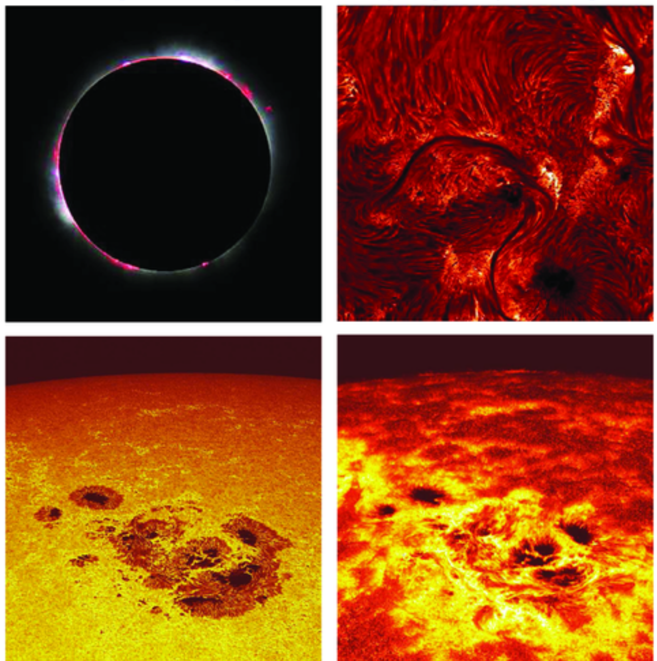
Hα IS EASY AND FIBRILS ARE CONTRAILS

Rob Rutten

14th European Solar Physics Meeting, September 2014, Dublin

simulation: J. Leenaarts
observation: L.H.M. Rouppe van der Voort



Chromosphere at eclipse — *Hα filtergram of chromosphere*

Photospheric spots & bright points — *Same area in chromospheric Ca^+*

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SOLAR NLTE IN A NUTSHELL

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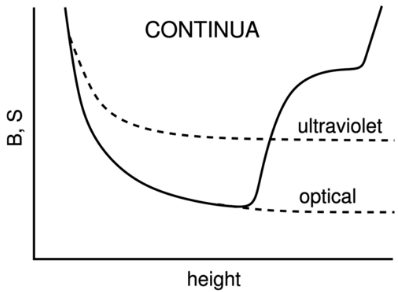
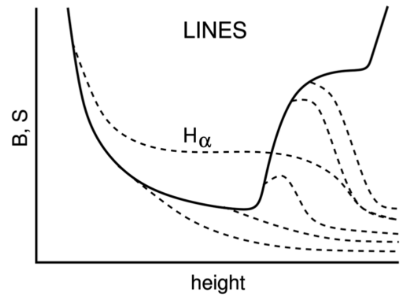
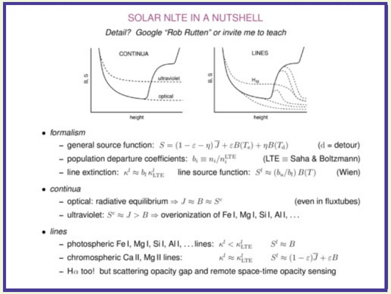




- *formalism*
  - general source function: $S = (1 - \varepsilon - \eta)\,\overline{J} + \varepsilon B(T_\mathrm{e}) + \eta B(T_\mathrm{d})$ (d = detour)
  - population departure coefficients: $b_i \equiv n_i / n_i^\mathrm{LTE}$ (LTE ≡ Saha & Boltzmann)
  - line extinction: $\kappa^l \approx b_l\, \kappa^l_\mathrm{LTE}$ line source function: $S^l \approx (b_u/b_l)\, B(T)$ (Wien)
- *continua*
  - optical: radiative equilibrium $\Rightarrow J \approx B \approx S^c$ (even in fluxtubes)
  - ultraviolet: $S^c \approx J > B \Rightarrow$ overionization of Fe I, Mg I, Si I, Al I, ...
- *lines*
  - photospheric Fe I, Mg I, Si I, Al I, ... lines: $\kappa^l < \kappa^l_\mathrm{LTE}$ $S^l \approx B$
  - chromospheric Ca II, Mg II lines: $\kappa^l \approx \kappa^l_\mathrm{LTE}$ $S^l \approx (1 - \varepsilon)\overline{J} + \varepsilon B$
  - Hα too! but scattering opacity gap and remote space-time opacity sensing



All solar NLTE on one slide. If you invite me to teach I will spend a week to derive these cartoons.

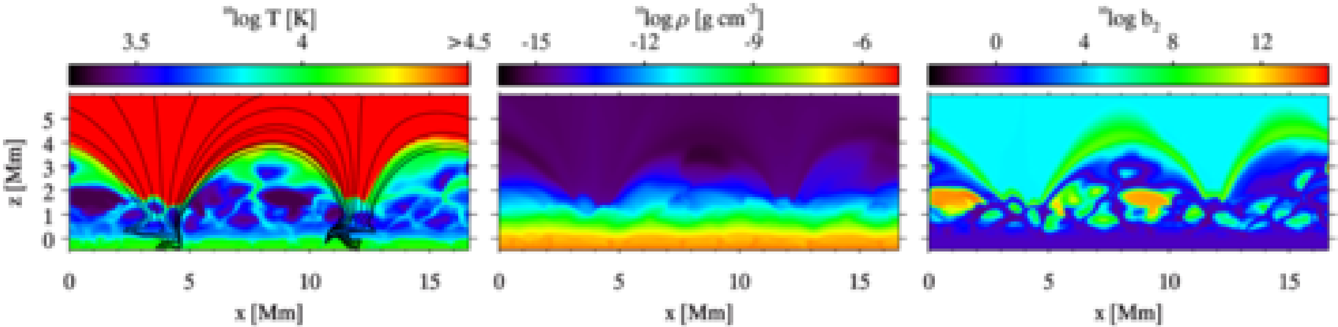
The first cartoon shows that the ultraviolet continua originate deeply at such a steep Planck function that the radiation field followed by their source function is superthermal in the upper photosphere. Standard two-level scattering theory applied to bound-free transitions. It produces substantial overionizaton of all neutral metal atoms, and therefore substantial underopacity for all their lines (Fe I, Ti I, Mg I, Al I, etc). If you invert or model say Fe I lines in polarimetry or irradiance studies you must evaluate the ionizing ultraviolet continua in NLTE. The common notion that LTE just means $S^l \approx B$ (not a bad assumption in the photosphere) ignores this substantial opacity NLTE.

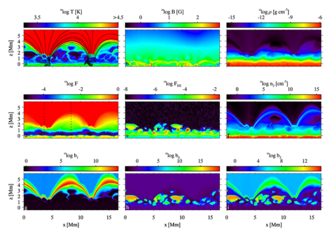
The second cartoon shows the typical behavior of strong scattering lines. Their source function follows $B(T_\mathrm{e})$ until the start of photon escape ("thermalization depth") through two-level scattering. They all then share a similar outward decline set by the $\sqrt{\varepsilon}$ law. If PRD applies such curves apply to different parts of the line (wings getting loose sooner).

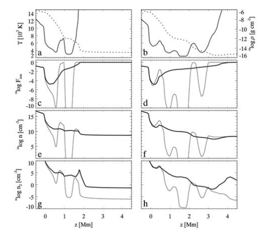
Hα is also a two-level scattering line, just like all other chromospheric lines, but its curve differs across the upper photosphere because this is transparent in Hα due to its large 10 eV excitation energy. The photons that originate in the deep photosphere get partially scattered back from the (model) chromosphere so that the radiation J builds up to a high plateau. So much for the Hα source function. Now the Hα opacity. For other chromospheric lines this is usually LTE. Actually also for Hα, but special.

Hα EXTINCTION: SLUGGISH RECOMBINATION SMOOTHING TO HOT LTE PAST

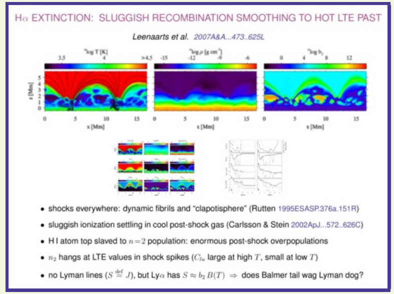
Leenaarts et al. *2007A&A...473..625L*







- shocks everywhere: dynamic fibrils and “clapotisphere” (Rutten 1995ESASP.376a.151R)
- slow Lyα thermalization in cool post-shock gas (Carlsson & Stein 2002ApJ...572..626C)
- H I atom top set by n_2 + Balmer loop: enormous post-shock overpopulations (also $n_{\rm cont}$)
- n_2 hangs at LTE values in shock spikes (C_{lu} large at high T, small at low T)
- no Lyman lines ($S \stackrel{\rm def}{=} J$), but Ly$\alpha$ has $S \approx b_2 \, B(T)$ $\Rightarrow$ does Balmer tail wag Lyman dog?



A venerable simulation, only 2D but very didactic. The two movies are available here *and* here*.*

The scene contains two opposite-polarity magnetic concentrations that expand with height. Shocks run up along them and produce dynamic fibrils. The clapotispheric domain in the "internetwork" between the field concentrations is filled with repetitive shocks and cool post-shock clouds.

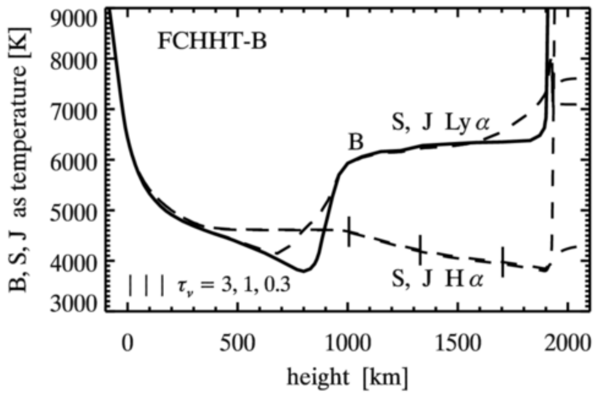
*Slow hydrogen ionization/recombination balancing in cool post-shock gas (*Carlsson & Stein 2002*) is due to enormous overexcitation of the n=2 population. Reason: the upward collision rate in the 10 eV Lyα jump is large in hot shocks but small in cool gas. In the latter the time needed to reach collisional balance (LTE population ratio) is long; typical three-minute shock repetitivity is too fast for settling.*

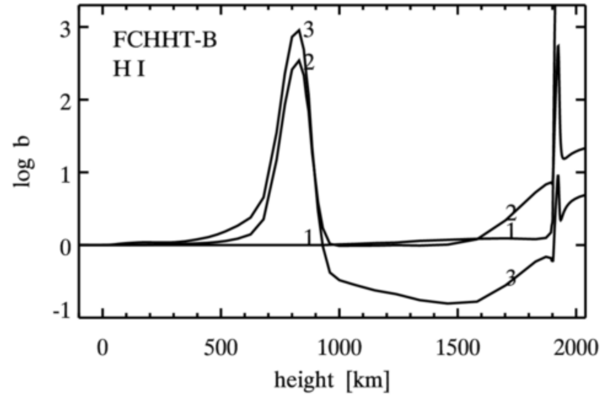
Within the hot and dense shocks the n=2 population does reach values near LTE (see bottom panels of the second movie). In the shock aftermath the overpopulation grows to gigantic values simply because the population stays at that high value while the temperature drops. So LTE holds for the Hα opacity — as long as you apply it at the hottest moment in the recent past and maintain that value!

In this simulation there were no Lyman lines. Since the Lyα source function has $S^l = b_2\,B(T_{\rm e})$ it seems to also dance up and down over these enormous factors. This worried me for some time (the tail wagging the elephant?) until I realized that it is B that dances up and down, not the radiation field J in Lyα. That stays near its highest value and smoothes out spatially as well (next screen).

Hα EXTINCTION: Lyα SCATTERING SMOOTHING TO HOT LTE NEARBY

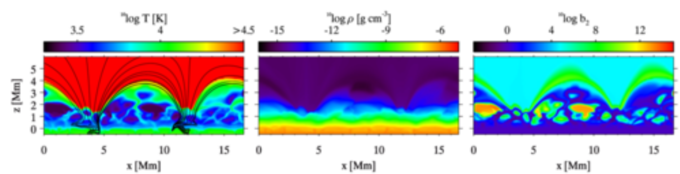
Rutten & Uitenbroek *2012A&A...540A..86R*



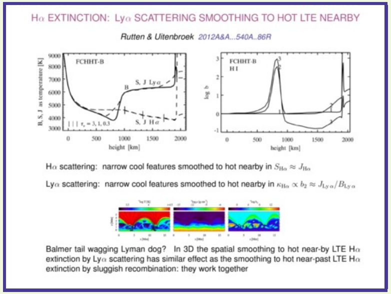


Hα scattering: narrow cool features smoothed to hot nearby in $S_{\mathrm{H}\alpha} \approx J_{\mathrm{H}\alpha}$

Lyα scattering: narrow cool features smoothed to hot nearby in $\kappa_{\mathrm{H}\alpha} \propto b_2 \approx J_{\mathrm{Ly}\,\alpha}/B_{\mathrm{Ly}\,\alpha}$



Balmer tail wagging Lyman dog? In 3D the spatial smoothing to hot near-by LTE Hα extinction by Lyα scattering has similar effect as the smoothing to hot near-past LTE Hα extinction by slow Lyα thermalization: they work together



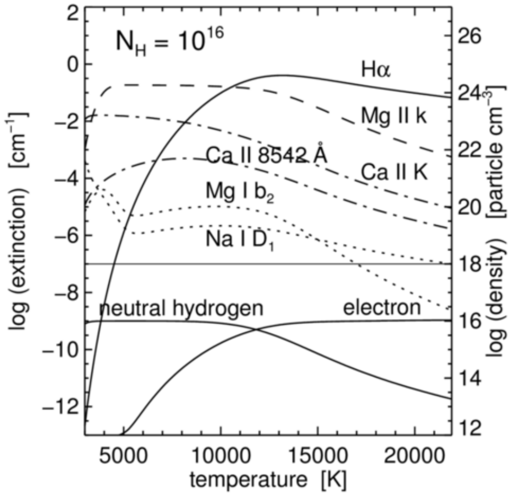
Not a simulation but classical 1D line synthesis from a static standard model. Such models describe the chromosphere as a single-state environment (and so cannot explain the simultaneous appearance of D_1, D_2, and D_3 in the flash spectrum), negating the terrific dynamics and fine structure that one sees in e.g., DOT Hα movies. But although hopelessly unrealistic, they remain didactically useful (my students have to understand every spectral feature of the magnificent computational star VALIIIC).

These plots illustrate the smoothing of Hα opacity through Lyα scattering. The temperature minimum in this model is a narrow cool feature in the stratification. It sits at very large optical depth in Lyα, but yet the scattering in this line smoothes it out. So if small cool features at Hα-forming heights are bordered by hot ones, the Hα opacity rises to their temperature through Lyα scattering.

In the 2D simulation of the previous slide such spatial Lyα smoothing did not occur because the Lyman transitions were left out for tractability. The spatial smoothing illustrated here works the same way as the temporal smoothing from slow recombination balancing shown there. They work together in setting the Hα opacity to the highest values nearby in both space and time. Hα is a remote senser!

Of course the Hα source function is smoothed also, connecting it to hot nearby values as also illustrated above. Through standard two-level scattering (don't worry about Thomas' "photo-electric control" which concers η detours but is only important in exotic circumstances such as flare rims).

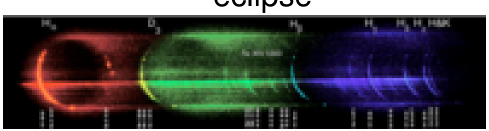
LTE EXTINCTION: Hα IS THE HIGH-TEMPERATURE CHAMPION



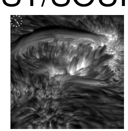
- *LTE extinction: valid at hot moments (Hα: thereafter and thereabouts)*
  - photosphere: Hα weaker than Mg II h & k and Ca II H & K lines
  - chromosphere: Hα $\approx$ Mg II and Ca II in shocked gas and remembers that
  - outbursts (Ellerman bombs, flares, CMEs): extraordinary Hα opacity

- *observational connotations*

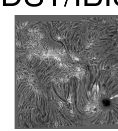
eclipse



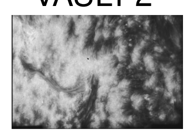
SST/SOUP



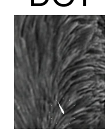
DST/IBIS

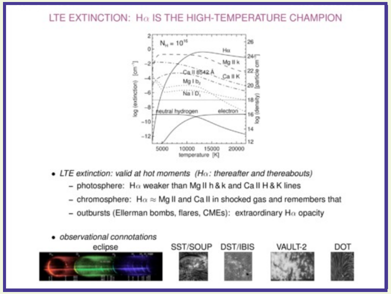


VAULT-2



DOT





The plot is a basic Saha-Boltzmann exercise, exactly like my Cecilia Payne emulation but for chromospheric lines. I should have made it twenty years ago. I find it an eye-opener! Take a cm^3 of solar-composition gas with given total hydrogen density and plot the LTE opacities of lines as function of temperature. When you reduce the hydrogen density you will find that these curves shift down and that their crossings shift to the left, but the patterns remain the same. The neutral hydrogen and electron densities are plotted at the bottom, scale at right. The electron-density plateau from metal ionization at 10^{-4} $N_{\rm Htot}$ for $T < 5\,000$ K falls just below the plot. The line is τ=1 for a 100-km slab.

First inspect the Mg II k opacity curve. At the far left, Mg I ionizes to Mg II. Then that dominates until Mg III takes over. Similarly so for Ca II K, but Ca II dominates sooner due to lower Ca I ionization energy. Mg I and Na I drop at first due to increasing temperature, then flatten due to increasing $N_{\rm e}$ (Mg I b$_2$ wins from excitation), and then differ because the Na II ionization energy is very high.

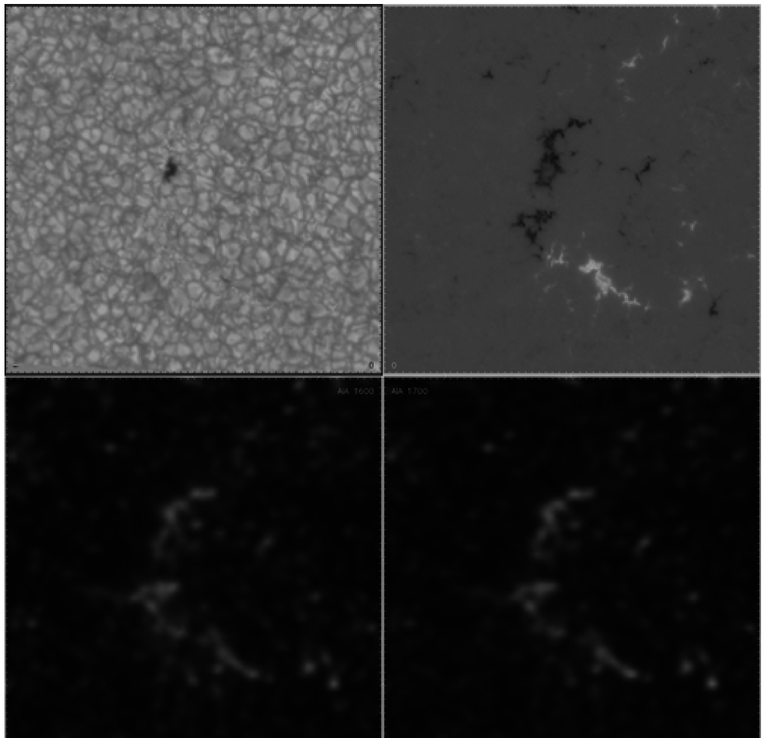
Hα is extraordinary! Its 10 eV excitation energy produces the very steep Boltzmann rise from nothing (so that Ca II K is much much stronger in the photospheric spectrum) to being even stronger than Mg II k above 12 000 K! And this goes on to much higher temperature. Even in coronal conditions hydrogen is still 10^{-5} neutral (because it lacks higher ionization stages to dump into). Combined with the gigantic hydrogen abundance this means opaque, opaque, opaque!

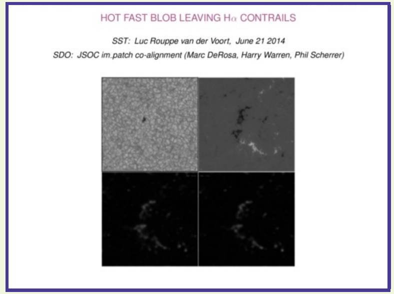
I didn't have time to open all the relevant clicker movies at the bottom. See next slide instead.

HOT FAST BLOB LEAVING Hα CONTRAILS

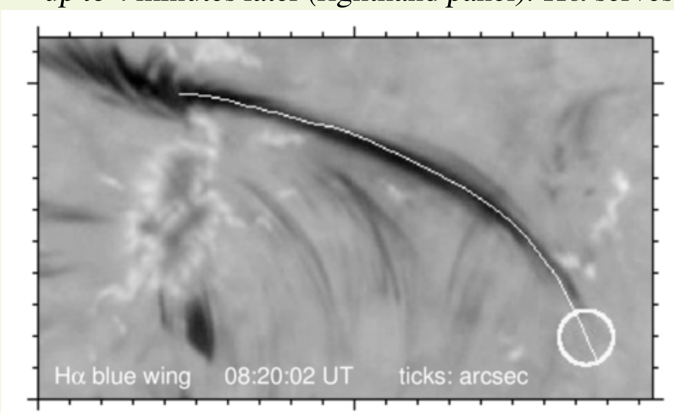
SST: Luc Rouppe van der Voort, June 21 2014

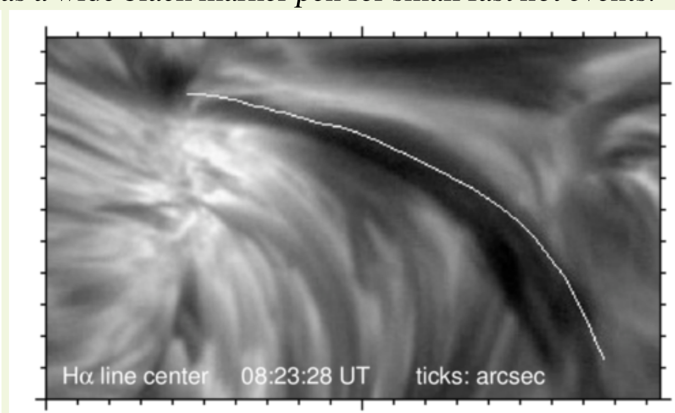
SDO: JSOC im_patch co-alignment (Marc DeRosa, Harry Warren, Phil Scherrer)





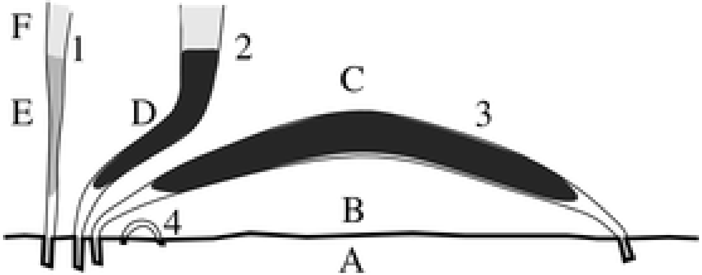
Luc's recent SST observations. My SDO alignment software uses minute JSOC im_patch downloads. Clockwise: continuum intensity, Stokes-V, AIA 1700 and 1600 Å. In AIA 171 and 193 Å I noticed a bright tadpole-shaped blob departing at speed from the upper tip of the black enhanced network patch, travelling to the right and down. It drew an Hα fibril behind it just as a jet draws a contrail! I showed this with multiple four-panel movies; below are cutouts. The circle is the location of the 171 tadpole head at the end of its track = white curve. In the Hα blue wing its track is outlined by an exceptionally dark contrail marking a very wide Hα core. In the movie its tip extends following the tadpole head. Hα line center showed a weak fibril at this time, but that darkened subsequently and outlined the track up to 4 minutes later (righthand panel). Hα serves as a wide black marker pen for small fast hot events.





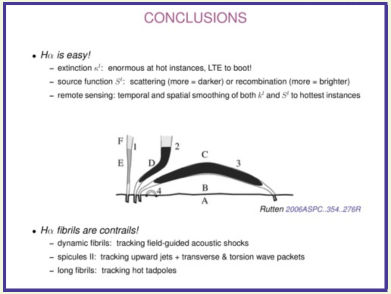
CONCLUSIONS

- *Hα is easy!*
  - extinction κ^l: enormous at hot instances, LTE to boot!
  - source function S^l: scattering (more = darker) or recombination (more = brighter)
  - remote sensing: temporal and spatial smoothing of both k^l and S^l to hottest instances



Rutten *2006ASPC..354..276R*

- *Hα fibrils are contrails!*
  - dynamic fibrils: tracking field-guided acoustic shocks
  - spicules II: tracking upward jets + transverse & torsion wave packets
  - long fibrils: tracking hot tadpoles



Hα has the LTE opacity of the highest-temperature instances in the past and nearby. As simple as that! The cartoon described my fibrilar bewilderment when I had noticed "straws" in a DOT Ca II H near-limb movie. They became spicules-II through Bart De Pontieu and Viggo Hansteen, who by then had already explained dynamic fibrils. The movies I showed here illustrate why Hα shows any type of fibril extraordinarily. They are contrails! Opaque from hot memory, dark from $\sqrt{\varepsilon}$ scattering.

In dynamic fibrils the hot fronts are simple acoustic shocks sloshed up into relatively empty fluxtubes by the interference pattern of the global p-mode oscillations. They appear in phased rows because the pattern humps are wider than the fluxtube separations along intergranular lanes. The Hα contrail memory makes them appear smoothly dark after the shock passage.

In spicules-II the hot blobs represent jets with transverse and torsional magnetic-wave additions. Their on-disk visibility as Hα RBEs and RREs is enhanced by the Hα contrail memory. Some theorists make much ado about precise wave naming, but in my view the difference with dynamic fibrils is a torsion kick inflicted by small-scale vorticity in the granular convection. It adds travel length.

The long fibrils that arch over internetwork areas are also Hα contrails. Due to heating events much as spicules-II, but at a more horizontal trajectory. They likely outline similar jetlike heating events (component reconnection? Alfvén-wave excitation?) with a torsion kick into long travel along bent-over fields, line-tied from ionization. Mapping the past horizontal field topography, not the present.

1

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14th European Solar Physics Meeting, September 2014, Dublin

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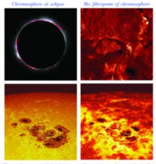

2

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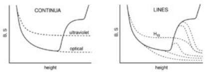

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- *continua*
  - optical: radiative equilibrium ⇒ $J \approx B \approx S^c$ (even in fluxtubes)
  - ultraviolet: $S^c \approx J > B$ ⇒ overionization of Fe I, Mg I, Si I, Al I, ...
- *lines*
  - photospheric Fe I, Mg I, Si I, Al I, ... lines: $\kappa^l < \kappa^l_{\rm LTE}$ $S^l \approx B$
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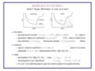


All solar NLTE on one slide. If you invite me to teach I will spend a week to derive these cartoons.

The first cartoon shows that the ultraviolet continua originate deeply at such a steep Planck function that the radiation field followed by their source function is superthermal in the upper photosphere. Standard two-level scattering theory applied to bound-free transitions. It produces substantial overionization of all neutral metal atoms, and therefore substantial underopacity for all their lines (Fe I, Ti I, Mg I, Al I, etc). If you invert or model say Fe I lines in polarimetry or irradiance studies you must evaluate the ionizing ultraviolet continua in NLTE. The common notion that LTE just means $S^l \approx B$ (not a bad assumption in the photosphere) ignores this substantial opacity NLTE.

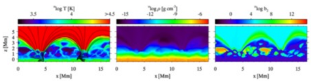
The second cartoon shows the typical behavior of strong scattering lines. Their source function follows $B(T_e)$ until the start of photon escape ("thermalization depth") through two-level scattering. They all then share a similar outward decline set by the $\sqrt{\varepsilon}$ law. If PRD applies such curves apply to different parts of the line (wings getting loose sooner).

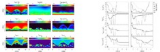
Hα is also a two-level scattering line, just like all other chromospheric lines, but its curve differs across the upper photosphere because this is transparent in Hα due to its large 10 eV excitation energy. The photons that originate in the deep photosphere get partially scattered back from the (model) chromosphere so that the radiation J builds up to a high plateau. So much for the Hα source function. Now the Hα opacity. For other chromospheric lines this is usually LTE. Actually also for Hα, but special.

6

Hα EXTINCTION: SLUGGISH RECOMBINATION SMOOTHING TO HOT LTE PAST

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

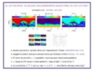




- shocks everywhere: dynamic fibrils and "clapotisphere" (Rutten 1995ESASP.376a.151R)
- sluggish ionization settling in cool post-shock gas (Carlsson & Stein 2002ApJ...572..626C)
- H I atom top slaved to $n=2$ population: enormous post-shock overpopulations
- n_2 hangs at LTE values in shock spikes (C_{lu} large at high T, small at low T)
- no Lyman lines ($S \stackrel{\rm def}{=} J$), but Lyα has $S \approx b_2\,B(T)$ ⇒ does Balmer tail wag Lyman dog?

7

start *index*



A venerable simulation, only 2D but very didactic. The two movies are available here and here.

The scene contains two opposite-polarity magnetic concentrations that expand with height. Shocks run up along them and produce dynamic fibrils. The clapotispheric domain in the "internetwork" between the field concentrations is filled with repetitive shocks and cool post-shock clouds.

Slow hydrogen ionization/recombination balancing in cool post-shock gas (Carlsson & Stein 2002) is due to enormous overexcitation of the n=2 population. Reason: the upward collision rate in the 10 eV Lyα jump is large in hot shocks but small in cool gas. In the latter the time needed to reach collisional balance (LTE population ratio) is long; typical three-minute shock repetitivity is too fast for settling.

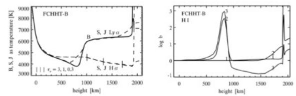
Within the hot and dense shocks the n=2 population does reach values near LTE (see bottom panels of the second movie). In the shock aftermath the overpopulation grows to gigantic values simply because the population stays at that high value while the temperature drops. So LTE holds for the Hα opacity — as long as you apply it at the hottest moment in the recent past and maintain that value!

In this simulation there were no Lyman lines. Since the Lyα source function has $S^l = b_2\,B(T_e)$ it seems to also dance up and down over these enormous factors. This worried me for some time (the tail wagging the elephant?) until I realized that it is B that dances up and down, not the radiation field J in Lyα. That stays near its highest value and smoothes out spatially as well (next screen).

8

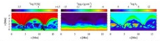
Hα EXTINCTION: Lyα SCATTERING SMOOTHING TO HOT LTE NEARBY

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



Hα scattering: narrow cool features smoothed to hot nearby in $S_{\rm H\alpha} \approx J_{\rm H\alpha}$

Lyα scattering: narrow cool features smoothed to hot nearby in $\kappa_{\rm H\alpha} \propto b_2 \approx J_{\rm Ly\alpha}/B_{\rm Ly\alpha}$



Balmer tail wagging Lyman dog? In 3D the spatial smoothing to hot near-by LTE Hα extinction by Lyα scattering has similar effect as the smoothing to hot near-past LTE Hα extinction by sluggish recombination: they work together

9

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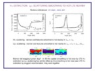


Not a simulation but classical 1D line synthesis from a static standard model. Such models describe the chromosphere as a single-state environment (and so cannot explain the simultaneous appearance of D_1, D_2, and D_3 in the flash spectrum), negating the terrific dynamics and fine structure that one sees in e.g., DOT Hα movies. But although hopelessly unrealistic, they remain didactically useful (my students have to understand every spectral feature of the magnificent computational star VALIIIC).

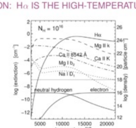
These plots illustrate the smoothing of Hα opacity through Lyα scattering. The temperature minimum in this model is a narrow cool feature in the stratification. It sits at very large optical depth in Lyα, but yet the scattering in this line smoothes it out. So if small cool features at Hα-forming heights are bordered by hot ones, the Hα opacity rises to their temperature through Lyα scattering.

In the 2D simulation of the previous slide such spatial Lyα smoothing did not occur because the Lyman transitions were left out for tractability. The spatial smoothing illustrated here works the same way as the temporal smoothing from slow recombination balancing shown there. They work together in setting the Hα opacity to the highest values nearby in both space and time. Hα is a remote senser!

Of course the Hα source function is smoothed also, connecting it to hot nearby values as also illustrated above. Through standard two-level scattering (don't worry about Thomas' "photo-electric control" which concers η detours but is only important in exotic circumstances such as flare rims).

10

LTE EXTINCTION: Hα IS THE HIGH-TEMPERATURE CHAMPION



- *LTE extinction: valid at hot moments (Hα: thereafter and thereabouts)*
  - photosphere: Hα weaker than Mg II h & k and Ca II H & K lines
  - chromosphere: Hα ≈ Mg II and Ca II in shocked gas and remembers that
  - outbursts (Ellerman bombs, flares, CMEs): extraordinary Hα opacity
- *observational connotations*

11

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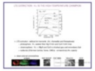


The plot is a basic Saha-Boltzmann exercise, exactly like my Cecilia Payne emulation but for chromospheric lines. I should have made it twenty years ago. I find it an eye-opener! Take a cm³ of solar-composition gas with given total hydrogen density and plot the LTE opacities of lines as function of temperature. When you reduce the hydrogen density you will find that these curves shift down and that their crossings shift to the left, but the patterns remain the same. The neutral hydrogen and electron densities are plotted at the bottom, scale at right. The electron-density plateau from metal ionization at $10^{-4}\,N_{\rm Htot}$ for $T < 5\,000$ K falls just below the plot. The line is τ=1 for a 100-km slab.

First inspect the Mg II k opacity curve. At the far left, Mg I ionizes to Mg II. Then that dominates until Mg III takes over. Similarly so for Ca II K, but Ca II dominates sooner due to lower Ca I ionization energy. Mg I and Na I drop at first due to increasing temperature, then flatten due to increasing N_e (Mg I b_2 wins from excitation), and then differ because the Na II ionization energy is very high.

Hα is extraordinary! Its 10 eV excitation energy produces the very steep Boltzmann rise from nothing (so that Ca II K is much much stronger in the photospheric spectrum) to being even stronger than Mg II k above 12 000 K! And this goes on to much higher temperature. Even in coronal conditions hydrogen is still 10^{-5} neutral (because it lacks higher ionization stages to dump into). Combined with the gigantic hydrogen abundance this means opaque, opaque, opaque!

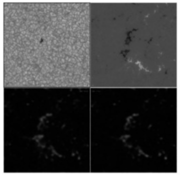
I didn't have time to open all the relevant clicker movies at the bottom. See next slide instead.

12

HOT FAST BLOB LEAVING Hα CONTRAILS

SST: Luc Rouppe van der Voort, June 21 2014

SDO: JSOC im.patch co-alignment (Marc DeRosa, Harry Warren, Phil Scherrer)



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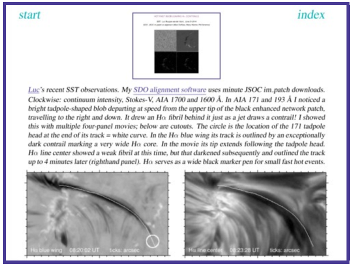

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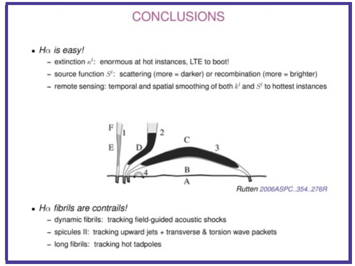

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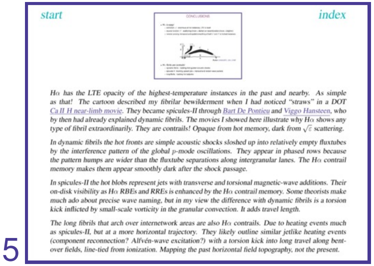

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