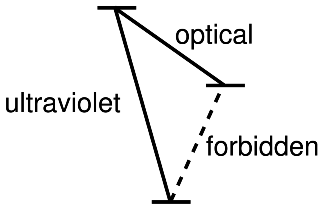
  worse for steeper deep temperature gradients (e.g., granule centers)

NLTE IN WEAK Fe I LINE (6301.5 Å, multiplet 816)

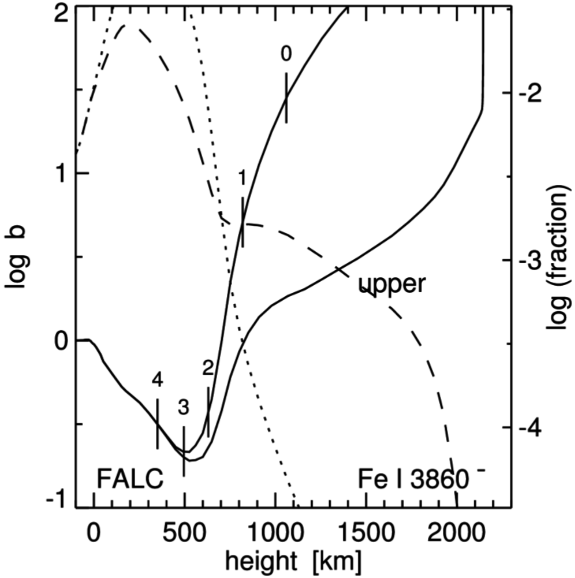


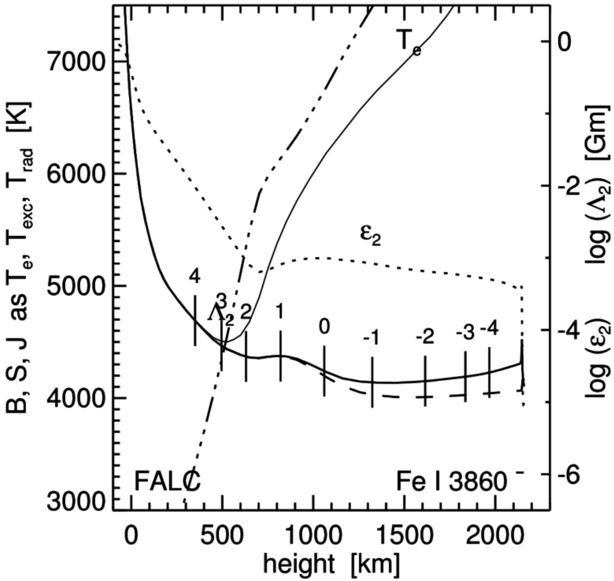


- left: b_l opacity decline from photospheric $J_{\rm UV} > B_{\rm UV}$ compresses τ scale around $\tau = 1$
- right: $S \approx B$ at $\tau = 1$ because $b_u < b_l \approx S < B$ split starts higher up
- source function: in two-level description this line scatters with deeper $S < B$, but Fe I has very rich term structure in which most optical Fe I lines are subordinate and forced to $b_u \approx b_l$ through upper-level sharing with stronger, more opaque UV lines



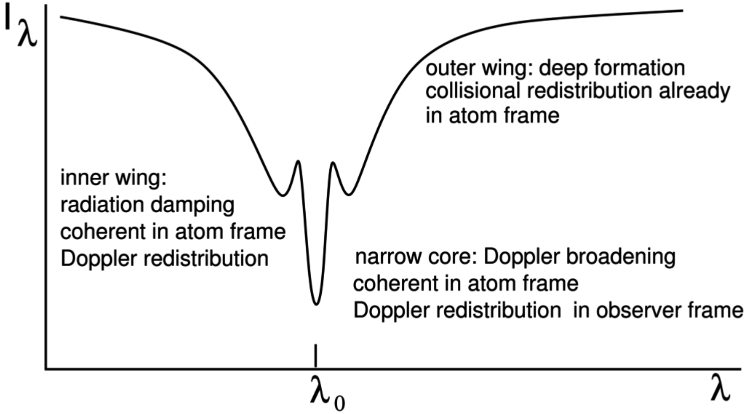
NLTE IN STRONG Fe I LINE (3859.9 Å, multiplet 4)

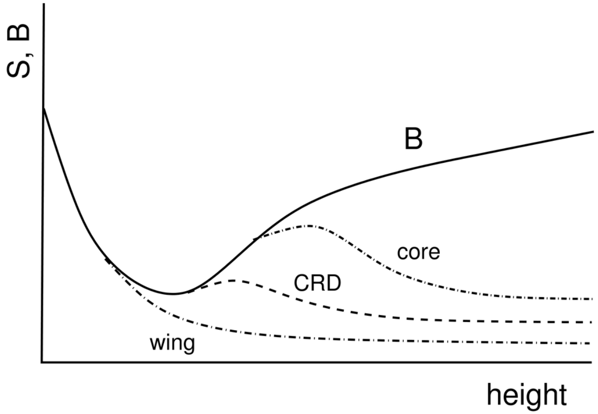




- left: b_l opacity increase from chromospheric $J_{\rm UV} < B_{\rm UV}$ extends τ scale around $\tau = 1$
- right: $S < B$ around $\tau = 1$ because $b_u < b_l \approx S < B$ split starts from deep thermalization
- two-level description works well, no multi-level detour interlocking
- such strong lines force $b_u \approx b_l$ across the photosphere for weaker upper-level sharers

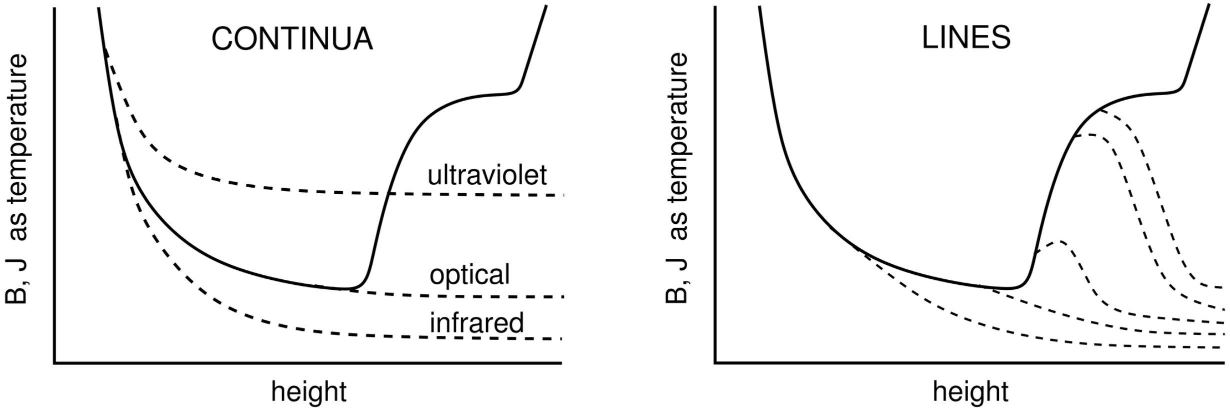
PARTIAL REDISTRIBUTION (Lyα, Mg II h & k, Ca IIHK, strong UV lines)





- Doppler core: monofrequent ("coherent") scatttering per atom in its moving frame; Doppler redistribution over parcel Doppler width for observer (snag: microturbulence?)
- inner damping wing: Heisenberg ⇒ coherent scattering with Doppler redistribution
- outer damping wing: collisional damping at high density ⇒ complete redistribution
- if the line is so strong that radiation damping dominates in the inner wings (high formation at low collider density) then the inner-wing photons are independent Doppler-wide ensembles with their own line source functions
- inner-wing line source functions decouple deeper from the Planck function than the core source function due to smaller opacity: they represent weaker lines
- the PRD core source function decouples further out than for complete redistribution because core photons cannot escape from deeper layers via occasional wing sampling

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

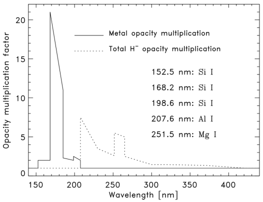
NON STATISTICAL EQUILIBRIUM (AKA “DYNAMIC IONIZATION”)

- *nature*
  - SE (statistical equilibrium): population equations (rate equations) sum to zero $=$ all populations and radiation defined instantly; NSE: non-zero sums $=$ memories
  - bound-bound relaxation time $=$ equilibrium settling time to new temperature: at small net radiative bracket (large radiative rates that nearly balance) Boltzmann sensitivity from $C_{lu} = C_{ul}(g_l/g_u)\exp(-E_{ul}/kT)$: slowest for strongest EUV lines at low T

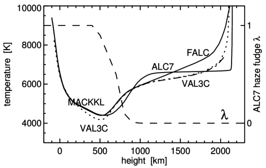
- *hydrogen*
  - Lyα closely in detailed radiative balance due to enormous opacity; collisional balancing to reach SE takes minutes in gas cooling below 8 000 K
  - hydrogen ionization/recombination occurs predominantly in a faster Balmer loop from $n = 2$ and follows Lyα settling: Lyα is the NSE culprit ($\Rightarrow$ “NSE Lyα balancing”)
  - key hydrogen NSE demonstrations:
    - 1D RADYN HD shocks: Carlsson & Stein 2002ApJ...572..626C
    - 2D Stagger MHD shocks: Leenaarts et al. 2007A&A...473..625L
    - 3D MHD+GOL spicules-II: tbd $=$ Bifrost? MURaM? Mancha?
  - other elements:
    - He: He I 584 Å candidate but competition from downward irradiation; others: tbd

- *effects on spectral irradiance*
  - optical: don’t bother, too deep $=$ too dense
  - ultraviolet: electron density boost at partial hydrogen ionization (10^3 at 10%) is highly NSE-sensitive to dynamic cooling (RRC: only NSE dynamism explains Hα)
  - submm and mm: idem, affecting H I ff extinction (RRC: ALMA will show Hα-like)

MODELING THE LINE HAZE FOR SPECTRAL IRRADIANCE



- *Bruls opacity fudge* 1992A&A...265..237B
  - fit MULTI output VALIIIC to VALII data
  - multipliers to bound-free metal and H$^-$ opacities



- *Avrett grosso-modo scattering trick* 2008ApJS..175..229A
  - post-VALIII models less steep photosphere from Kurucz lines
  - no Kurucz reversals from imposed $S = (1-\lambda)\,J + \lambda\,B$

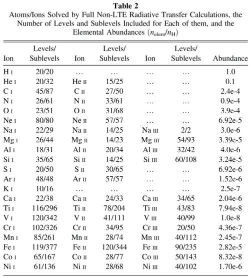


Table 2

Atoms/Ions Solved by Full Non-LTE Radiative Transfer Calculations, the Number of Levels and Sublevels Included for Each of them, and the Elemental Abundances ($n_{\rm elem}/n_{\rm H}$)

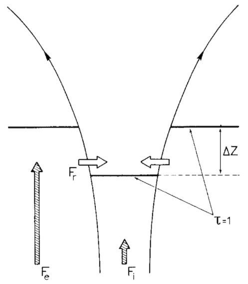
Ion	Levels/ Sublevels	Ion	Levels/ Sublevels	Ion	Levels/ Sublevels	Abundance
H I	20/20	…	…	…	…	1.0
He I	20/32	He II	15/25	…	…	0.1
C I	45/87	C II	27/50	…	…	2.4e-4
N I	26/61	N II	33/61	…	…	0.9e-4
O I	23/51	O II	31/68	…	…	3.9e-4
Ne I	80/80	Ne II	57/57	…	…	6.92e-5
Na I	22/29	Na II	14/25	Na III	2/2	3.0e-6
Mg I	26/44	Mg II	14/23	Mg III	54/93	3.39e-5
Al I	18/31	Al II	20/34	Al III	32/42	4.0e-6
Si I	35/65	Si II	14/25	Si III	60/108	3.24e-5
S I	20/50	S II	30/65	…	…	6.92e-6
Ar I	48/48	Ar II	57/57	…	…	1.52e-6
K I	10/16	…	…	…	…	2.5e-7
Ca I	22/38	Ca II	24/33	Ca III	34/65	2.04e-6
Ti I	116/296	Ti II	78/204	Ti III	43/83	7.94e-8
V I	120/342	V II	41/111	V III	40/99	1.0e-8
Cr I	102/326	Cr II	34/95	Cr III	20/50	4.36e-7
Mn I	85/261	Mn II	28/74	Mn III	40/112	2.45e-7
Fe I	119/377	Fe II	120/344	Fe III	90/235	2.82e-5
Co I	65/167	Co II	28/77	Co III	50/143	8.32e-8
Ni I	61/136	Ni II	28/68	Ni III	40/102	1.70e-6

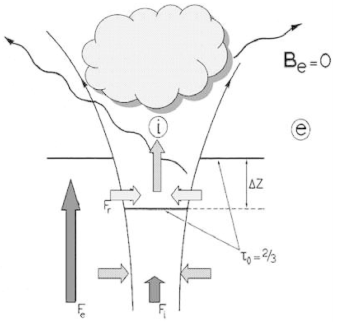
- *Uitenbroek RH options*
  - Bruls / Kurucz lines LTE / Kurucz lines 2-level
  - FTS versus RH

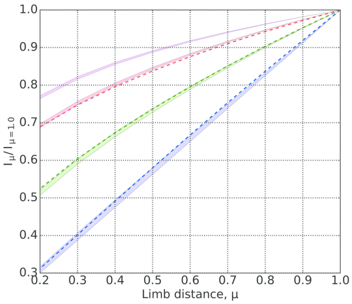
- *Fontenla brute-force solution* 2015ApJ...809..157F
  - very many lines in detail
  - good result but ony doable for 1D model

- *suggestions for massive spectral synthesis (RH 1.5D?)*
  - distill Bruls-like fudge from Fontenla et al. results
  - impose strong-line b departures from schematic Fe-like model atom

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: dissociaton
  - 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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  - NLTE lines and contina
  - NSE
- *modeling "haze" lines*
  - methods
  - demo: FTS versus RH
- *modeling network / plage "fluxtubes"*
  - methods
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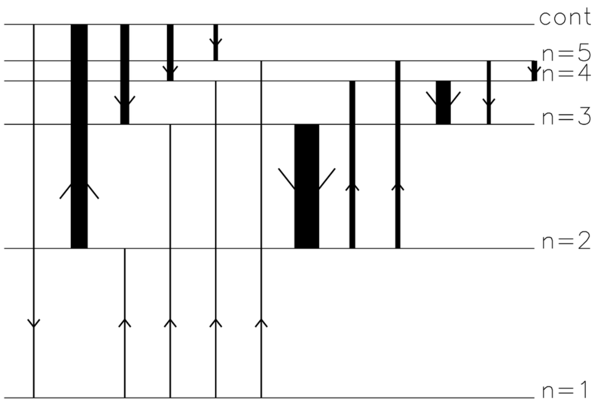
- *to do for spectral irradiance modeling*
  - haze: define tractable recipe
  - fluxtubes: 3D(t) MHD with NLTE synthesis
  - caveat: hydrogen NSE

NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

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

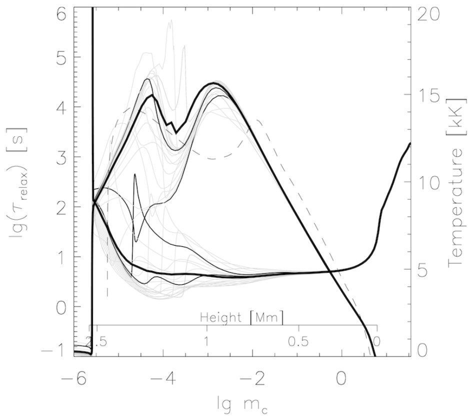


atom top ~ 3.4 eV alkali: NLTE-SE ionization loop
- driven by photon pumping Balmer continuum, scattering from deep, ≈5300 K, smooth
- closure by photon losses in n_α lines

atom bottom actually up to 10 eV: non-E Lyα
- 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
- 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 $n = 2$: instantaneous statistical-equilibrium balance driven by Balmer continuum $J \neq B$ and closed by cascade recombination, with $b_\mathrm{cont}/b_2 \approx 10^{-1}$ 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)

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

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

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

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

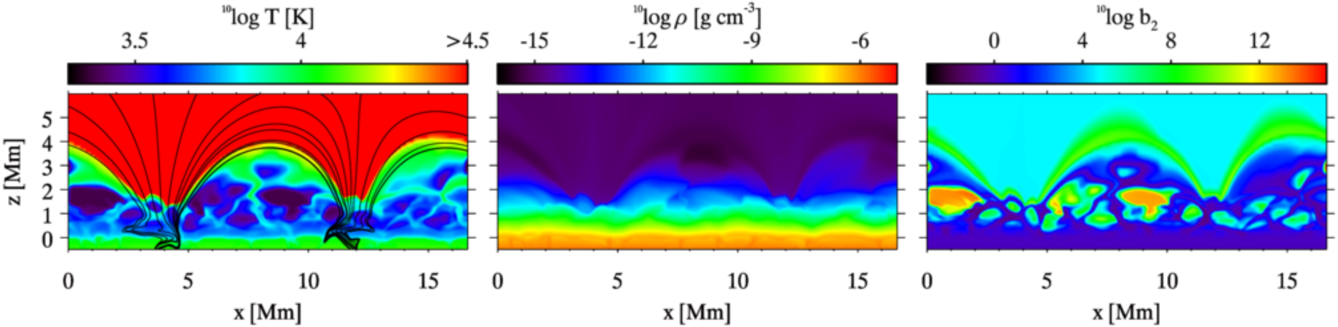
Einstein relation

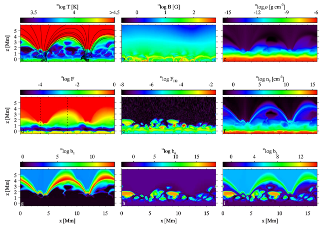
$$C_{lu} = C_{ul} \frac{g_l}{g_u}\, {\rm e}^{-E_{ul}/kT}$$

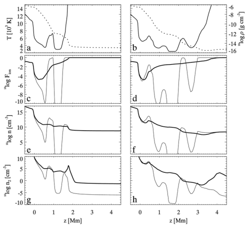
C_{ul} is not very temperature sensitive (any collider will do); C_{lu} has Boltzmann sensitivity

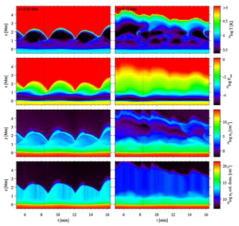
NON-E HYDROGEN IONIZATION IN 2D MHD SHOCKS

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







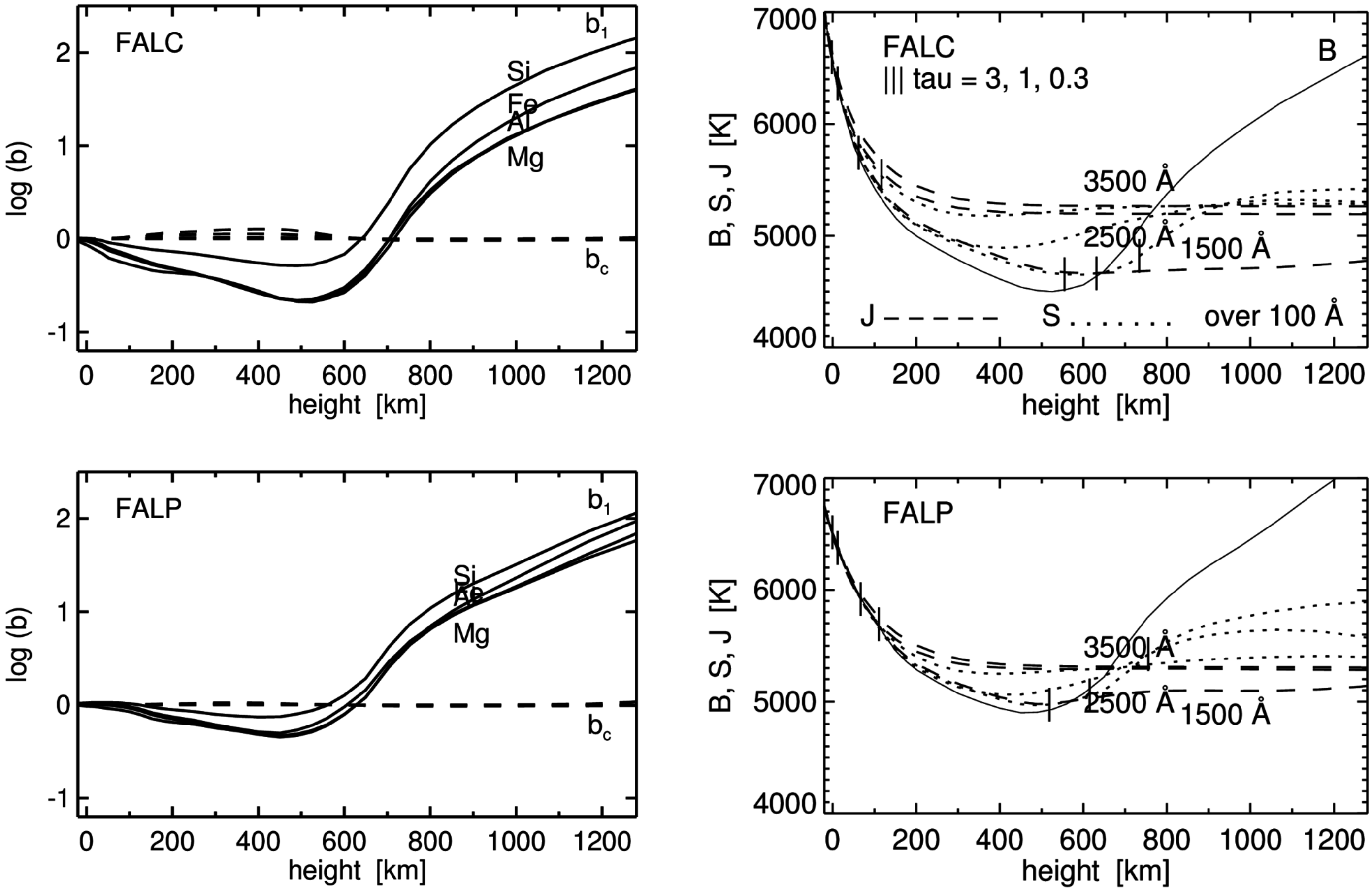


- in shocks Lyα has $S \!\approx\! B$ from high T (fast balancing) and N_e (10% H ionization)
- retarded collisional balancing in Lyα: n_2 hangs near high shock value $n_2 \approx n_2^{\rm LTE}$
- gigantic post-shock $n\!=\!2$ overpopulations versus LTE ("S-B underestimates")
- yet larger post-shock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

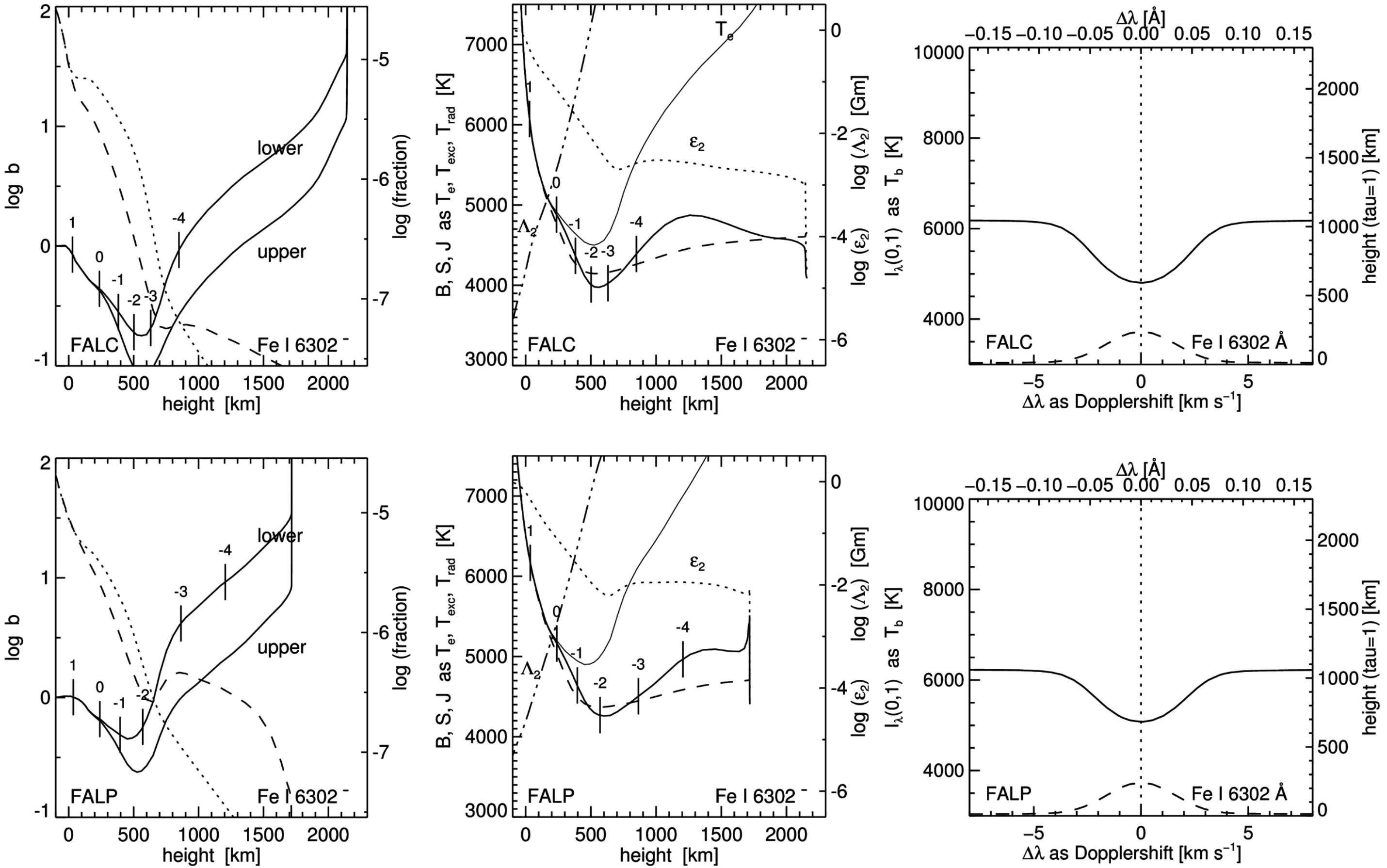
RECENT DEVELOPMENTS IN PRD LINE SYNTHESIS

- *RH code: Uitenbroek 2001ApJ...557..389U*
  - Rybicky & Hummer: not $\mathbf{\Lambda}(S)$ but $\mathbf{\Psi}(j)$ iteration; preconditioning
  - overlappping 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
  - 252×252×496 grid, 1024 CPUs: 2 days for Mg II k $\approx$ doable
- *next: 3D PRD with multigrid (Bjørgen & Leenaarts 2017A&A...599A.118B)*

ULTRAVIOLET CONTINUA IN FALC AND FALP



Fe I 6301.5 Å IN FALC AND FALP



standard polarimetry line

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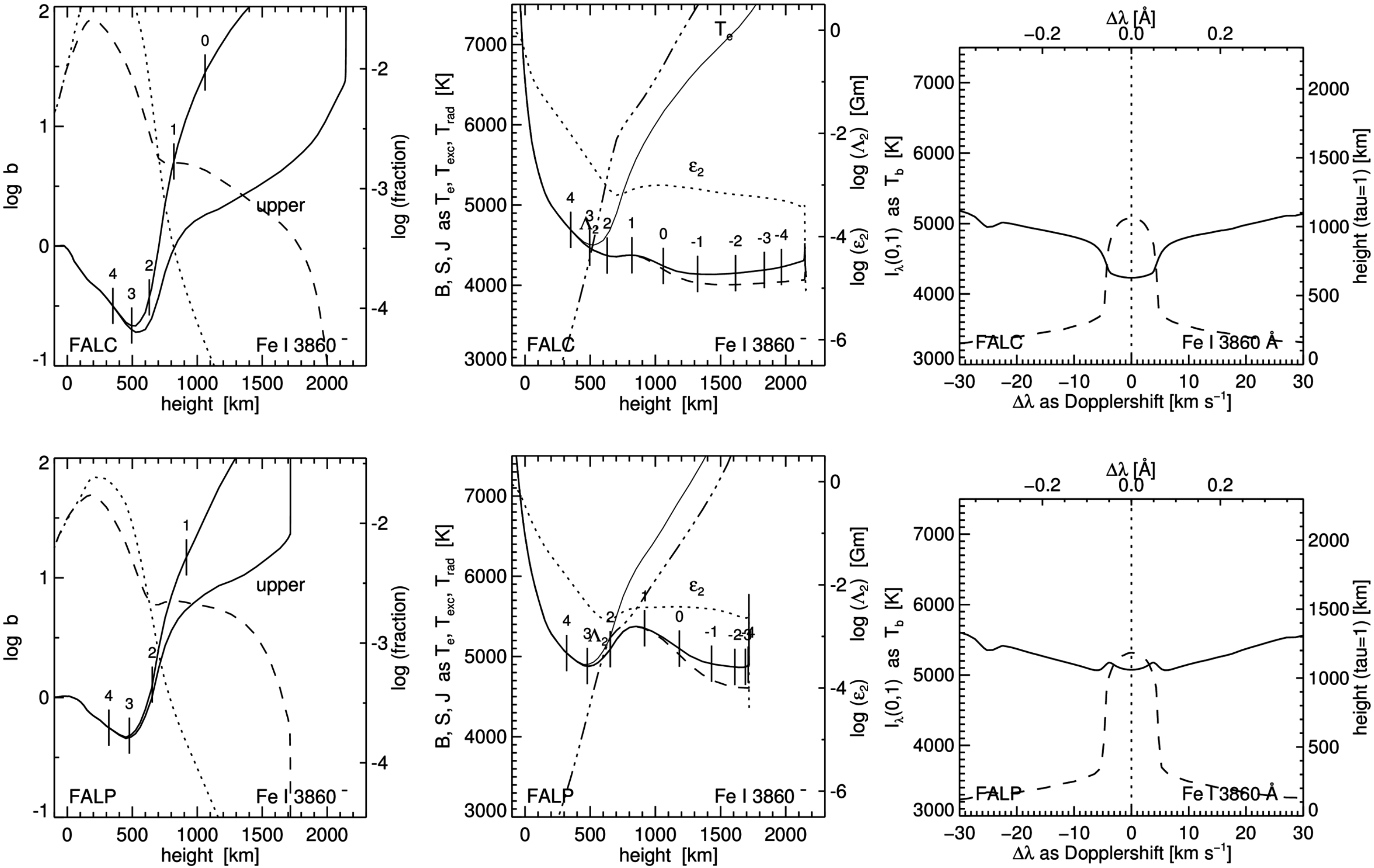
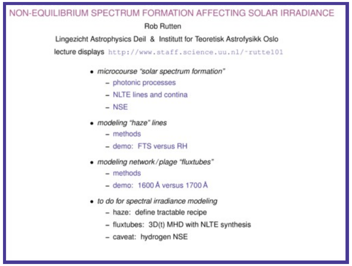


strong ground-state Fe I line



NON-EQUILIBRIUM SPECTRUM FORMATION AFFECTING SOLAR IRRADIANCE

Rob Rutten

Lingezicht Astrophysics Deil & Institutt for Teoretisk Astrofysikk Oslo

lecture displays `http://www.staff.science.uu.nl/~rutte101`

- *microcourse "solar spectrum formation"*
  - photonic processes
  - NLTE lines and contina
  - NSE
- *modeling "haze" lines*
  - methods
  - demo: FTS versus RH
- *modeling network / plage "fluxtubes"*
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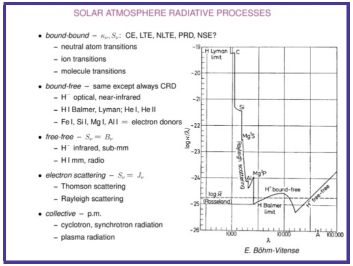
  - caveat: hydrogen NSE

1

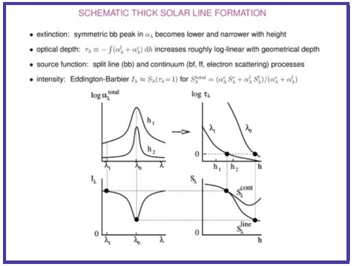


SOLAR ATMOSPHERE RADIATIVE PROCESSES

- *bound-bound* – κ_ν, S_ν: CE, LTE, NLTE, PRD, NSE?
  - neutral atom transitions
  - ion transitions
  - molecule transitions
- *bound-free* – same except always CRD
  - H^- optical, near-infrared
  - H I Balmer, Lyman; He I, He II
  - Fe I, Si I, Mg I, Al I = electron donors
- *free-free* – $S_\nu = B_\nu$
  - H^- infrared, sub-mm
  - H I mm, radio
- *electron scattering* – $S_\nu = J_\nu$
  - Thomson scattering
  - Rayleigh scattering
- *collective* – p.m.
  - cyclotron, synchrotron radiation
  - plasma radiation

E. Böhm-Vitense

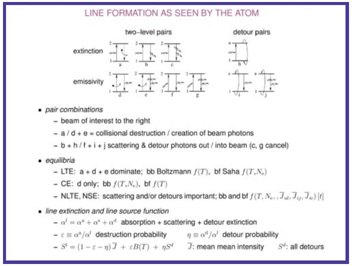
2



SCHEMATIC THICK SOLAR LINE FORMATION

- extinction: symmetric bb peak in α_λ becomes lower and narrower with height
- optical depth: $\tau_\lambda \equiv -\int(\alpha^l_\lambda + \alpha^c_\lambda)\,\mathrm{d}h$ increases roughly log-linear with geometrical depth
- source function: split line (bb) and continuum (bf, ff, electron scattering) processes
- intensity: Eddington-Barbier $I_\lambda \approx S_\lambda(\tau_\lambda\!=\!1)$ for $S^{\rm total}_\lambda = (\alpha^c_\lambda S^c_\lambda + \alpha^l_\lambda S^l_\lambda)/(\alpha^c_\lambda + \alpha^l_\lambda)$

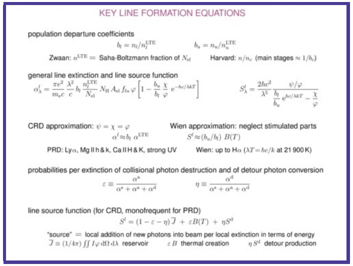
3



LINE FORMATION AS SEEN BY THE ATOM

- *pair combinations*
  - beam of interest to the right
  - a / d + e = collisional destruction / creation of beam photons
  - b + h / f + i + j scattering & detour photons out / into beam (c, g cancel)
- *equilibria*
  - LTE: a + d + e dominate; bb Boltzmann $f(T)$, bf Saha $f(T,N_e)$
  - CE: d only; bb $f(T,N_e)$, bf $f(T)$
  - NLTE, NSE: scattering and/or detours important; bb and bf $f(T, N_e, , \overline{J}_{ul}, \overline{J}_{ij}, \overline{J}_{ic})\;[t]$
- *line extinction and line source function*
  - $\alpha^l = \alpha^a + \alpha^s + \alpha^d$ absorption + scattering + detour extinction
  - $\varepsilon \equiv \alpha^a/\alpha^l$ destruction probability $\eta \equiv \alpha^d/\alpha^l$ detour probability
  - $S^l = (1-\varepsilon-\eta)\,\overline{J} + \varepsilon B(T) + \eta S^d$ $\overline{J}$: mean mean intensity S^d: all detours

4



KEY LINE FORMATION EQUATIONS

population departure coefficients

$$b_l = n_l/n_l^{\rm LTE} \qquad b_u = n_u/n_u^{\rm LTE}$$

Zwaan: $n^{\rm LTE} =$ Saha-Boltzmann fraction of $N_{\rm el}$ Harvard: n/n_c (main stages $\approx 1/b_c$)

general line extinction and line source function

$$\alpha^l_\lambda = \frac{\pi e^2}{m_e c}\,\frac{\lambda^2}{c}\,b_l\,\frac{n_l^{\rm LTE}}{N_{\rm el}}\,N_{\rm H}\,A_{\rm el}\,f_{lu}\,\varphi\left[1-\frac{b_u}{b_l}\,\frac{\chi}{\varphi}\,{\rm e}^{-hc/\lambda kT}\right] \qquad S^l_\lambda = \frac{2hc^2}{\lambda^5}\,\frac{\psi/\varphi}{\frac{b_l}{b_u}\,{\rm e}^{hc/\lambda kT}-\frac{\chi}{\varphi}}$$

CRD approximation: $\psi = \chi = \varphi$ Wien approximation: neglect stimulated parts

$$\alpha^l \approx b_l\;\alpha^{\rm LTE} \qquad S^l \approx (b_u/b_l)\;B(T)$$

PRD: Lyα, Mg II h & k, Ca II H & K, strong UV Wien: up to Hα ($\lambda T = hc/k$ at 21 900 K)

probabilities per extinction of collisional photon destruction and of detour photon conversion

$$\varepsilon \equiv \frac{\alpha^a}{\alpha^s+\alpha^a+\alpha^d} \qquad \eta \equiv \frac{\alpha^d}{\alpha^s+\alpha^a+\alpha^d}$$

line source function (for CRD, monofrequent for PRD)

$$S^l = (1-\varepsilon-\eta)\,\overline{J} + \varepsilon B(T) + \eta S^d$$

"source" = local addition of new photons into beam per local extinction in terms of energy

$\overline{J} \equiv (1/4\pi)\iint I\varphi\,\mathrm{d}\Omega\,\mathrm{d}\lambda$ reservoir εB thermal creation ηS^d detour production

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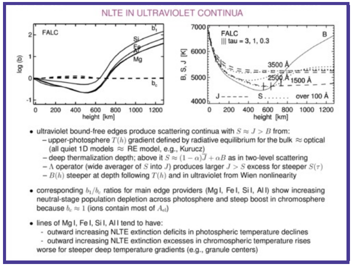

NLTE IN ULTRAVIOLET CONTINUA

- ultraviolet bound-free edges produce scattering continua with $S \approx J > B$ from:
  - upper-photosphere $T(h)$ gradient defined by radiative equilibrium for the bulk ≈ optical (all quiet 1D models ≈ RE model, e.g., Kurucz)
  - deep thermalization depth; above it $S \approx (1-\alpha)\overline{J} + \alpha B$ as in two-level scattering
  - Λ operator (wide averager of S into J) produces larger $J > S$ excess for steeper $S(\tau)$
  - $B(h)$ steeper at depth following $T(h)$ and in ultraviolet from Wien nonlinearity
- corresponding b_1/b_c ratios for main edge providers (Mg I, Fe I, Si I, Al I) show increasing neutral-stage population depletion across photosphere and steep boost in chromosphere because $b_c \approx 1$ (ions contain most of $A_{\rm el}$)
- lines of Mg I, Fe I, Si I, Al I tend to have:
  - outward increasing NLTE extinction deficits in photospheric temperature declines
  - outward increasing NLTE extinction excesses in chromospheric temperature rises

  worse for steeper deep temperature gradients (e.g., granule centers)

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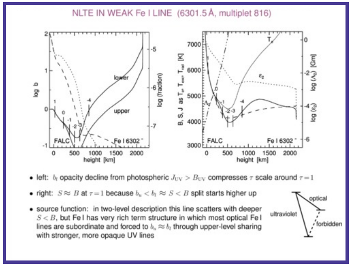

NLTE IN WEAK Fe I LINE (6301.5 Å, multiplet 816)

- left: b_l opacity decline from photospheric $J_{\rm UV} > B_{\rm UV}$ compresses τ scale around $\tau = 1$
- right: $S \approx B$ at $\tau = 1$ because $b_u < b_l \approx S < B$ split starts higher up
- source function: in two-level description this line scatters with deeper $S < B$, but Fe I has very rich term structure in which most optical Fe I lines are subordinate and forced to $b_u \approx b_l$ through upper-level sharing with stronger, more opaque UV lines

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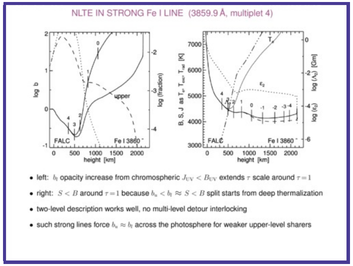

NLTE IN STRONG Fe I LINE (3859.9 Å, multiplet 4)

- left: b_l opacity increase from chromospheric $J_{\rm UV} < B_{\rm UV}$ extends τ scale around $\tau = 1$
- right: $S < B$ around $\tau = 1$ because $b_u < b_l \approx S < B$ split starts from deep thermalization
- two-level description works well, no multi-level detour interlocking
- such strong lines force $b_u \approx b_l$ across the photosphere for weaker upper-level sharers

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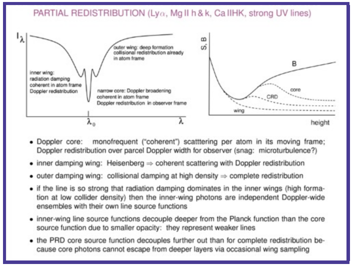

PARTIAL REDISTRIBUTION (Lyα, Mg II h & k, Ca IIHK, strong UV lines)

- Doppler core: monofrequent ("coherent") scatttering per atom in its moving frame; Doppler redistribution over parcel Doppler width for observer (snag: microturbulence?)
- inner damping wing: Heisenberg ⇒ coherent scattering with Doppler redistribution
- outer damping wing: collisional damping at high density ⇒ complete redistribution
- if the line is so strong that radiation damping dominates in the inner wings (high formation at low collider density) then the inner-wing photons are independent Doppler-wide ensembles with their own line source functions
- inner-wing line source functions decouple deeper from the Planck function than the core source function due to smaller opacity: they represent weaker lines
- the PRD core source function decouples further out than for complete redistribution because core photons cannot escape from deeper layers via occasional wing sampling

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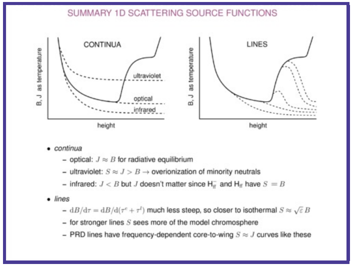

SUMMARY 1D SCATTERING SOURCE FUNCTIONS

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

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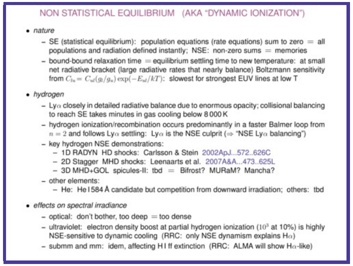

NON STATISTICAL EQUILIBRIUM (AKA "DYNAMIC IONIZATION")

- *nature*
  - SE (statistical equilibrium): population equations (rate equations) sum to zero = all populations and radiation defined instantly; NSE: non-zero sums = memories
  - bound-bound relaxation time = equilibrium settling time to new temperature: at small net radiative bracket (large radiative rates that nearly balance) Boltzmann sensitivity from $C_{lu} = C_{ul}(g_l/g_u)\exp(-E_{ul}/kT)$: slowest for strongest EUV lines at low T
- *hydrogen*
  - Lyα closely in detailed radiative balance due to enormous opacity; collisional balancing to reach SE takes minutes in gas cooling below 8 000 K
  - hydrogen ionization/recombination occurs predominantly in a faster Balmer loop from $n = 2$ and follows Lyα settling: Lyα is the NSE culprit (⇒ "NSE Lyα balancing")
  - key hydrogen NSE demonstrations:
    - 1D RADYN HD shocks: Carlsson & Stein 2002ApJ...572..626C
    - 2D Stagger MHD shocks: Leenaarts et al. 2007A&A...473..625L
    - 3D MHD+GOL spicules-II: tbd = Bifrost? MURaM? Mancha?
  - other elements:
    - He: He I 584 Å candidate but competition from downward irradiation; others: tbd
- *effects on spectral irradiance*
  - optical: don't bother, too deep = too dense
  - ultraviolet: electron density boost at partial hydrogen ionization (10^3 at 10%) is highly NSE-sensitive to dynamic cooling (RRC: only NSE dynamism explains Hα)
  - submm and mm: idem, affecting H I ff extinction (RRC: ALMA will show Hα-like)

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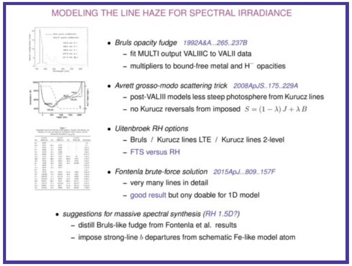

MODELING THE LINE HAZE FOR SPECTRAL IRRADIANCE

- *Bruls opacity fudge* *1992A&A...265..237B*
  - fit MULTI output VALIIIC to VALII data
  - multipliers to bound-free metal and H^- opacities
- *Avrett grosso-modo scattering trick* *2008ApJS..175..229A*
  - post-VALIII models less steep photosphere from Kurucz lines
  - no Kurucz reversals from imposed $S = (1-\lambda)\,J + \lambda\,B$
- *Uitenbroek RH options*
  - Bruls / Kurucz lines LTE / Kurucz lines 2-level
  - FTS versus RH
- *Fontenla brute-force solution* *2015ApJ...809..157F*
  - very many lines in detail
  - good result but ony doable for 1D model
- *suggestions for massive spectral synthesis (RH 1.5D?)*
  - distill Bruls-like fudge from Fontenla et al. results
  - impose strong-line b departures from schematic Fe-like model atom

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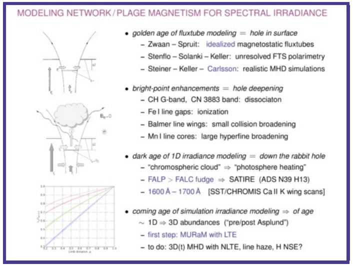

MODELING NETWORK / PLAGE MAGNETISM FOR SPECTRAL IRRADIANCE

- *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: dissociaton
  - 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" ⇒ "photosphere heating"
  - FALP > FALC fudge ⇒ SATIRE (ADS N39 H13)
  - 1600 Å – 1700 Å [SST/CHROMIS Ca II K wing scans]
- *coming age of simulation irradiance modeling ⇒ of age*
  - ~ 1D ⇒ 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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  - caveat: hydrogen NSE

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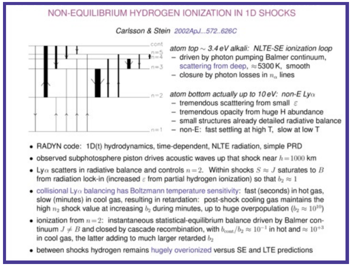

NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

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 Lyα
- tremendous scatttering 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
- 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 $n = 2$: instantaneous statistical-equilibrium balance driven by Balmer continuum $J \neq B$ and closed by cascade recombination, with $b_{\rm cont}/b_2 \approx 10^{-1}$ 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

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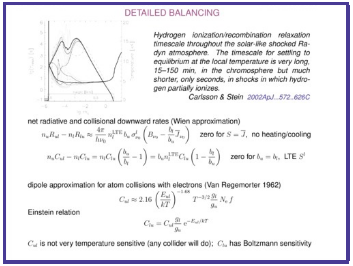

DETAILED BALANCING

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)

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

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

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

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

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

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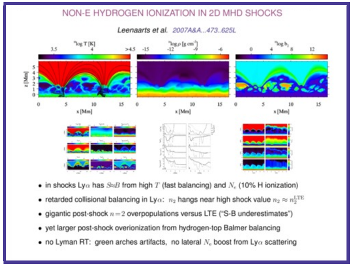

NON-E HYDROGEN IONIZATION IN 2D MHD SHOCKS

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
- no Lyman RT: green arches artifacts, no lateral N_e boost from Lyα scattering

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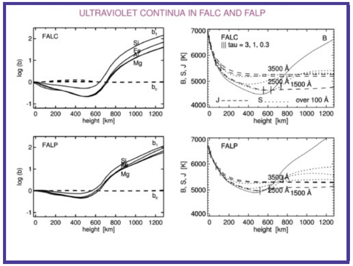

ULTRAVIOLET CONTINUA IN FALC AND FALP

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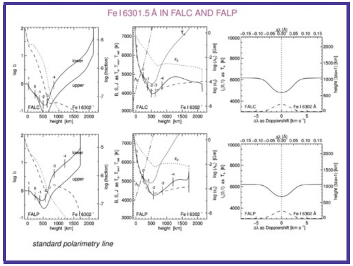

Fe I 6301.5 Å IN FALC AND FALP

standard polarimetry line

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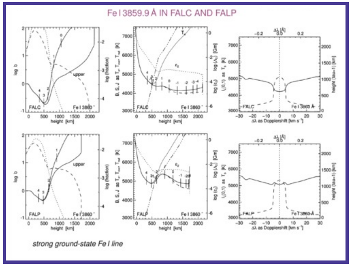

Fe I 3859.9 Å IN FALC AND FALP

strong ground-state Fe I line

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22