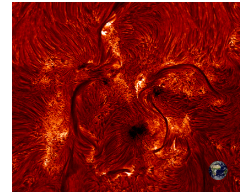
THE SUN WITH ALMA

Rob Rutten

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

2016arXiv161105308R = IAUS 327 = tutorial

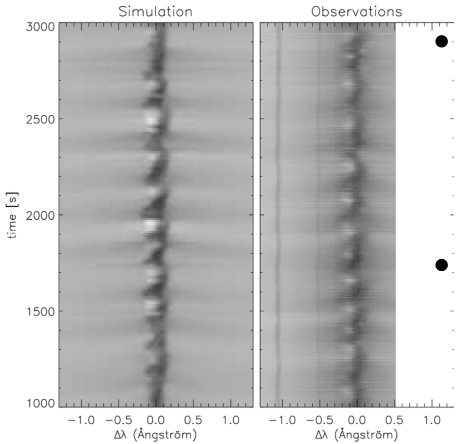


- *solar observing with ALMA*
  - technique: blocking filters ⇒ detector detuning (Pavel Yakoubov)
  - tests: 2014 and 2015 – images public 2017
  - Cycle 4, started December 2016 – program list

- *simulation predictions: low-chromosphere shocks and 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. 1702.06018v1: Bifrost quiet-sun field measurement

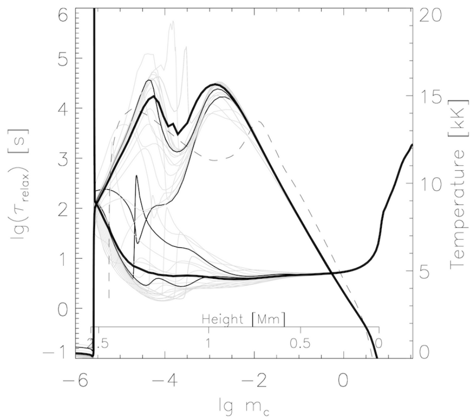
- *my predictions: high-chromosphere heating events and post-hot contrail canopies*
  - Hα fibrils are opaque post-hot contrails
  - ALMA continua have yet larger post-hot extinction than Hα
  - ALMA will show high-chromosphere canopies and hopefully the heating events

INTERNETWORK H_{2V} GRAINS $=$ ACOUSTIC SHOCKS



- *Ca II K_{2V} grains (Rutten & Uitenbroek 1991SoPh..134...15R)*
  - extended and confused literature (600 references)
  - most likely non-magnetic phenomenon
  - most likely acoustic shocks
  - wave interference reminiscent of “clapotis”
- *observation (Lites, Rutten & Kalkofen 1993ApJ...414..345L)*
  - sawtooth line-center shift
  - triangular whiskers
  - H_{2V} grains
- *simulation (Carlsson & Stein 1997ApJ...481..500C)*
  - 1D radiation hydrodynamics
  - subsurface piston derived from Fe I Doppler
  - emulation of observer’s diagnostics
- *analysis*
  - source function breakdown
  - dynamical chromosphere

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)

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

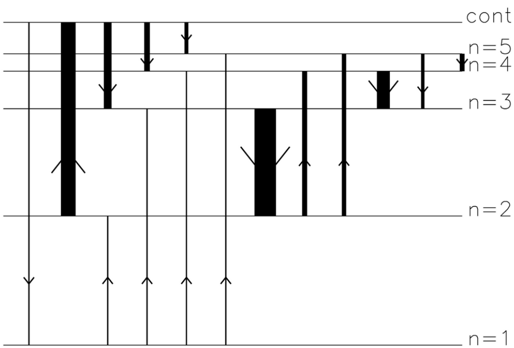
Einstein relation

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

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

NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

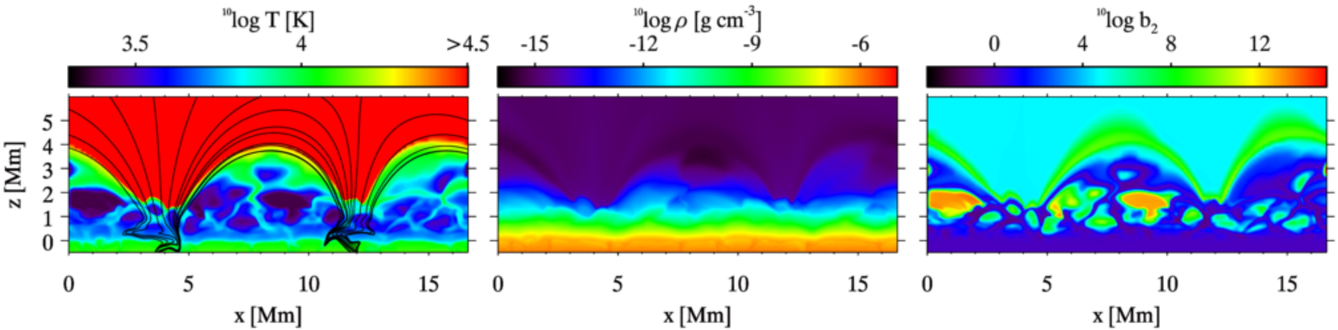
Carlsson & Stein 2002ApJ...572..626C

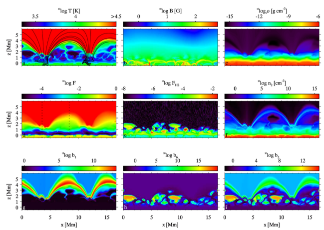


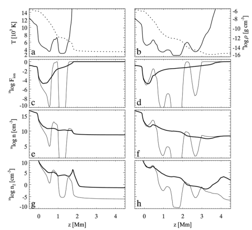
- RADYN code: 1D(t) hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed subphotosphere piston drives acoustic waves up that shock near $h = 1000$ km
- Lyα scatters in radiative balance and controls $n = 2$. Within shocks $S \approx J$ saturates to B from radiation lock-in (increased ε from partial hydrogen ionization) so that $b_2 \approx 1$
- collisional Lyα balancing has Boltzmann temperature sensitivity: fast (seconds) in hot gas, slow (minutes) in cool gas, resulting in retardation: post-shock cooling gas maintains the high n_2 shock value at increasing b_2 during minutes, up to huge overpopulation ($b_2 \approx 10^{10}$)
- ionization from $n = 2$ in the 3.4 eV alkali-like hydrogen top is an instantaneous statistical-equilibrium balance driven by Balmer continuum $J \neq B$ and closed by cascade recombination, with $b_{\rm cont}/b_2 \approx 10^{-1}$ in hot and $\approx 10^{+3}$ in cool gas, adding to the retarded b_2
- between shocks hydrogen remains hugely overionized versus SE and LTE predictions

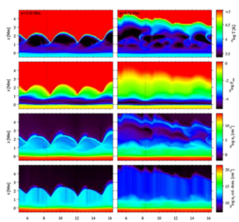
NON-E HYDROGEN IONIZATION IN 2D MHD SHOCKS

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





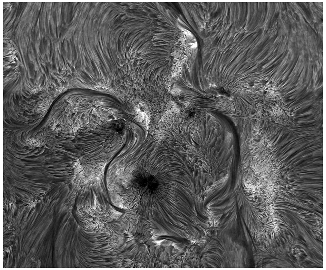


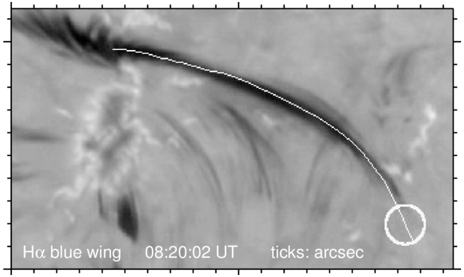


- in shocks Lyα has $S \approx B$ from high T (fast balancing) and N_e (10% H ionization)
- retarded collisional balancing in Lyα: n_2 hangs near high shock value $n_2 \approx n_2^{\rm LTE}$
- gigantic post-shock $n = 2$ overpopulations versus LTE ("S-B underestimates")
- yet larger post-shock overionization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

LONG H-alpha FIBRILS AS CONTRAILS AFTER HEATING EVENTS

Rutten 2017A&A...598A..89R *Rutten & Rouppe van der Voort 2017A&A...597A.138R*

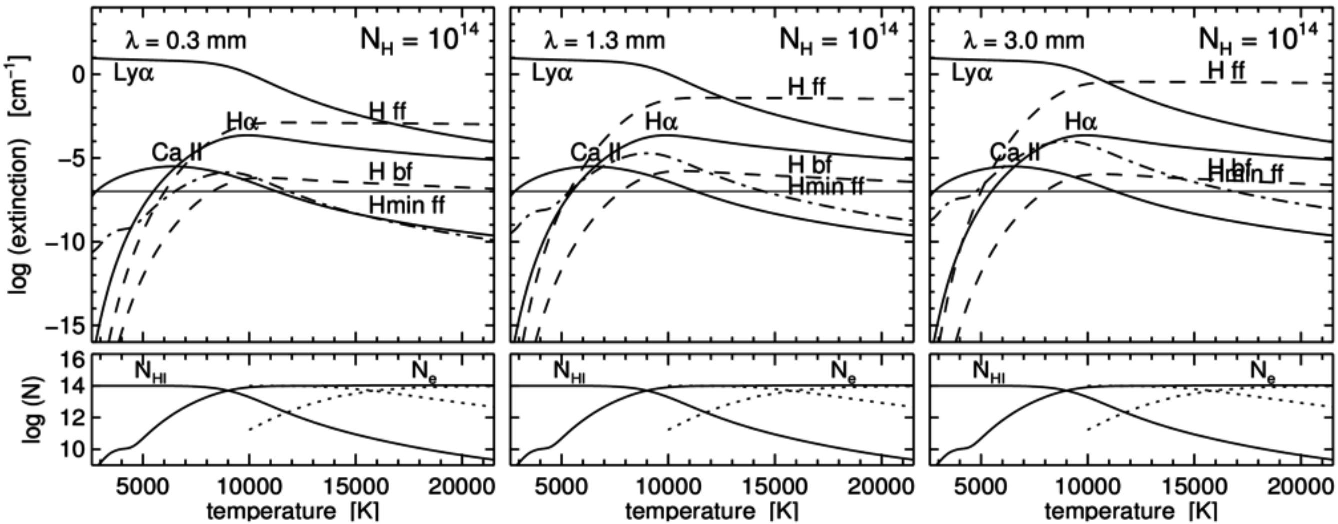




- *scenes*
  - Ca II H: instantaneous, bright = hot, internetwork shocks, thin active-region fibrils
  - Hα: long memory in cooling gas, ubiquitous long fibrils = contrail tracks
  - Lyα: dark = past, bright = instantaneous sampling of heating events
- *contrail example*
  - propagating heating event extending in Hα wing, He II 304, Fe IX 171
  - three-four minutes later followed by dark Hα core fibril
  - retracting with increasing redshift
- *issues*
  - are all long Hα fibrils contrails?
  - do they map magnetic field topography only at launch = H ionization?
  - precursor nature? Spicule-II-like? Component reconnection? Alfvénic wave burst?

SOLAR MM-WAVELENGTH EXTINCTION

Rutten 2017A&A...598A..89R *tutorial 2016arXiv161105308R*



- ALMA: "linear thermometer" since H ff and Hmin ff have S $=$ B ("source function LTE") but where is $\tau = 1$? ("extinction non-LTE" $\Rightarrow$ "non-E extinction")
- Hα at high T: LTE or larger instantaneous extinction enforced by Lyα
- H ff at high T: yet larger extinction $\propto \lambda^2$
- cooling recombining contrail fibrils: large post-hot Hα extinction, larger H I ff extinction
- prediction: fibril canopies more opaque than in Hα, hiding shock regime underneath, dark from low actual temperature, less lateral contrast from lack of scattering and Dopplershifts
- ALMA $=$ game changer: linear thermometer with extraordinary PSBE feature opacities

PREDICTIONS FOR SOLAR ALMA

- *conclusion 2017A&A...598A..89R* $=$ *prediction list*

  1. ALMA sun mostly covered by long fibrils (unlike simulations sofar)
  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 or less in long contrail fibrils
  4. heating events best detectable with large-array ALMA (@ temperatures)?
  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 (@ check and employ)
  8. internetwork shocks only in quietest areas, with 4000 K cooling clouds (@ how cool?)
  9. no Ellerman bombs (hidden by fibrils)
  10. flaring active-region fibrils poke through (@ reconnection temperature?)
  11. off-limb spicules-II more opaque than in Hα and Ca II H (@ check and employ)
  12. coronal rain much more opaque than in Hα (@ check and employ)

  "Hopefully these predictions will soon be verified with actual ALMA observations. I look forward to be proven right or wrong."

- *conclusion 2016arXiv161105308R*
  - line(s): H I 30-α in Band 6? potentially PSBE-cleaned wonderful Zeeman diagnostic!

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

CLAPOTISPHERE

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

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

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

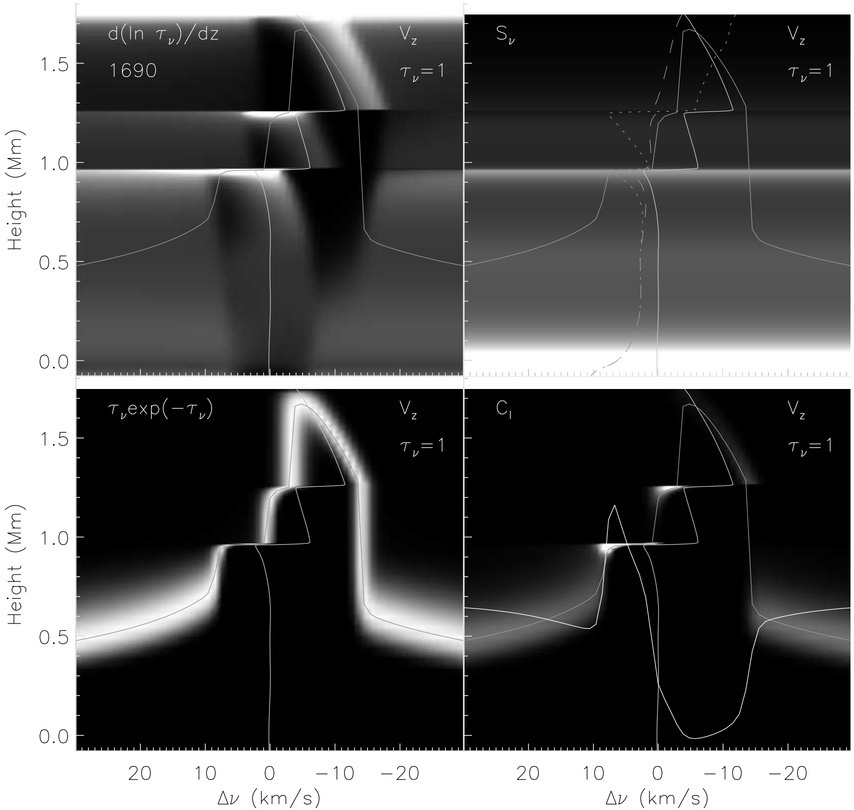
“When the crests of such waves coincide, their amplitudes combine, creating huge standing waves, much steeper than traveling waves. This phenomenon is called “clapotis”. Off the northern tip of New Zealand, where major wave patterns collide in deep water, clapotis is regularly seen. The pinnacling waves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

Dowd 1981 (not on ADS)

SHOCK GRAIN DIAGNOSIS

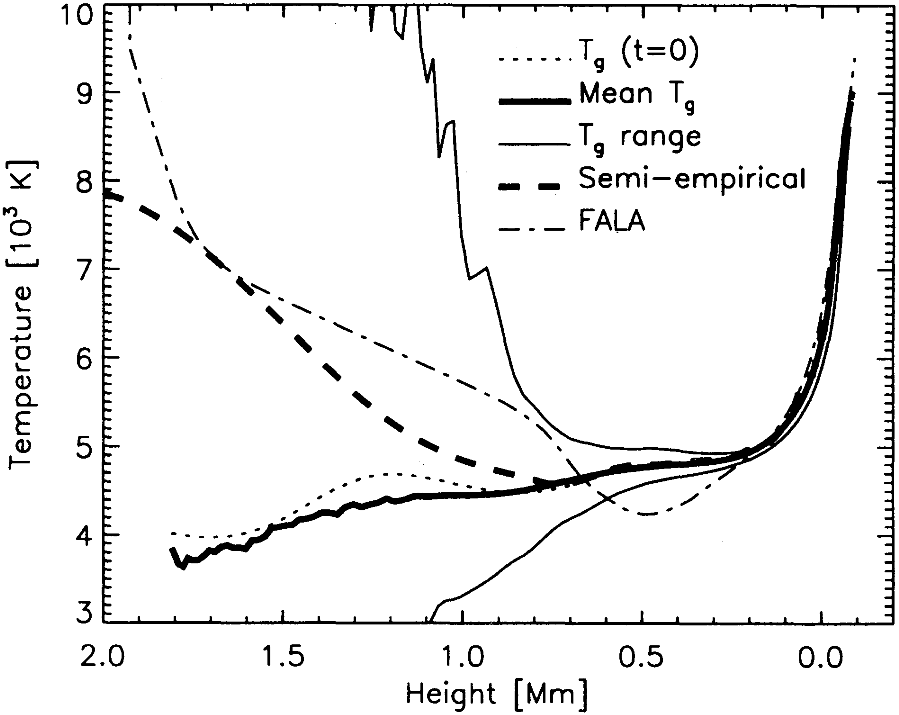
Carlsson & Stein 1997ApJ...481..500C

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



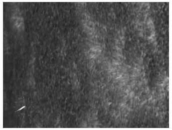
SHOCK-RIDDEN COOL LOWER CHROMOSPHERE

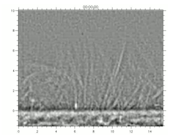
Carlsson & Stein 1995ApJ...440L..29C

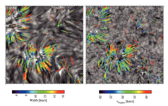


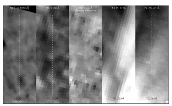
- mean T(h) (thick solid) remains close to RE starting model (dotted)
- bandwidth of T fluctuations (thin solid borders) very large above 1000 km
- a fit of the mean ultraviolet intensities needs a temperature rise (dashed)

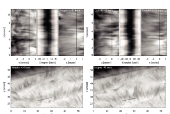
STRAWS / SPICULES-II / RBEs / RREs

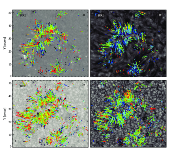


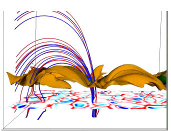












- *observations*
  - "straws", DOT Ca II H
    Rutten 2006ASPC..354..276R
  - "spicules-II", Hinode Ca II H
    De Pontieu et al. 2007Sci...318.1574D
  - "rapid blue excursions", SST Hα
    Rouppe van der Voort et al. 2009ApJ...705..272R
  - "coronal heating events", Hinode Hα + SDO EUV
    De Pontieu et al. 2011Sci...331...55D
  - "torsion-swaying jets", SST Hα + Ca II 8542 Å
    De Pontieu et al. 2012ApJ...752L..12D
  - "rapid red excursions", SST Hα
    Sekse et al. 2013ApJ...769...44S
- *simulation: Martínez-Sykora et al. 2011ApJ...736....9M*
  - feature called a spicule-II but questionable
  - no others in simulations so far
  - driver unknown (Pereira et al. 2012ApJ...759...18P)
- *upshot: ubiquitous small magnetic heating events possibly important in*
  - quiet-sun (also unipolar) coronal heating
  - fast solar wind driving
  - solar wind element segregation

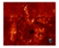
SOLAR RYDBERG LINES WITH ALMA?

Rutten 2016arXiv161003104J

- *"linear thermometer"*
  - H^- free-free + H I free-free: $S = B$
  - 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?*
  - H I 30α in Band 6 (1.3 mm, 0.5 arcsec resolution)
  - cleanly present thanks to large post-hot non-E extinction?
  - 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?

THE SUN WITH ALMA

Rob Rutten



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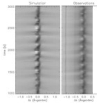

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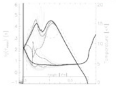

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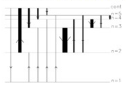

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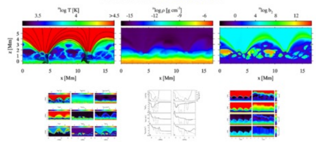

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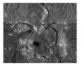

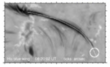

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  - are all long Hα fibrils contrails?
  - do they map magnetic field topography only at launch = H ionization?
  - precursor nature? Spicule-II-like? Component reconnection? Alfvénic wave burst?

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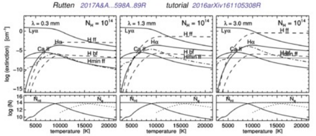
SOLAR MM-WAVELENGTH EXTINCTION

Rutten 2017A&A...598A..89R *tutorial 2016arXiv161105308R*



- ALMA: "linear thermometer" since H ff and Hmin ff have S = B ("source function LTE") but where is $\tau = 1$? ("extinction non-LTE" ⇒ "non-E extinction")
- Hα at high T: LTE or larger instantaneous extinction enforced by Lyα
- H ff at high T: yet larger extinction $\propto \lambda^2$
- cooling recombining contrail fibrils: large post-hot Hα extinction, larger H I ff extinction
- prediction: fibril canopies more opaque than in Hα, hiding shock regime underneath, dark from low actual temperature, less lateral contrast from lack of scattering and Dopplershifts
- ALMA = game changer: linear thermometer with extraordinary PSBE feature opacities

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PREDICTIONS FOR SOLAR ALMA

- *conclusion 2017A&A...598A..89R = prediction list*
  1. ALMA sun mostly covered by long fibrils (unlike simulations sofar)
  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 or less in long contrail fibrils
  4. heating events best detectable with large-array ALMA (@ temperatures)?
  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 (@ check and employ)
  8. internetwork shocks only in quietest areas, with 4000 K cooling clouds (@ how cool?)
  9. no Ellerman bombs (hidden by fibrils)
  10. flaring active-region fibrils poke through (@ reconnection temperature?)
  11. off-limb spicules-II more opaque than in Hα and Ca II H (@ check and employ)
  12. coronal rain much more opaque than in Hα (@ check and employ)

  "Hopefully these predictions will soon be verified with actual ALMA observations. I look forward to be proven right or wrong."
- *conclusion 2016arXiv161105308R*
  - line(s): H130-α in Band 6? potentially PSBE-cleaned wonderful Zeeman diagnostic!

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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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CLAPOTISPHERE

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

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

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

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

Dowd 1981 (not on ADS)

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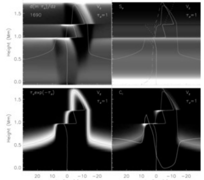
SHOCK GRAIN DIAGNOSIS

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

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



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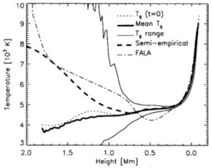
SHOCK-RIDDEN COOL LOWER CHROMOSPHERE

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



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

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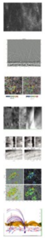

STRAWS / SPICULES-II / RBEs / RREs

- *observations*
  - "straws", DOT Ca II H
    Rutten 2006ASPC..354..276R
  - "spicules-II", Hinode Ca II H
    De Pontieu et al. 2007Sci...318.1574D
  - "rapid blue excursions", SST Hα
    Rouppe van der Voort et al. 2009ApJ...705..272R
  - "coronal heating events", Hinode Hα + SDO EUV
    De Pontieu et al. 2011Sci...331...55D
  - "torsion-swaying jets", SST Hα + Ca II 8542 Å
    De Pontieu et al. 2012ApJ...752L..12D
  - "rapid red excursions", SST Hα
    Sekse et al. 2013ApJ...769...44S
- *simulation: Martínez-Sykora et al.* 2011ApJ...736....9M
  - feature called a spicule-II but questionable
  - no others in simulations so far
  - driver unknown (Pereira et al. 2012ApJ...759...18P)
- *upshot: ubiquitous small magnetic heating events possibly important in*
  - quiet-sun (also unipolar) coronal heating
  - fast solar wind driving
  - solar wind element segregation

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SOLAR RYDBERG LINES WITH ALMA?

Rutten 2016arXiv161003104J

- *"linear thermometer"*
  - H$^-$ free-free + H I free-free: $S = B$
  - 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?*
  - H I 30α in Band 6 (1.3 mm, 0.5 arcsec resolution)
  - cleanly present thanks to large post-hot non-E extinction?
  - 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?

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1 .jpg

16 .jpg

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