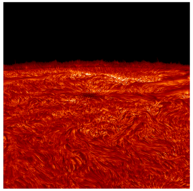
TEMPORAL CHROMOSPHERIC FINE STRUCTURE



Rob Rutten

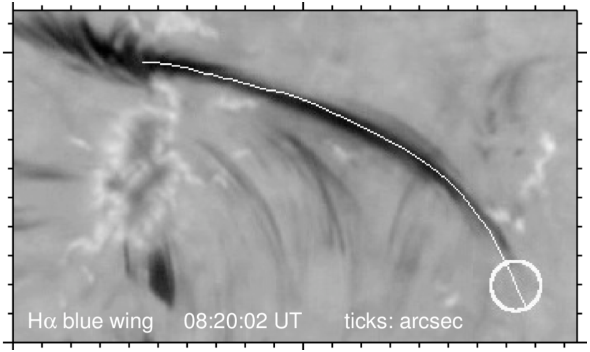
Rutten & Rouppe van der Voort *2017A&A...597A.138R*
Rutten *2017A&A...598A..89R*
Rutten *2016arXiv161105308R (IAUS 327)*

- *Hα fibril ∼ contrail from jet engine*
  - fat Hα line-center fibril after spicule-II-like quiet-Sun heating event
  - precursor heating to coronal temperature; contrail non-E opaque
  - fibrilar nature Hα chromosphere ≈ coronal heating? Find more engines...
- *SDO – SST pipeline = robust black boxes ready for you*
  - order and download SDO cutouts (small = fast: ∼ sequence duration)
  - co-align all AIAs to HMI with 0.1″ precision
  - co-align all SDOs to SST with 0.1″ precision and browse
- *detecting precursor-contrail pairs = difficult but worthwhile*
  - SST: statistical evidence of ubiquity, but precursors too small for AIA
  - CLASP: hard to detect even in super-opaque Lyα (Kubo san)
  - DKIST? not with SE Ca II 8542 Å; with non-E He I 10830 Å?
  - ALMA?! even a super-Zeeman non-E line?

LONG Hα FIBRIL AS CONTRAIL AFTER PROPAGATING HEATING EVENT

SST 2014-06-21 first shown ESPM Dublin 2014

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



- Hα blue wing: fantail with slender extending dark thread $=$ wide blueshifted core
- propagating heating event extending in IRIS 1400 Å (Si IV), AIA 304, 171, 193 Å
- two-four minutes later dark Hα core fibril, retracting with increasing redshift at both ends
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  - Hα fibril $\sim$ contrail: not representing cool present but hot precursor past
  - precursor RBE-like but more horizontal trajectory?
  - are many / most / all long Hα fibrils contrails? Hard to find, much confusion

SDO – SST PIPELINE

RR project: Sunspot 2013 – surgery Jan 2017 – Sunspot 2017

- *Step 1: find precise solar location (X, Y, t)*
  - **gbo_findlocation.pro**: match granulation wherever to that in HMI continuum
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  - optionally, at much activity, improves AIA co-alignments by matching 304 Å and Hα
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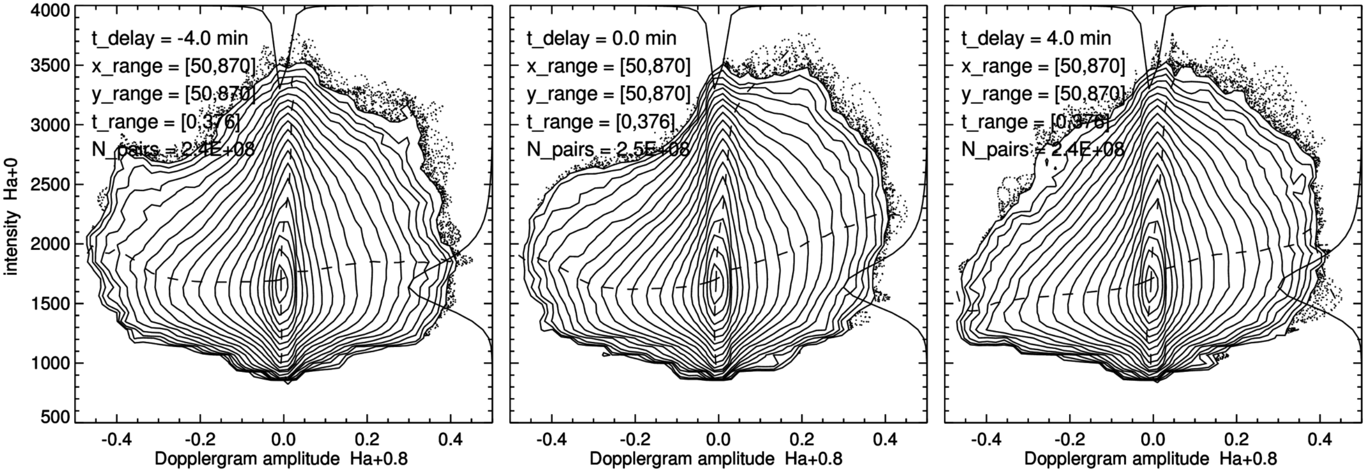
@RR: RUN DEMO SST CONTRAIL DATA 2014-06-21

```
cd,'/home/rutten/data/SST/2014-06-21-quiet'     ; no 8542 here, too large
; assoc into IRIS SJI, SST CRISPEX, all SDO files
files=['iris2sst/sji1400_algbo.fits','iris2sst/sji2796_algbo.fits',$
       'crispex/crispex.6563.08:02:31.time_corrected.aligned.icube']
allsdo=1                ; all SDO channels, whyse not
sstspecsavs='crispex/spectfile.6563.idlsave'    ; Halpha wavs specification
addlabels=1             ; superimpose SDO channel identifiers
intscale=-20            ; set greyscale to max-min stepping 20 per movie
selbox=[50,50,860,860]  ; cut off borders with black stripes in SST frames
; startup parameters
wavindA=24              ; Halpha outer wing Doppler, black=blue
wavindB=20              ; Halpha line-center intensity
doppA=1
;; time_delay=13        ; NO!  better start session at dt=0, slide delay later
plotscatter=1           ; show scatter plot
itthis=88               ; start at long Ha-wing precursor for blinking AIA

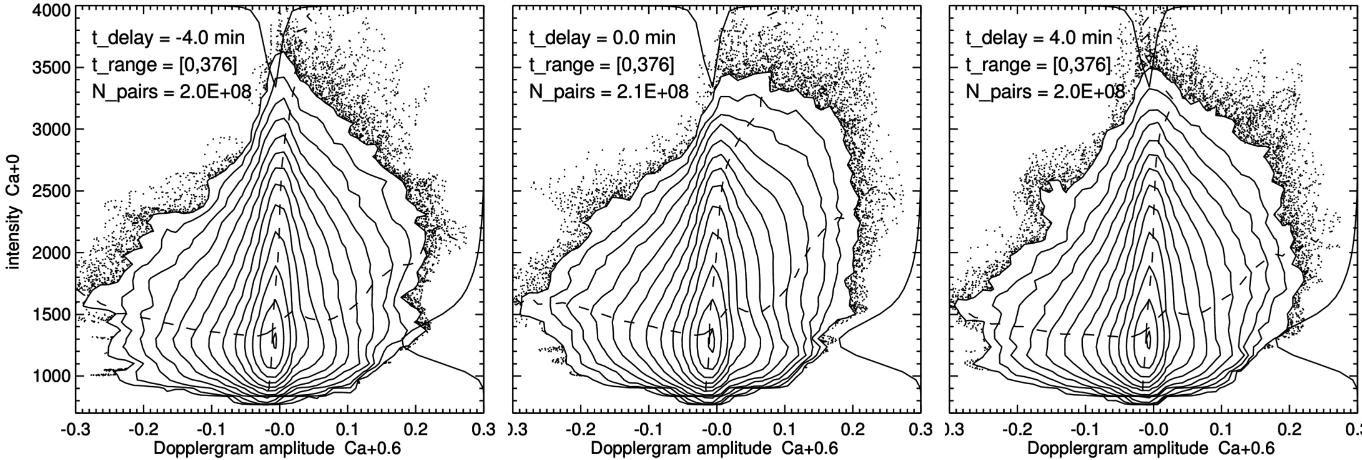
movex,files,ntfile=ntfile,$
; display options
  intscale=intscale,selbox=selbox,magnification=magnification,$
  addlabels=addlabels,plotmax=plotmax,plotscale=plotscale,$
  cadence=cadence,xrange=xrange,yrange=yrange,trange=trange,$
; ----- keywords for SDO and SST data
  allsdo=allsdo,sdodir=sdodir,sstspecsavs=sstspecsavs,sstlcs=sstlcs,$
; ----- optional startup parameters one may set
  plotprofile=plotprofile,plottimeline=plottimeline,$
  plotpower=plotpower,plotscatter=plotscatter,$
  wavindA=wavindA,wavindB=wavindB,doppA=doppA,doppB=doppB,$
  itthis=itthis,itfirst=itfirst,itlast=itlast,time_delay=time_delay
```

SCATTER Hα INTENSITY VERSUS DOPPLER



- Hα line-center intensity before / during / after far-wing Doppler in all 2.5$\times 10^8$ samples
- Strous format: factor 2 density contours to avoid plot saturation (current pro de Wijn)
- $\Delta t = -4$ min: no correlation (prof de Wijn curves perpendicular)
- $\Delta t = \ \ 0$ min: significant instantaneous correlation very-bright-at-medium-downdraft
- $\Delta t = +4$ min: significant correlation dark-after-hot-updraft, also when skipping contrail
- delay movies: contrail only all 377 time steps contrail skipped
- same signature $\Rightarrow$ evidence dark contrails and bright downfalls after RBE-like updrafts
- small-amplitude signature remains at smearing $\Rightarrow$ many unresolved (SST or Lyα?)

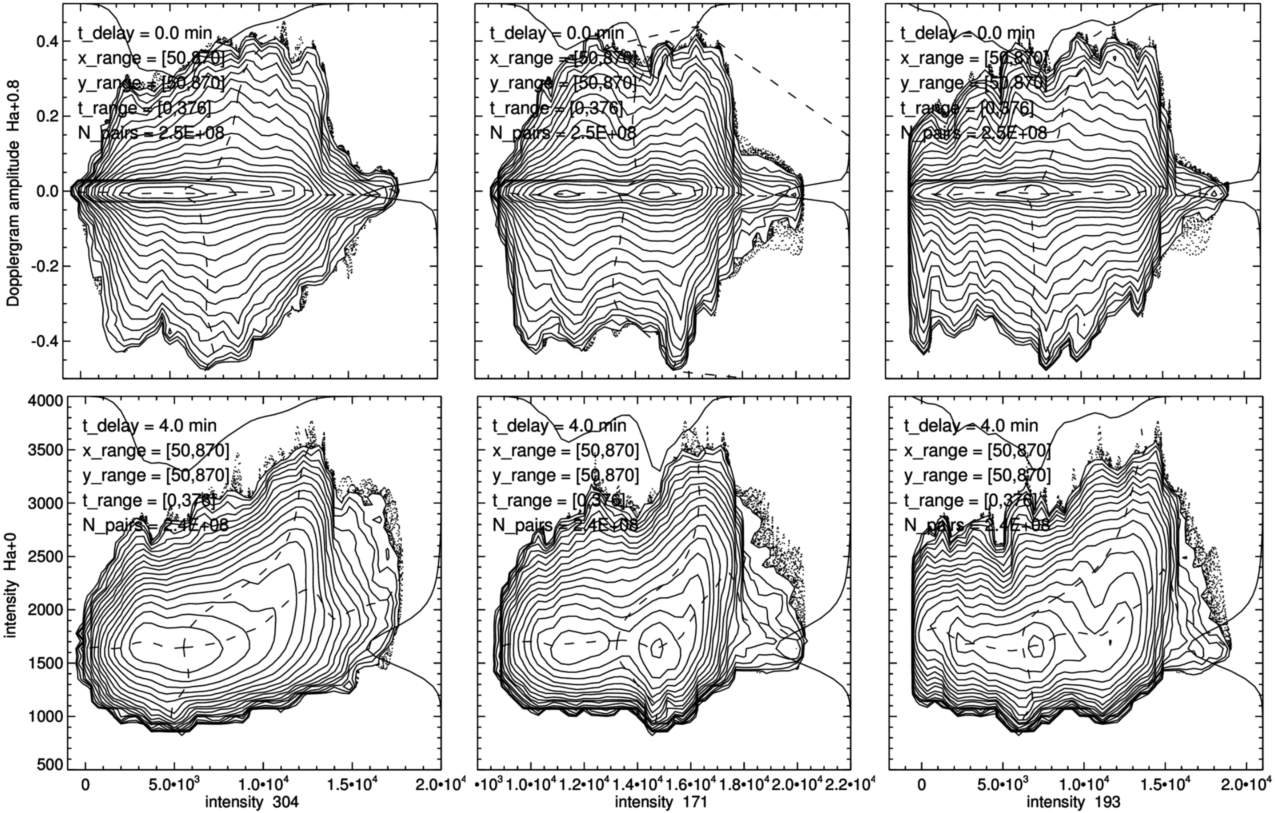
SCATTER Ca II 8542 Å INTENSITY VERSUS DOPPLER



- Ca II 8542 Å line-center intensity before / during / after far-wing Doppler
- $\Delta t = -4$ min $\approx \Delta t = +4$ min: no sign of memory as for Hα
  expected: no large jump as Lyα, hence fast settling to low temperature, SE valid
- $\Delta t = 0$ min:
  - right: instantaneous correlation very-bright-at-hot-downdraft as Hα
  - left: slight instantaneous correlation bright-at-updraft $=$ internetwork shocks

no contrail signature $\Longrightarrow$ Ca II 8542 Å shows non-ionizing chromosphere (CaII ionizes before H I)

SCATTER Hα DOPPLER AND INTENSITY VERSUS AIA 304, 171, 193 Å



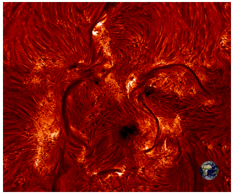
- no time-delay signature $\Rightarrow$ no evidence of precursor heating (flag at right $=$ microflare)
- AIA diagnostic formation mostly thin; heating features likely small / slender $=$ too small?
- try: subtraction, running difference, slender-feature alignment, sharper telescope, ...

THE SUN WITH ALMA

Rob Rutten

2017A&A...598A..89R $=$ *12 specific predictions*

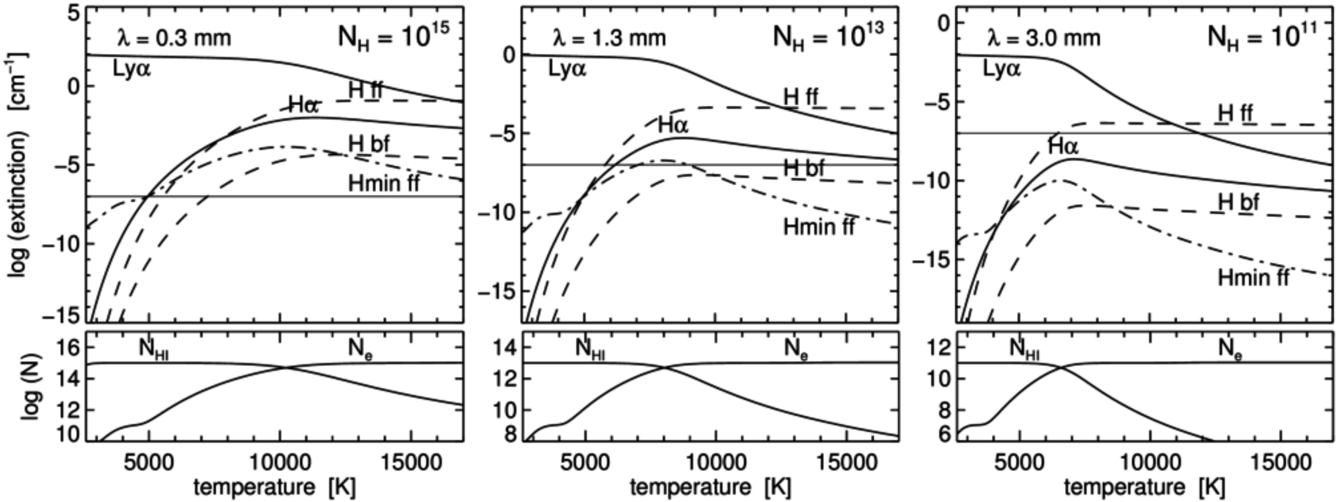
2016arXiv161105308R $=$ *IAUS 327* $=$ *tutorial*



- *solar observing with ALMA*
  - technique: blocking filters $\Rightarrow$ detector detuning (Pavel Yakoubov)
  - tests: 2014 and 2015 – images public 2017
  - Cycle 4 started Dec 2016: small array, continuum only, pointing? – program list
  - eventually sharp: at full baselines D/lambda gains $10^4/10^3 = 10$ over SST (but UV)
- *simulation predictions: low-chromosphere shocks and structural magnetism*
  - Wedemeyer et al. 2007A&A...471..977W: CO5BOLD quiet-sun shocks
  - Loukitcheva et al. 2015A&A...575A..15: Bifrost quiet-sun plage
  - Loukitcheva et al. 2017A+A...601A..43L: Bifrost quiet-sun field measurement
- *my predictions: high-chromosphere heating events and post-hot contrail canopies*
  - many if not most Hα fibrils are opaque post-heating contrails
  - ALMA continua have yet larger hot and post-hot extinction than Hα
  - ALMA will show high-chromosphere canopies and hopefully the heating events
  - H I 30α may show up in Band 6 (1.3 mm) and be a super Zeeman diagnostic

SAHA-BOLTZMANN HYDROGEN EXTINCTION

Rutten *2017A&A...598A..89R* *2016arXiv161105308R (IAUS 327 tutorial)*



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

SOLAR RYDBERG LINES WITH ALMA?

Rutten 2016arXiv161003104J

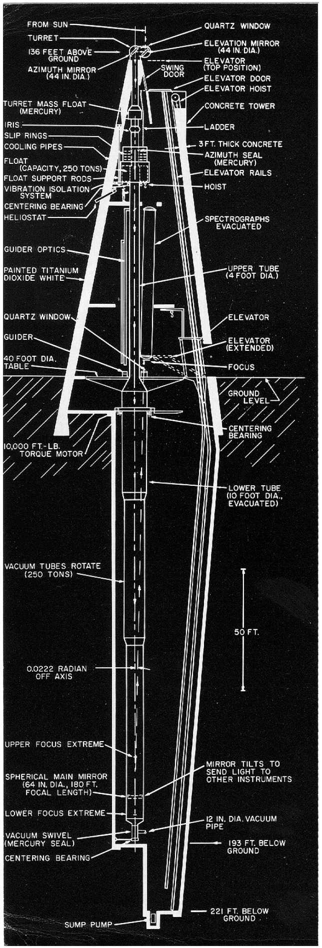
- *"linear thermometer"*
  - H^- free-free + H I free-free: $S \equiv B$
  - thick feature: $T_b = T(\tau_\nu = 1)$
  - thin feature: cloud contribution $\Delta T_b = \tau T$
- *solar Rydberg lines so far*
  - in μm range Mg I stronger than H I
  - prediction H I α lines $n = 4 - 18$
  - H I 19α, 21α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

CONCLUSIONS

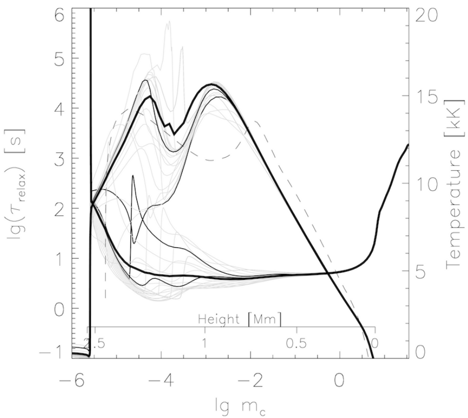
- *chromosphere: very much time dependent*
  - importance: ubiquitous small heating events
  - action: where hydrogen ionizes
  - boring: where hydrogen does not ionize

- *solar physics: in good shape*
  - population: youngsters here
  - observation: DKIST, ALMA coming; sharper EUV?
  - interpretation: LTE ⇒ NLTE ⇒ non-E ⇒ multi-fluid

- *Sacramento Peak Observatory @ 65: claim to fame*
  - world-leading solar physicists
  - world-leading solar physics
  - splendid mankind endeavour



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)

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

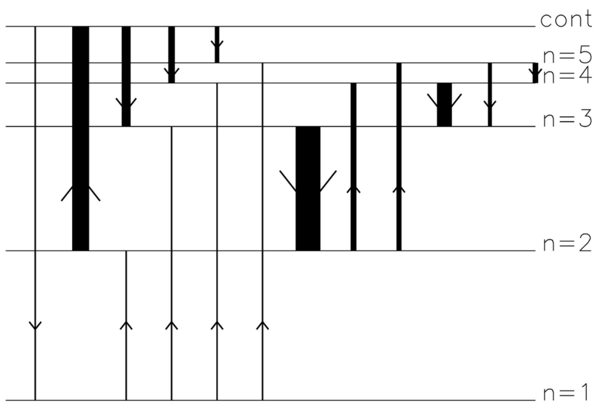
Einstein relation

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

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

NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

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



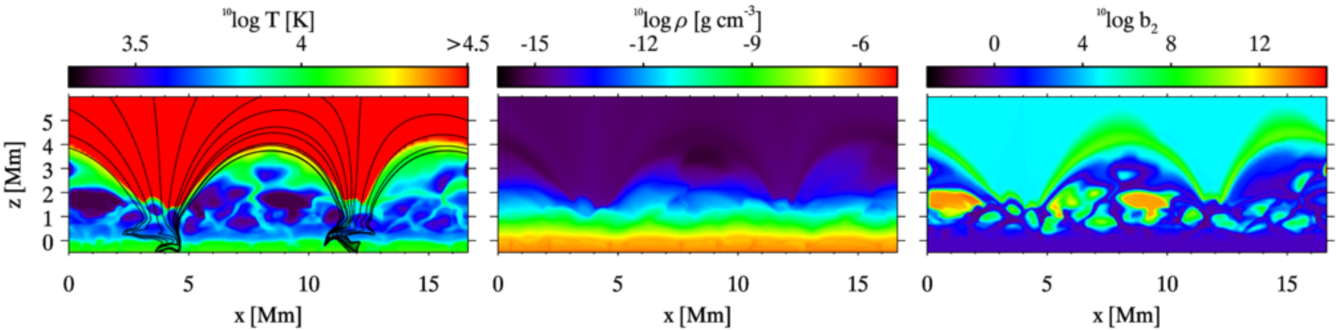
atom top ~ 3.4 eV alkali: NLTE-SE ionization loop
– driven by photon pumping Balmer continuum, scattering from deep, ≈5300 K, smooth
– closure by photon losses in n_α lines

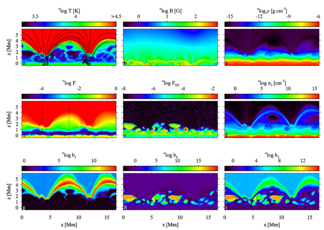
atom bottom actually up to 10 eV: non-E Lyα
– tremendous scatttering from small ε
– tremendous opacity from huge H abundance
– detailed radiative balance
– non-E: fast settling at high T, slow at low T

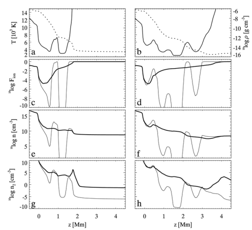
- RADYN code: 1D(t) hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed subphotosphere piston drives acoustic waves up that shock near $h=1000$ km
- Lyα scatters in radiative balance and controls $n=2$. Within shocks $S \approx J$ saturates to B from radiation lock-in (increased ε from 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

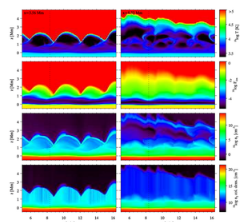
NON-E HYDROGEN IONIZATION IN 2D MHD SHOCKS

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



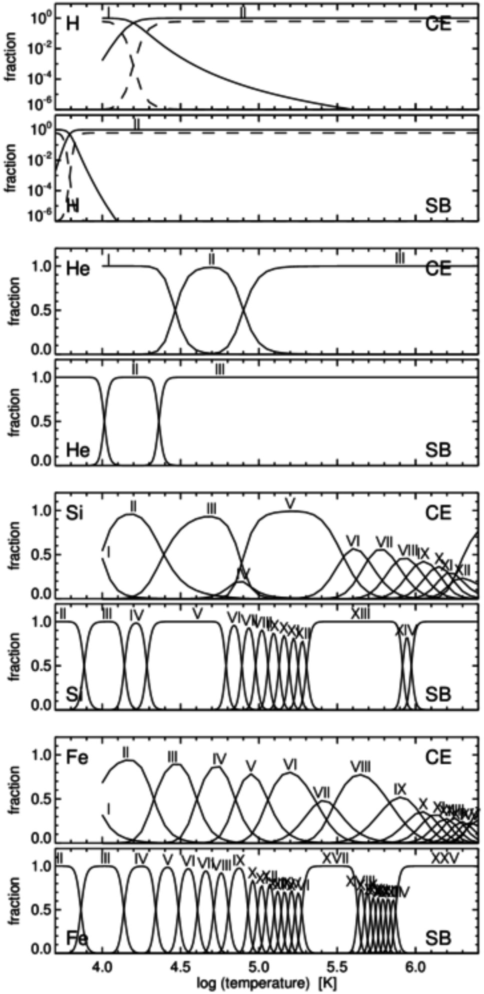






- in shocks Lyα has $S \approx B$ from high T (fast balancing) and N_e (10% H ionization)
- retarded collisional balancing in Lyα: n_2 hangs near high shock value $n_2 \approx n_2^{\mathrm{LTE}}$
- gigantic post-shock $n = 2$ overpopulations versus LTE (“S-B underestimates”)
- yet larger post-shock overionization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

CORONAL EQUILIBRIUM VERSUS SAHA-BOLTZMANN IONIZATION

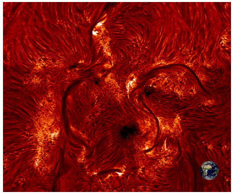


Rutten + Rouppe van der Voort 2017A&A...597A.138R
"Carole Jordan versus Cecilia Payne"

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

PREDICTIONS FOR SOLAR ALMA

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



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

SOLAR PRIORITY PROPOSALS IN CYCLE 4

https://almascience.nao.ac.jp/observing/highest-priority-projects

total: 376 prioritized proposals out of 1600 solar: 4% started: December 2016

1. 2016.1.00030.S Shimizu et al.: Micro- and nano-flaring heating events
2. 2016.1.00050.S De Pontieu et al.: Chromospheric heating
3. 2016.1.00070.S Shimojo et al.: High-energy electrons
4. 2016.1.00156.S Okamoto et al.: Wave heating in prominences
5. 2016.1.00166.S Fleischman et al.: Chromosphere hermal structure
6. 2016.1.00182.S Bastian et al.: Spicules
7. 2016.1.00201.S Yokoyama et al.: Chromospheric jets
8. 2016.1.00202.S White et al.: Quiet-Sun chromosphere
9. 2016.1.00298.S Leenaarts et al.: Plage chromosphere
10. 2016.1.00423.S Wedemeyer et al.: Chromospheric heating
11. 2016.1.00572.S Bastian et al.: Quiet sun
12. 2016.1.00788.S Kobelski et al.: Microflares
13. 2016.1.01129.S Reardon et al.: Internetwork waves
14. 2016.1.01408.S Antolin et al.: Coronal rain
15. 2016.1.01532.S Chen et al.: Penumbral energy release events

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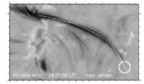

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RR project Sunspot 2013 – Sunspot 2017

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3

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       'crispex/crispex.6563.08:02:31.time_corrected.aligned.icube']
allsdo=1                ; all SDO channels, whyse not
sstspecsavs='crispex/spectfile.6563.idlsave'     ; Halpha wavs specification
addlabels=1             ; superimpose SDO channel identifiers
intscale=-20            ; set greyscale to max-min stepping 20 per movie
selbox=[50,50,860,860]  ; cut off borders with black stripes in SST frames
; startup parameters
wavindA=24              ; Halpha outer wing Doppler, black=blue
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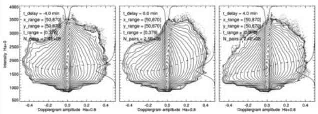
movex,files,ntfile=ntfile,$
; display options
  intscale=intscale,selbox=selbox,magnification=magnification,$
  addlabels=addlabels,plotmax=plotmax,plotscale=plotscale,$
  cadence=cadence,xrange=xrange,yrange=yrange,trange=trange,$
; ----- keywords for SDO and SST data
  allsdo=allsdo,sdodir=sdodir,sstspecsavs=sstspecsavs,sstlcs=sstlcs,$
; ----- optional startup parameters one may set
  plotprofile=plotprofile,plottimeline=plottimeline,$
  plotpower=plotpower,plotscatter=plotscatter,$
  wavindA=wavindA,wavindB=wavindB,doppA=doppA,doppB=doppB,$
  itthis=itthis,itfirst=itfirst,itlast=itlast,time_delay=time_delay
```

4

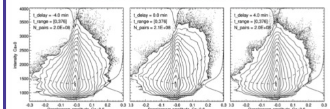
SCATTER Hα INTENSITY VERSUS DOPPLER



- Hα line-center intensity before / during / after far-wing Doppler in all $2.5{\times}10^8$ samples
- Strous format: factor 2 density contours to avoid plot saturation (current pro de Wijn)
- $\Delta t = -4$ min: no correlation (prof de Wijn curves perpendicular)
- $\Delta t = 0$ min: significant instantaneous correlation very-bright-at-medium-downdraft
- $\Delta t = +4$ min: significant correlation dark-after-hot-updraft, also when skipping contrail
- delay movies: contrail only all 377 time steps contrail skipped
- same signature ⇒ evidence dark contrails and bright downfalls after RBE-like updrafts
- small-amplitude signature remains at smearing ⇒ many unresolved (SST or Lyα?)

5

SCATTER Ca II 8542 Å INTENSITY VERSUS DOPPLER

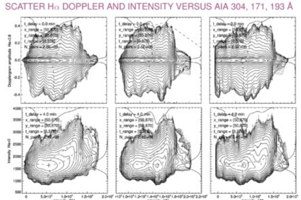


- Ca II 8542 Å line-center intensity before / during / after far-wing Doppler
- $\Delta t = -4$ min ≈ $\Delta t = +4$ min: no sign of memory as for Hα
  expected: no large jump as Lyα, hence fast settling to low temperature, SE valid
- $\Delta t = 0$ min:
  - right: instantaneous correlation very-bright-at-hot-downdraft as Hα
  - left: slight instantaneous correlation bright-at-updraft = internetwork shocks

no contrail signature ⇒ Ca II 8542 Å shows non-ionizing chromosphere (CaII ionizes before H I)

6

SCATTER Hα DOPPLER AND INTENSITY VERSUS AIA 304, 171, 193 Å



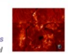
- no time-delay signature ⇒ no evidence of precursor heating (flag at right = microflare)
- AIA diagnostic formation mostly thin; heating features likely small / slender = too small?
- try: subtraction, running difference, slender-feature alignment, sharper telescope, ...

7

THE SUN WITH ALMA

Rob Rutten

2017A&A...598A..89R = 12 specific predictions
2016arXiv161105308R = IAUS 327 = tutorial

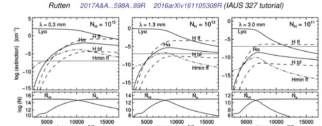


- *solar observing with ALMA*
  - technique: blocking filters ⇒ detector detuning (Pavel Yakoubov)
  - tests: 2014 and 2015 – images public 2017
  - Cycle 4 started Dec 2016: small array, continuum only, pointing? – program list
  - eventually sharp: at full baselines D/lambda gains $10^4/10^3 = 10$ over SST (but UV)
- *simulation predictions: low-chromosphere shocks and structural magnetism*
  - Wedemeyer et al. 2007A&A...471..977W: CO5BOLD quiet-sun shocks
  - Loukitcheva et al. 2015A&A...575A..15: Bifrost quiet-sun plage
  - Loukitcheva et al. 2017A+A...601A..43L: Bifrost quiet-sun field measurement
- *my predictions: high-chromosphere heating events and post-hot contrail canopies*
  - many if not most Hα fibrils are opaque post-heating contrails
  - ALMA continua have yet larger hot and post-hot extinction than Hα
  - ALMA will show high-chromosphere canopies and hopefully the heating events
  - H I 30α may show up in Band 6 (1.3 mm) and be a super Zeeman diagnostic

8

SAHA-BOLTZMANN HYDROGEN EXTINCTION

Rutten 2017A&A...598A..89R 2016arXiv161105308R (IAUS 327 tutorial)



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

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SOLAR RYDBERG LINES WITH ALMA?

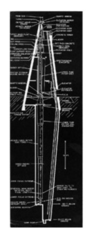
Rutten 2016arXiv161003104J

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

10

CONCLUSIONS

- *chromosphere: very much time dependent*
  - importance: ubiquitous small heating events
  - action: where hydrogen ionizes
  - boring: where hydrogen does not ionize
- *solar physics: in good shape*
  - population: youngsters here
  - observation: DKIST, ALMA coming; sharper EUV?
  - interpretation: LTE ⇒ NLTE ⇒ non-E ⇒ multi-fluid
- *Sacramento Peak Observatory @ 65: claim to fame*
  - world-leading solar physicists
  - world-leading solar physics
  - splendid mankind endeavour



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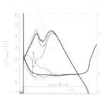
DETAILED BALANCING



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)

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

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

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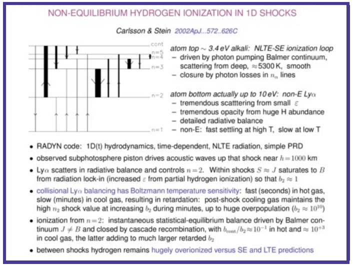

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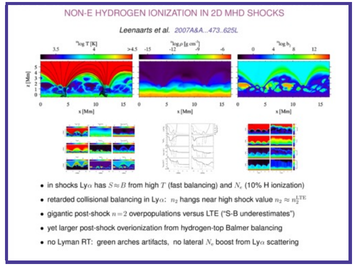

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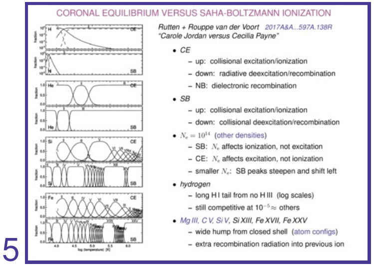

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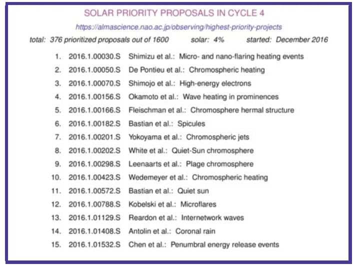

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thumbs/thumb-\par .jpg

1 .jpg

19 .jpg

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