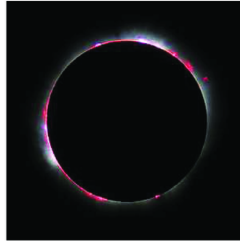


CHROMOSPHERE OBSERVATIONS & DIAGNOSTICS

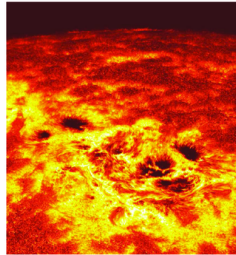
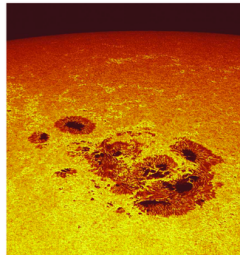
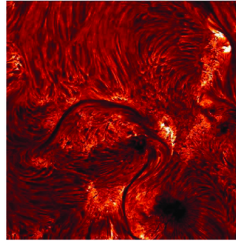
Rob Rutten

line formation displays: lectures on my website (google my name)
brief tutorial: [2016arXiv161105308R](#) = proceedings IAU-S327 Cartagena

Chromosphere at eclipse



H α filtergram of chromosphere



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

1868 – 1970 : chromosphere = off-limb flash spectrum

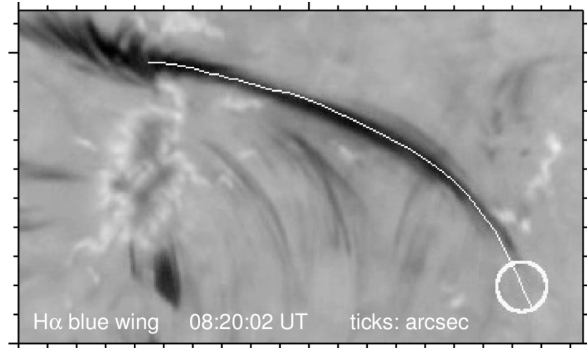
1960 – 2010 : chromosphere = temperature plateau in static 1D NLTE-SE models

2000 – present : chromosphere = sum small dynamic magnetics feeding the corona

¿conjecture : chromosphere = propagating heating events and aftermath contrails?

LONG $H\alpha$ FIBRIL AS CONTRAIL AFTER PROPAGATING HEATING EVENT

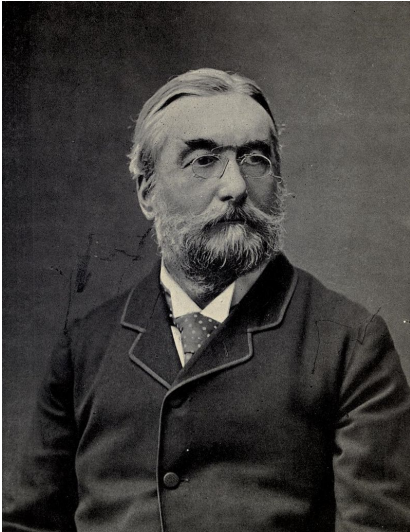
Rutten & Rouppe van der Voort 2016arXiv160907616R @ A&A



- $H\alpha$ 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
- three-four minutes later dark $H\alpha$ core fibril, retracting with increasing redshift
- Ca II 8542 Å shows only start of heating event and finish of redshifted contraction
- $H\alpha$ fibril \sim contrail: not representing cool present but much hotter precursor past
 - ¿ RBE-like but more horizontal trajectory?
 - ¿ line-tying by H ionization: contrail outlines precursor field?
 - ¿ more such? Yes! Are all long $H\alpha$ fibrils contrails? Maybe ...

NORMAN LOCKYER

wikipedia



Sir Joseph Norman Lockyer, FRS (17 May 1836 – 16 August 1920), known simply as Norman Lockyer, was an English scientist and astronomer. Along with the French scientist Pierre Janssen he is credited with discovering the gas helium.

In 1885 he became the world's first professor of astronomical physics at the Royal College of Science, South Kensington, now part of Imperial College. At the college, the Solar Physics Observatory was built for him and here he directed research until 1913.

To facilitate the transmission of ideas between scientific disciplines, Lockyer established the general science journal *Nature* in 1869. He remained its editor until shortly before his death.

CHROMOSPHERE NAMING

Abstract of Norman Lockyer's paper read Nov. 26, 1868; Procs. Royal Society of London, 17, 131

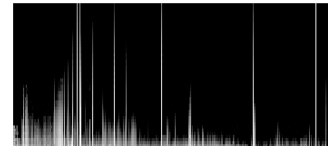
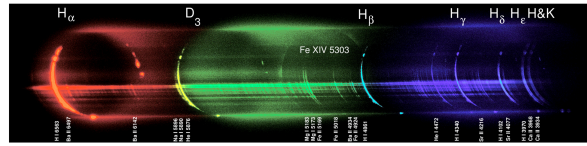
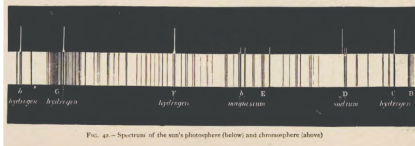
1868RSPS...17..131L = full report

Details are given of the observations made by the new instrument, which was received incomplete on the 16th of October. These observations include the discovery, and exact determination of the lines, of the prominence-spectrum on the 20th of October, and of the fact that the prominences are merely local aggregations of a gaseous medium which entirely envelopes the sun. The term *Chromosphere* is suggested for this envelope, in order to distinguish it from the cool absorbing atmosphere on the one hand, and from the white light-giving photosphere on the other. The possibility of variations in the thickness of this envelope is suggested, and the phenomena presented by the star in Corona are referred to.

Two of the lines correspond with Fraunhofer's C and F; another lies 8° or 9° (of Kirchhoff's scale) from D towards E. There is another bright line, which occasionally makes its appearance near C, but slightly less refrangible than that line. It is remarked that the line near D has no corresponding line ordinarily visible in the solar spectrum. The author has

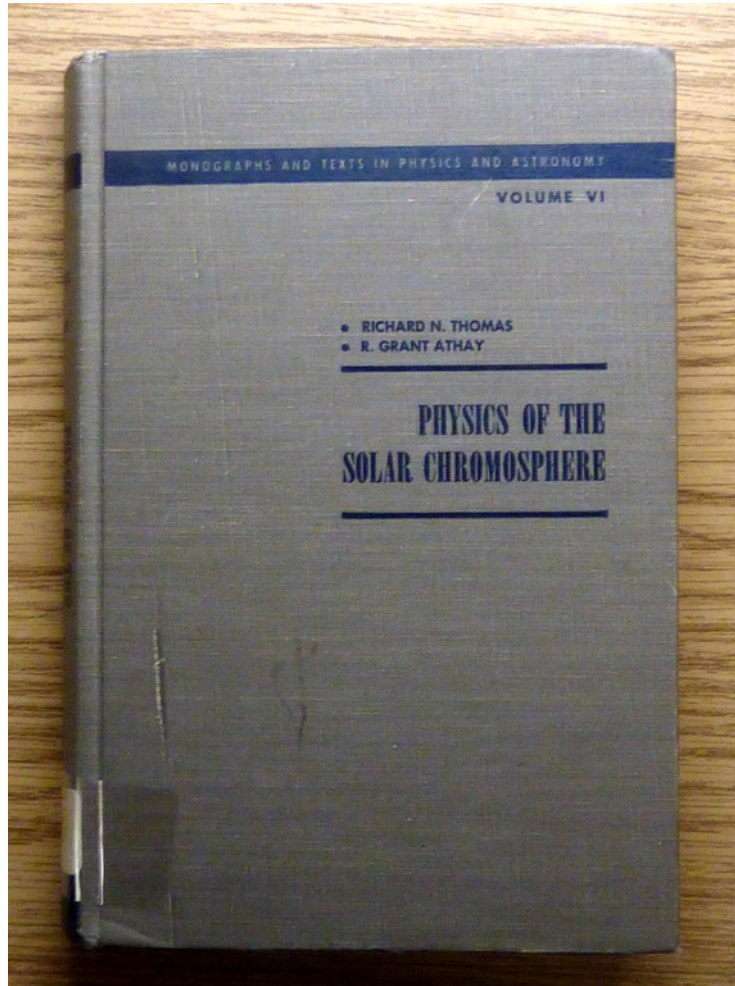
Fraunhofer's "C" is $H\alpha$, "F" is $H\beta$, the non-Fraunhofer line near "D" ($Na I D_1 + Na I D_2$) is He I D_3 , and the occasional "less refrangible" line near $H\alpha$ is He I 6678 Å.

SOLAR FLASH SPECTRUM



- *chromosphere naming = definition (Lockyer 1868 outside eclipse)*
 - strong: H I Balmer lines, He I D $_3$, Ca II H & K
 - weaker: Mg I b, Na I D, Sr II, Ba II
- *chromosphere research = flash spectrometry*
 - Menzel thesis = 1898–1908 Campbell [1930PLicO..17....1M](#) (302 pp, on ADS)
 - Thomas & Athay book = 1952 HAO [1961psc..book....A](#) (422 pp, not on ADS)
 - Dunn et al. = 1962 HAO [1968ApJS...15..275D](#) (275 pp, on ADS; [RR digitized](#))
- *chromosphere = enigma*
 - flash spectrum \neq reversed disk spectrum
 - both hot (He I D $_3$) and cool (Na I D $_1$ & D $_2$) lines
 - spatial extent exceeds radiative-equilibrium scale height

ECLIPSE WISDOM



attention reader

see De Jager's comments on this book
in Z. Astrophysik; v. 55; p. 66 (1962)

(rather damaging!)

Besprechungen

THOMAS, R. N., und R. G. ATHAY: *Physics of the Solar Chromosphere*. X + 422 Seiten. Interscience Publishers, Inc., New York 1961. Geb. \$ 15.50.

Der Titel des Buches verspricht mehr, als der Inhalt gibt. Jeder, der schon einmal durch ein $H\alpha$ -Filter oder durch ein Spektrohelioskop die bezaubernde Struktur der Chromosphärenoberfläche gesehen oder das Profil des Sonnenrandes beobachtet hat, wird — sobald er den Titel „Physik der Chromosphäre“ hört — an eine Erklärung der Dynamik dieser Gasmassen denken. Er wird an Probleme der Schall-, Stoß- und Gravitationswellen und an die Dissipation von deren Energie denken. Vielleicht wird er sich fragen, was die Autoren von der Rolle halten, die Magnetfelder und magnetohydrodynamische Wellen spielen und in welchem Maße von ihnen die verschiedenen Strukturen der ruhigen bzw. gestörten Gebiete dieses merkwürdigen Teiles der Sonne bestimmt werden.

Von allem dem wird er aber in diesem Buche nichts finden: Die betreffenden Probleme werden kaum erwähnt, geschweige denn besprochen.

und so weiter... four pages more

Upshot: the book treats the derivation of a model atmosphere from the spectrograms taken by the 1952 HAO eclipse expedition but ignores the inhomogeneity and dynamics of the chromosphere such as sound, shock, gravity and MHD waves, as well as magnetic fields.

CHROMOSPHERE POTPOURRI

- *line formation theory*

- flash spectrum @ Harvard, Boulder \Rightarrow Mihalas (1970, 1978): summary
- static 1D “standard” models: VALIIC more Avrett hydrogen exam
- non-E: detailed balancing 1D Radyn 2D Stagger 3D Bifrost

- *chromosphere diagnostics*

Na I D₁+Mg I b₂ Ly α +H α H α +Ca II 8542 Å Ca II H & K+Mg II h & k
Si IV mm He I+He II

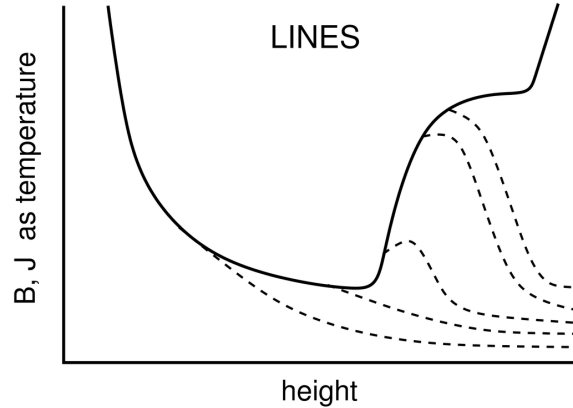
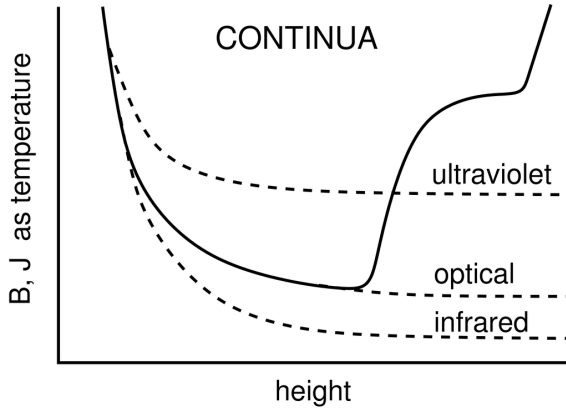
- *chromospheric & coronal heating ingredients*

- gravity waves
- acoustic waves
- Alfvénic waves
- reconnection

- *fine structure*

- sketched: Noyes 1979 Gabriel 1976 Wedemeyer 2016 Rutten 2016
- observed and explained: Ca II grains dynamic fibrils
- observed but not explained: straws/spicules-II/RBEs/RREs long H α fibrils
- fibril-field alignment for NLFFF: yes partly ; only at launch?

SUMMARY 1D SCATTERING SOURCE FUNCTIONS



- *continua*

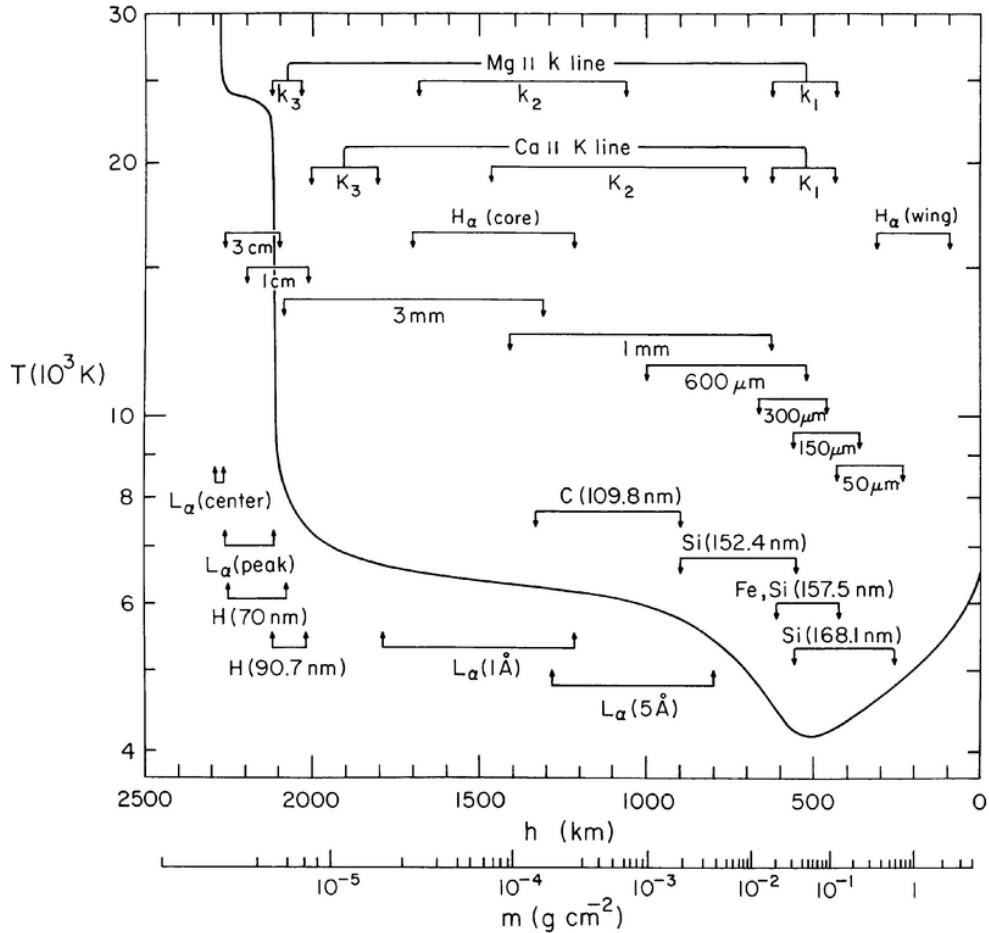
- optical: $J \approx B$ for radiative equilibrium
- ultraviolet: $S \approx J > B \rightarrow$ overionization of minority neutrals
- infrared: $J < B$ but J doesn't matter since H_{ff}^- and H_{ff} have $S = B$

- *lines*

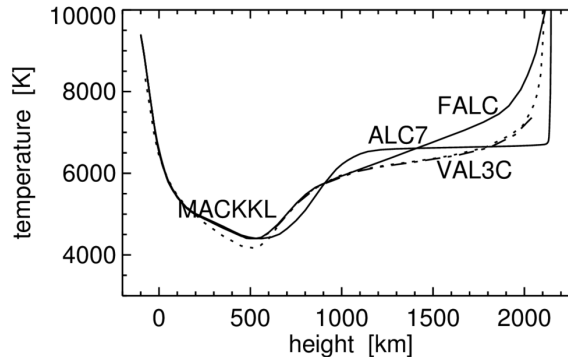
- $dB/d\tau = dB/d(\tau^c + \tau^l)$ much less steep, so closer to isothermal $S \approx \sqrt{\epsilon} B$
- for stronger lines S sees more of the model chromosphere
- PRD lines have frequency-dependent core-to-wing S curves like these

VALIIC MODEL

Vernazza, Avrett, Loeser 1981ApJS...45..635V



AVRETT SOLAR-ANALOG STARS



- VAL3C = Vernazza, Avrett, Loeser 1981ApJS...45..635V: best-fit to UV continua
- MACKKL = Maltby et al. 1986ApJ...306..284M: less steep upper photosphere
- FALC = Fontenla, Avrett, Loeser 1993ApJ...406..319F: ambipolar diffusion
- ALC7 = Avrett & Loeser 2008ApJS..175..229A: UV-line fit; update 2015ApJ...811...87A

[...] *The results may be interpreted as holding for a computationally existing star called VALIII [...]. This star is remarkably like the Sun in its temporally and spatially averaged continuous spectral distribution, but in contrast to the Sun it does obey hydrostatic equilibrium and static plane-parallel geometry, and it contains only those atoms, ions and electrons that were specified in the Pandora code, fortunately with just the corresponding cross-sections. Its modeling is exact! The advantage of studying the star VALIII rather than the star Sol is that the physics of VALIII radiation is fully understandable. Also, it keeps adhering to these course notes ad infinitum while solar physics evolves to more complexity.*

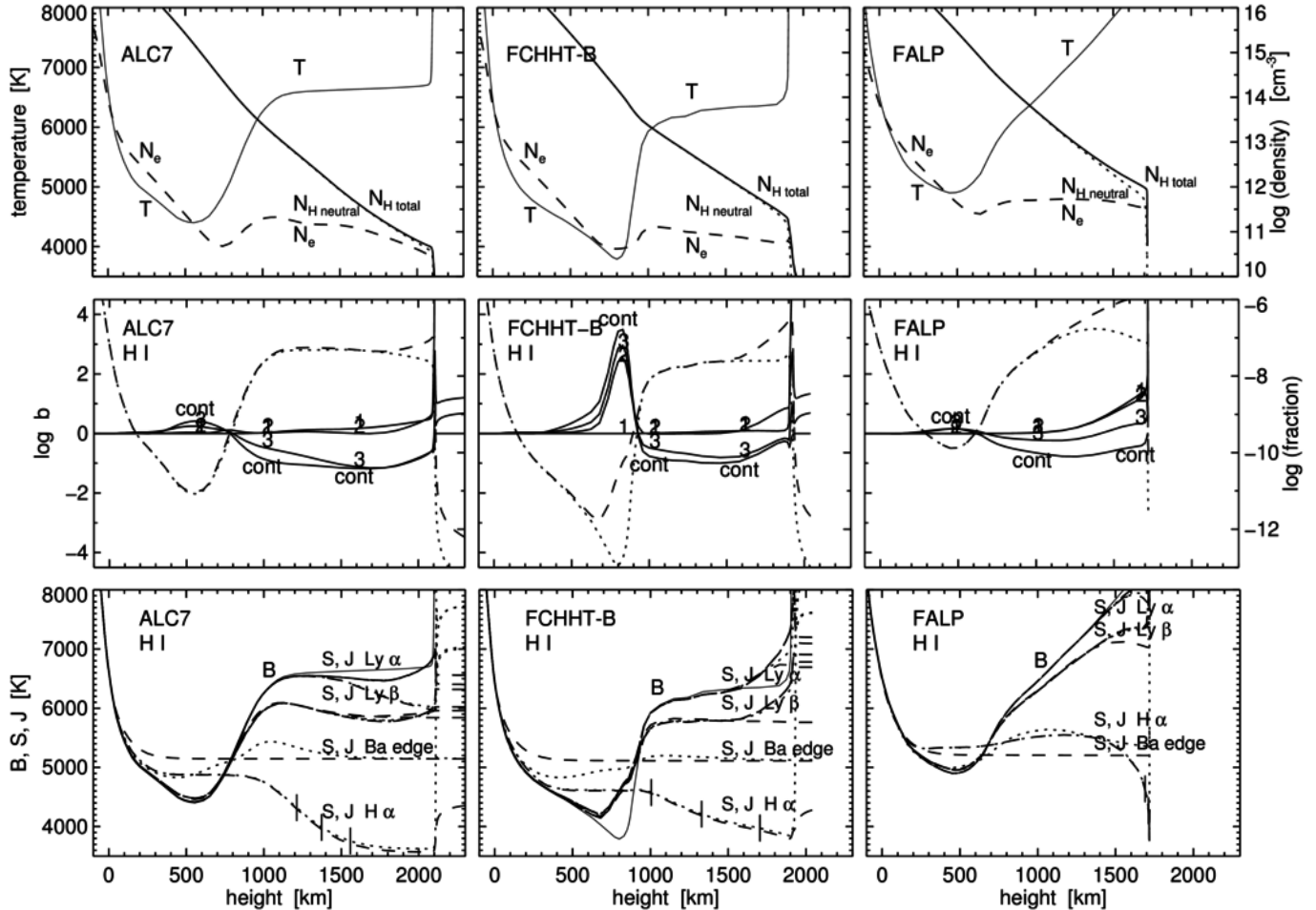
Rutten “Radiative Transfer in Stellar Atmospheres”

EXPLAIN EVERYTHING – INCLUDING SIMILARITIES AND DIFFERENCES

ALC7: 2008ApJS..175..229A

FCHHT-B: 2009ApJ...707..482F

FALP: 1993ApJ...406..319F



CHROMOSPHERE POTPOURRI

- *line formation theory*

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Si IV mm He I+He II

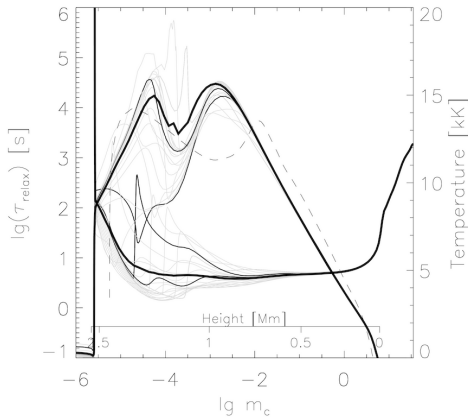
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- fibril-field alignment for NLFFF: yes partly ; only at launch?

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)

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

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

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

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

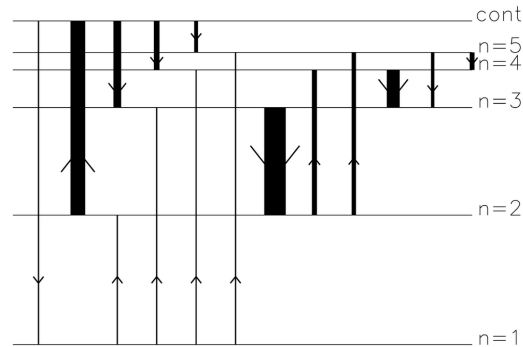
Einstein relation

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

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

NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

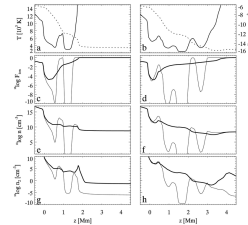
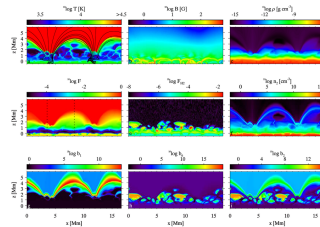
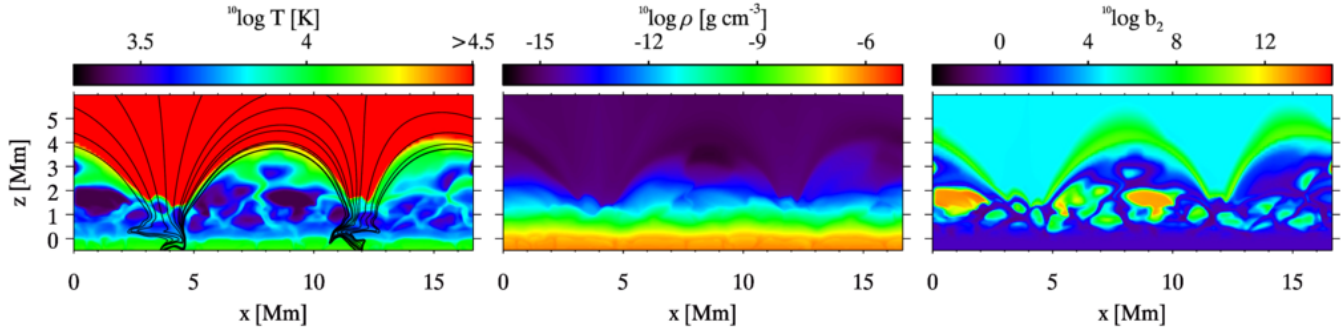
Carlsson & Stein 2002ApJ...572..626C



- RADYN code: 1D(t) hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed subphotosphere piston drives acoustic waves up that shock near $h=1000$ km
- $Ly\alpha$ 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 $Ly\alpha$ 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 $b_{cont}/b_2 \approx 10^{-1}$ 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 $\text{Ly}\alpha$ has $S \approx B$ from high T (fast balancing) and N_e (10% H ionization)
- retarded collisional balancing in $\text{Ly}\alpha$: n_2 hangs near high shock value $n_2 \approx n_2^{\text{LTE}}$
- 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 $\text{Ly}\alpha$ scattering

BIFROST SOLAR-ANALOG STAR

- *Bifrost: a Modular Python/C++ Framework for Development of High-Throughput Data Analysis Pipelines* [2017AAS...22923605C](#)
- *Vertical crustal motion observed in the BIFROST project* [2003JGeo...35..425S](#)
- *BIFROST project: 3-D crustal deformation rates derived from GPS confirm post-glacial rebound in Fennoscandia* [2001EP&S...53..703S](#)
- *"SPACE" 2013-2015: ASGARD Balloon and BIFROST Parabolic Flights: Latest Developments in Hands-On Space Education Projects for Secondary School Students* [2015ESASP.730..635D](#)
- *BIFROST: conference hotel in Iceland* ([not on ADS](#))
- Bifrost: computational star in Carlssonscandia, remarkably like the Sun in its spectral characteristics and likewise non-plane-parallel, inconstant, and inconsistent, with the virtue of showing much spatio-temporal fine structure similar to solar fine structure:
 - granules and intergranules
 - acoustic box modes similar to solar p -mode interference patterns
 - non-diagnosed internal gravity waves
 - clapotispheric internetwork shocks
 - magnetic network concentrations
 - dynamic fibrils
 - Ellerman reconnection bursts*¿ but lacking spicules-II? component reconnection? Alfvénic (torsion?) wave bursts?*
- Bifrost analogs in chromosphere-formation stage: CO5BOLD MuRAM Mancha

BIFROST

- *code*

- Gudiksen et al. [2011A&A...531A.154G](#) Bifrost description
- Carlsson & Leenaarts [2012A&A...539A..39C](#) cooling + heating approximations
- Leenaarts et al. [2012A&A...543A.109L](#) fast angle-dependent PRD
- Martinez-Sykora et al. [2012ApJ...753..161M](#) ambipolar diffusion
- Pereira et al. [2013A&A...554A.118P](#) 3D simulation better than standard 1D models
- Olluri et al. [2013AJ...145...72O](#) non-E 3D solver
- Golding et al. [2014ApJ...784...30G](#) non-E He ionization
- Carlsson et al. [2016A&A...585A...4C](#) publicly available snapshot
- Sukhorukov & Leenaarts [2016A&A...597A..46S](#) PRD in 3D simulations

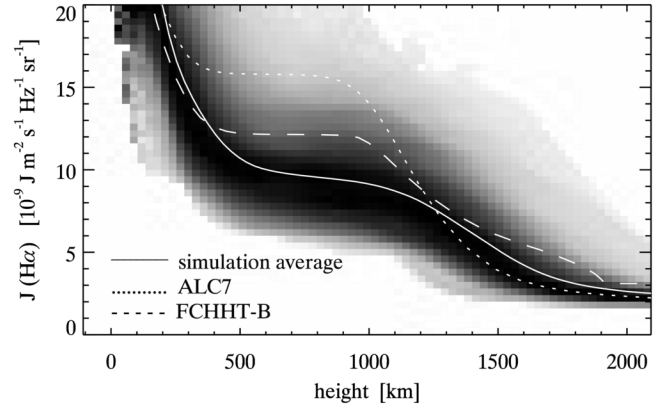
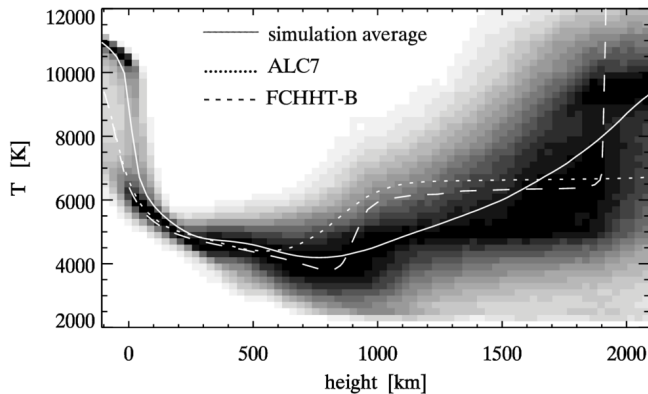
- *warnings*

- no Ly α RT, so no N_e boosting from Ly α surround scattering around hot structures
- for H α RT must be 3D as in MULTI3D of Leenaarts & Carlsson [2009ASPC..415...87L](#), not column-wise as in RH1.5D of Pereira & Uitenbroek [2015A&A...574A...3P](#)
- for H and He features RT must be time-dependent, not snapshot-wise SE

- *morals*

When analog-star lines match solar lines one still has to find out how they came about in the analog star. This task is non-trivial. When analog-star lines do not match solar lines, one should not simply blame the solar observations but appreciate the mismatch as potentially informative.

BIFROST VERSUS 1D STANDARD MODELS



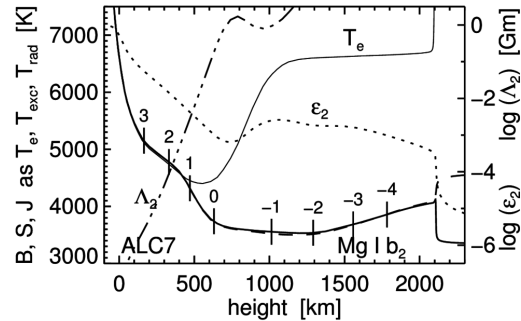
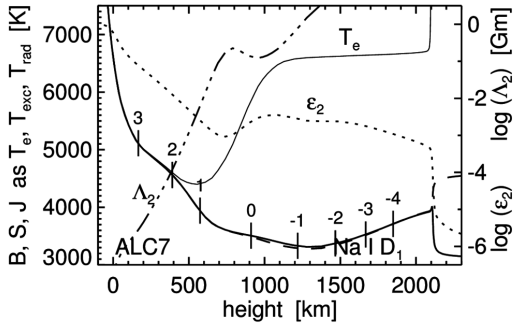
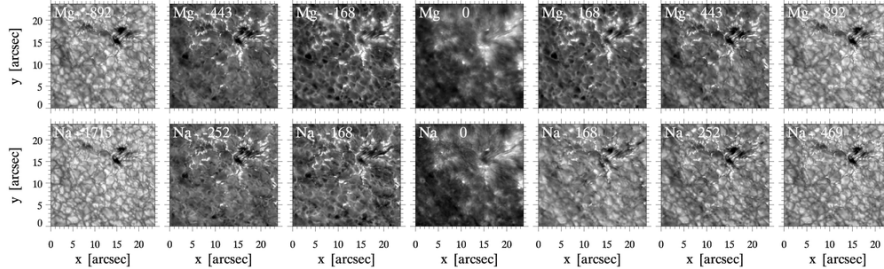
- Bifrost = state-of-the-art: 3D(t), \vec{B} , non-HE, SE populations but NE for H
Leenaarts, Carlsson & Rouppe van der Voort [2012ApJ...749..136L](#)
- ALC7 = UV fit: 1D static, no \vec{B} , HE + microturbulence, SE populations
Avrett & Loeser [2008ApJS..175..229A](#)
- FCHHT-B = UV fit: 1D static, no \vec{B} , HE + imposed acceleration, SE populations
Fontenla, Curdt, Haberreiter, Harder & Tian [2009ApJ...707..482F](#)

The T and $J_\nu(\text{H}\alpha)$ behaviors seem arguably similar. However, the conceptual differences between plane-parallel static hydrostatic-equilibrium modeling and 3D(t) MHD simulation are enormous. The $T(h)$ stratifications in the simulation vary tremendously, with shocks propagating upwards and sideways and the increase to coronal temperature dancing up and down in height. Bifrost has no “the temperature minimum” or “the transition region”.

BIFROST ANALYSES – SOFAR

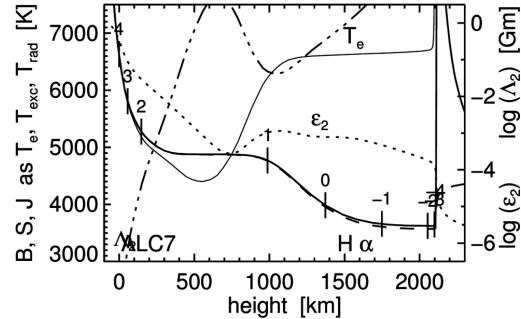
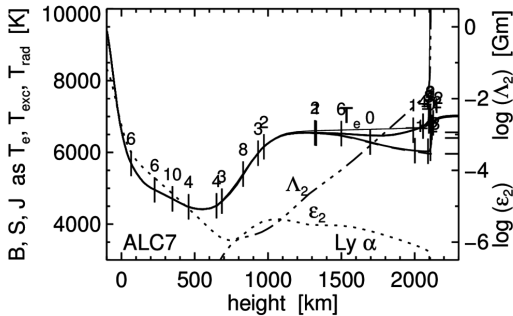
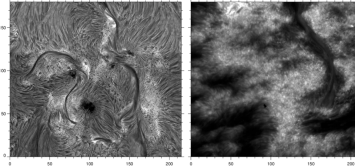
Hayek et al. 2010A&A...517A..49H solar-type stars
Martinez-Sykora et al. 2011ApJ...732...84M EUV line asymmetries
Leenaarts et al. 2012ApJ...749..136L 3D H α formation
Stepán et al. 2012ApJ...758L..43S Ly α Hanle
de la Cruz Rodriguez et al. 2012A&A...543A..34D Ca II 8542 Å inversion test
Olluri et al. 2013ApJ...767...43O non-E in O IV ratios
Martinez-Sykora et al. 2013ApJ...771...66M Ca II and H α from a spicule-II
Leenaarts et al. 2013ApJ...772...89L Mg II h & k for IRIS I
Leenaarts et al. 2013ApJ...772...90L Mg II h & k for IRIS II
Pereira et al. 2013ApJ...778..143 Mg II h & k for IRIS
Hansteen & Archontis 2014ApJ...788L...2A reconnecting strong-field simulation
Olluri et al. 2015ApJ...802....5O optically thin emission lines
Leenaarts et al. 2015ApJ...802..136L H α fibrils versus field
Stepán et al. 2015ApJ...803...65S scattering polarization Ly α
Pereira et al. 2015ApJ...806...14P MgII triplet formation
Carlsson et al. 2015ApJ...809L..30C Mg II k from plage
Hansteen et al. 2015ApJ...811..106H heating from footpoint braiding
Rathore et al. 2015ApJ...811...81R IRIS C II formation
Guerreiro et al. 2015ApJ...813...61G quiet-Sun heating events
Martinez-Sykora et al. 2016ApJ...817...46M non-E Si IV/O IV ratios
Golding et al. 2016ApJ...817..125G non-E He ionization
Noberga-Siverio et al. 2016ApJ...822...18N H α surge
Kato et al. 2016ApJ...827....7K waves from magnetic pumping
de la Cruz Rodriguez et al. 2016ApJ...830L..30D Mg II h & k + Mg II triplet inversions
Schmit+DePontieu 2016ApJ...831..158S IRIS Si IV QS internetwork versus IRIS
Martinez-Sykora et al. 2016ApJ...831L...1M 2.5D ambipolar misalignment fibrils-field
Leenaarts et al. 2016A&A...594A.104L spatial structure in He I 10830
Golding et al. 2016arXiv161000352G He resonance lines

Na I D₁ AND Mg I b₂



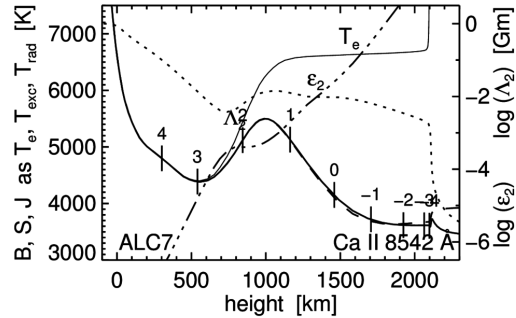
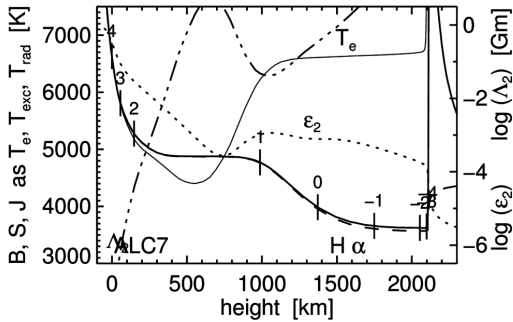
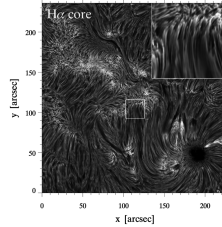
- similar NLTE formation = heavy two-level scattering
- core intensities do not sense ALC7 chromosphere
- narrow Na I D₁ flanks reverse reversed granulation
- ζ non-E? minority stages: recombination $\propto N_e$ senses Ly α settling and scattering
- SST: Dopplergrams \approx unsigned fluxtube magnetograms (Na I D₁ formation)
 - ζ non-E enhanced in cooling recombining downflows? (SE = Bifrost snapshot OK)

Ly α and H α



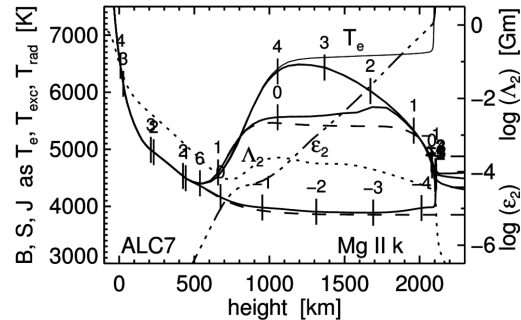
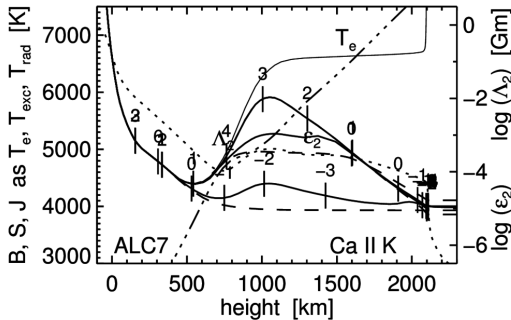
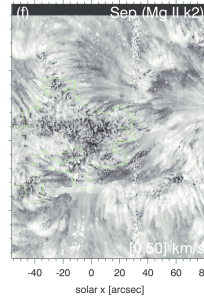
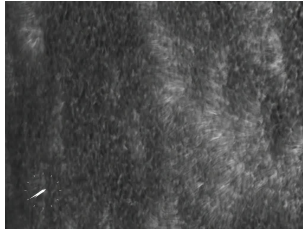
- both: heavy NLTE scatterers with $S \approx J$
 - Ly α : boxed-in by enormous extinction \Rightarrow radiative detailed balance: $S = J$
 in shocks (\approx ALC7 chromosphere) collisional thermalization: $b_2 \approx b_1$
 in cool gas surrounding hot structures $b_2 \gg 1$ from Ly α surround scattering
 in post-hot cool gas slow $S \approx J$ thermalization with $b_2 \gg 1$: S^l memory of hot past
 - H α : photons created in granulation
 scatter 3D across upper-photosphere opacity gap and through chromosphere
 in shocks etc. Boltzmann extinction $b_2 \approx b_1$
 in post-hot cool gas $b_2 \gg 1$: extinction memory of hot past
- ¿ Ly α scene: heating events bright down-throat, cooling contrails dark from scattering
 H α scene: RBE/RRE heating events, cooling contrails dark from non-E opacity

H α and Ca II 8542 Å



- both: heavy NLTE scatterers with $S \approx J$ sampled at similar $\tau = 1$ heights
 - both: Saha-Boltzmann or larger extinction in shocks and ALC7
 - core widths: both decrease away from network = decreasing temperature
 - H α fibrils extend further, contradicting [Saha-Boltzmann extinction sensitivities](#)
- ¿ fibril opacity in Ca II 8542 Å instantaneous, in H α post-hot non-E?

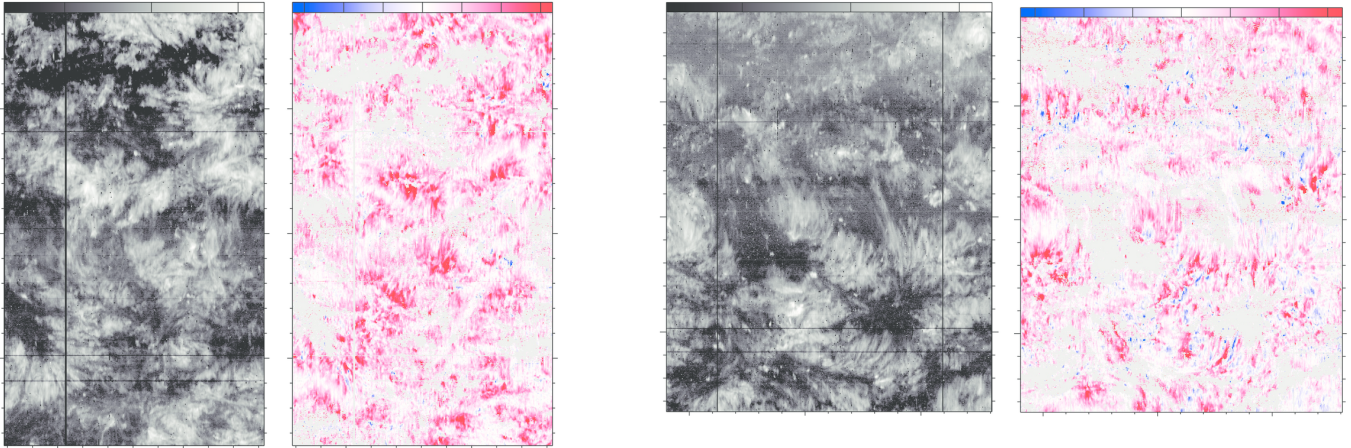
Ca II H & K and Mg II h & k



- both: heavy NLTE scatterers with PRD source function splits
 - both: near-Saha-Boltzmann extinction everywhere; abundance ratio 18
 - both: absence of non-E sensitivities = instantaneous chromosphere
 - both: slender fibrils emanating from network, in Ca II H & K better at narrower bandwidth, in Mg II k best in k_2 peak separation
- ¿ slender fibrils = propagating heating events?

CLOSED AND OPEN QUIET-SUN INTERNETWORK IN Si IV

Peter et al. in preparation



- thin to thickish (ratio < 2) line formation

- Gaussian fits

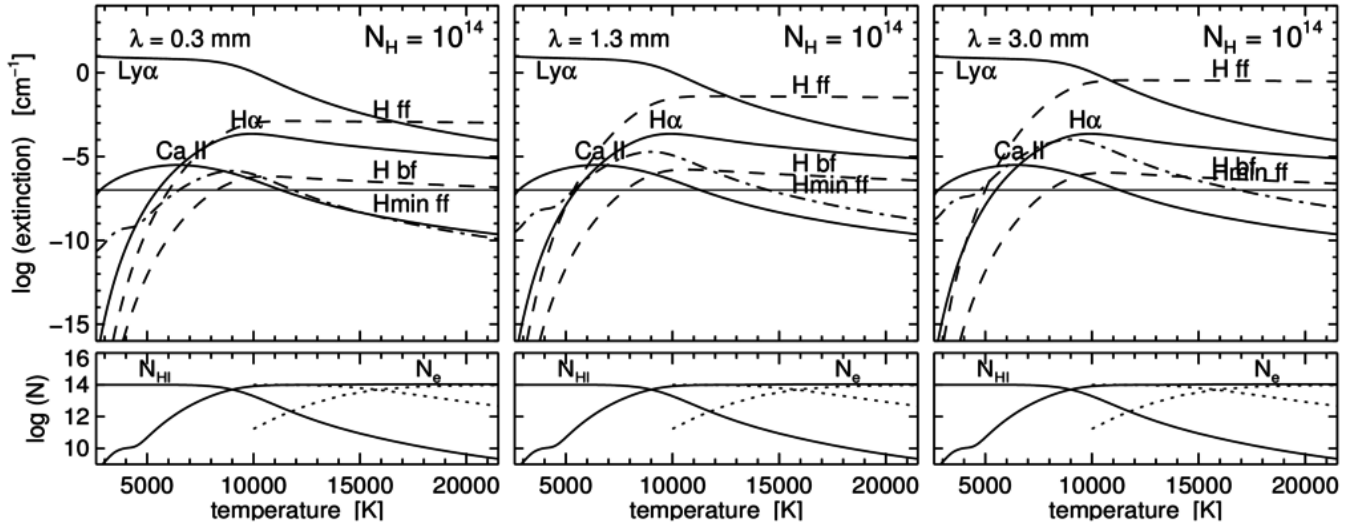
- widths \approx non-thermal widths

¿ redshifted fibrils away from network \approx recombining $H\alpha$ contrails?

¿ roundish coronal-hole blueshifts in network = down-throat heating events?

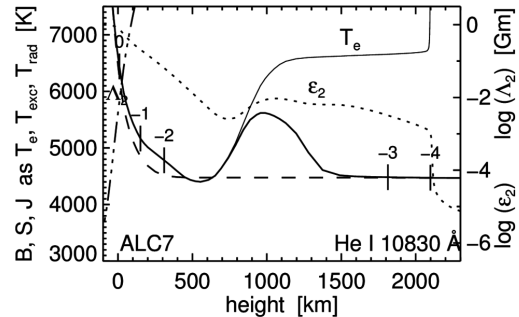
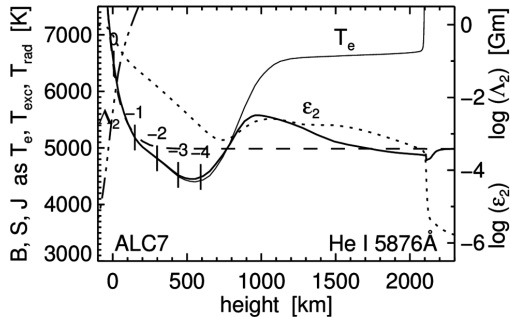
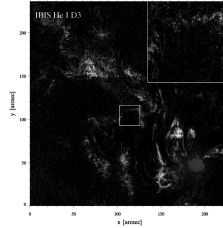
MM-WAVELENGTH EXTINCTION

Rutten 2016arXiv160901122R @ A&A 2016arXiv161105308R @ IAU S327 Cartagena



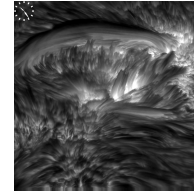
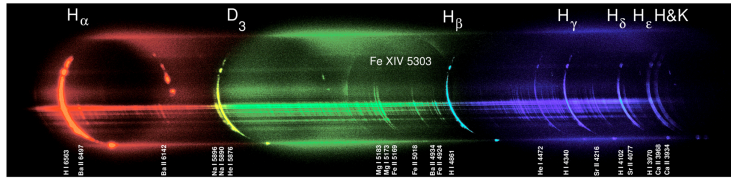
- ALMA: “linear thermometer” from H ff and H min ff having $S = B$
line(s) = Zeeman diagnostic? H I 30- α ?
Cycle 4 solar observations Ca started December (small array, continuum only)
- H α at high T: LTE or larger extinction enforced by Ly α
- H ff at high T: yet larger extinction $\propto \lambda^2$
- ⚡ cooling recombining contrail fibrils with large post-hot H α extinction have larger post-hot H I ff extinction
- ⚡ prediction: fibril canopies yet more opaque than in H α , dark from low actual T, less lateral contrast from lack of scattering and Dopplershift differences

He I and He II



- optical He I lines: nothing in ALC7, nor in atlases, nor in Moore-Minnaert-Houtgast
- more complex non-E formation than H I: not only He I 584 acting as Ly α but ionization/recombination not limited to the atom top as for H I (smooth Balmer continuum driving from below) but sensing hot and structured irradiation from above
- see Bifrost He papers and more to come
- to-do for 2018 = 150 years after Lockyer: explain He I D₃ in flash spectrum
- ¿ long dark H α -like He II 304 fibrils also memorial-opacity contrails?

CONCLUSION



- *past: “most difficult solar domain” (Judge & Peter 1998)*
 - physics: β -flip neutral-gas R-HD domination to plasma R-MHD field domination
 - radiation: thick-to-thin scattering with NLTE PRD ζ non-E? line formation
 - structure: utterly small-scale 3D and utterly time-dependent
- *present: from “dermatology” to most promising solar domain*
 - ground: SST/CRISP, [SST/CHROMIS], [ALMA]
 - space: IRIS
 - modeling: BIFROST
- *future: “understand as simple a thing as a star” (Eddington 1926) – D3 after 150 years?*
 - ground: hi-res ALMA, DKIST, EST?
 - space: SO/Ly α , Solar-C?
 - modeling: multi-fluid simulation, 3D(t) inversion
- *three unrelated invitations*

THREE UNRELATED INVITATIONS

- *Sacramento Peak Farewell Workshop*
 - August 7-11, then travel to August 21 eclipse
 - invitation to submit contribution abstracts: soon in SolarNews
 - non-presenting participation may have to be limited
- *get into my camera*
 - Rob's mugshot studio next to toilets
 - get into my astronomer portrait collection
 - become famous
- *this Saturday*
 - join me in sea kayaking
 - all day including lunch
 - tell me before lunch

CHROMOSPHERE POTPOURRI

- *line formation theory*

- flash spectrum @ Harvard, Boulder \Rightarrow Mihalas (1970, 1978): summary
- static 1D “standard” models: VALIIC more Avrett hydrogen exam
- non-E: detailed balancing 1D Radyn 2D Stagger 3D Bifrost

- *chromosphere diagnostics*

Na I D₁+Mg I b₂ Ly α +H α H α +Ca II 8542 Å Ca II H & K+Mg II h & k
Si IV mm He I+He II

- *chromospheric & coronal heating ingredients*

- gravity waves
- acoustic waves
- Alfvénic waves
- reconnection

- *fine structure*

- sketched: Noyes 1979 Gabriel 1976 Wedemeyer 2016 Rutten 2016
- observed and explained: Ca II grains dynamic fibrils
- observed but not explained: straws/spicules-II/RBEs/RREs long H α fibrils
- fibril-field alignment for NLFFF: yes partly ; only at launch?

DYNAMIC FIBRILS

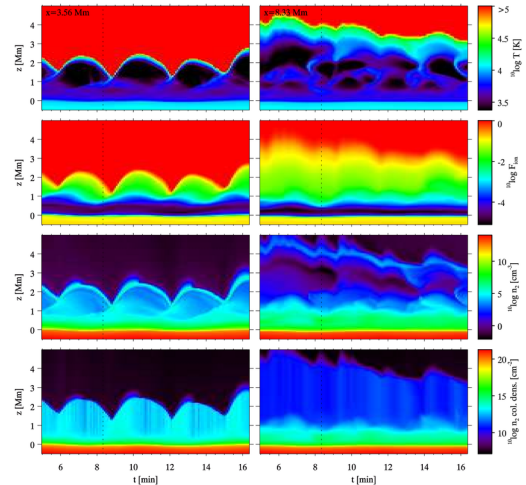
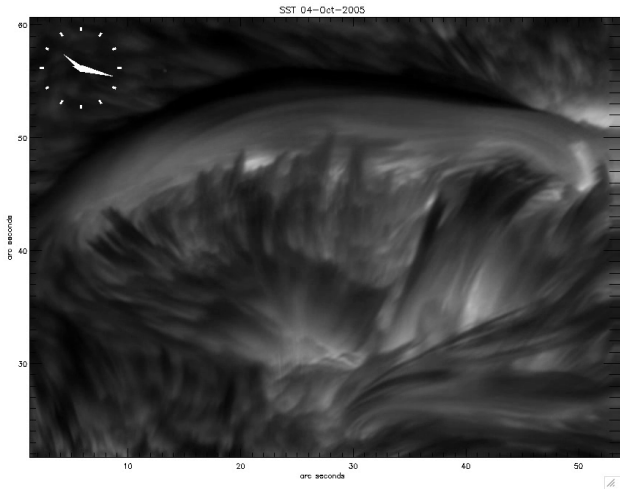
H α : Hansteen et al. 2006ApJ...647L..73H, De Pontieu et al. 2007ApJ...655..624D (plage)

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non-E 2D MHD simulation: Leenaarts et al. 2007A&A...473..625L



explanation: p -mode-driven 3–5 minute shock waves along inclined field as slanted wave guide with lowered cutoff frequency; fan pattern = surface network strings

Michalitsanos 1973SoPh...30...47M

Bel & Leroy 1977A&A...55..239B

Suematsu 1990LNP...367..211S

De Pontieu et al. 2004Natur.430..536D

THE FIVE-MINUTE PERIOD OSCILLATION IN MAGNETICALLY ACTIVE REGIONS

A. G. MICHALITSANOS* **

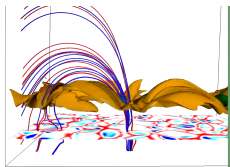
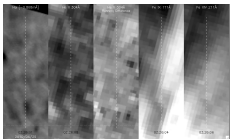
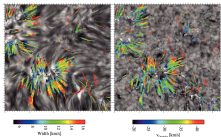
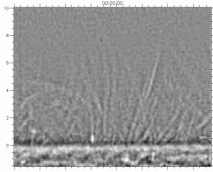
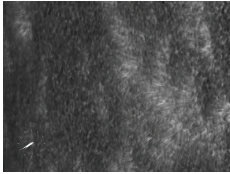
Institute of Astronomy, University of Cambridge, Cambridge, England

If we incline the magnetic field (with respect to g) through 45 degrees in Figure 1d, we note that in Region I, $\omega(k_x)$ is no longer asymptotic to ω_s as k_x tends to zero. Therefore, for an inclined magnetic field, magnetosonic waves may propagate vertically at frequencies $\omega < \omega_s$. If in Equation (3) we set $a=0$ and $k_x=0$, and let $b = -g\gamma/2V_s^2$ we will obtain the critical magnetosonic-gravity frequency ω_c , where

$$\omega_c^2 = \omega_s^2 \left(\frac{1}{2} - \frac{1}{\gamma\beta} \right) + \omega_s^2 \left[\left(\frac{1}{\gamma\beta} - \frac{1}{2} \right)^2 + \frac{2 \cos^2 \theta}{\gamma\beta} \right]^{1/2}, \quad (4)$$

and $\theta = \arccos(B_z/B_0)$. Therefore, at levels where $\beta < 1$, the critical magnetosonic-gravity frequency is less than the critical sonic-gravity frequency ω_s when the field is inclined from the vertical.

STRAWS / SPICULES-II / RBES



- *observations*

- “straws”, DOT Ca II H

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

- “spicules-II”, SST Ca II H

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- “heating events”, Hinode + SDO H α + EUV

- De Pontieu et al. 2011Sci...331...55D*

- *simulation: Martínez-Sykora et al. 2011ApJ...736....9M*

- complex emergence, steep gradients, intense currents

- spicular Joule heating (green), outflow (blue)

- nearby coronal loop heating (red)

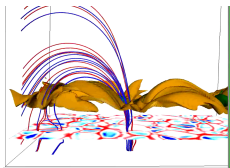
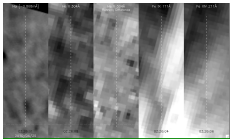
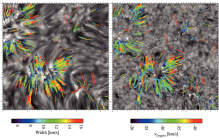
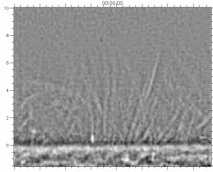
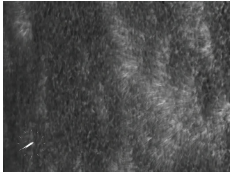
- *expectations*

- quiet-sun (also unipolar) coronal heating

- fast solar wind driving

- solar wind element segregation

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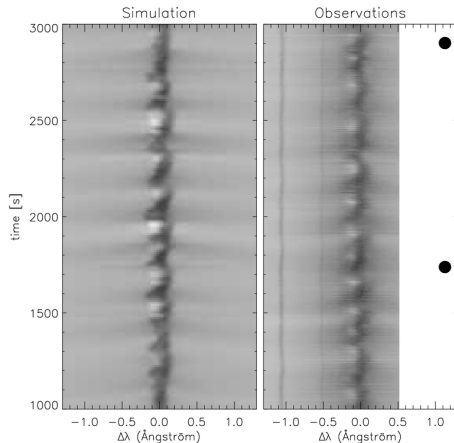
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INTERNETWORK H_{2V} GRAINS = ACOUSTIC SHOCKS

- *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

DYNAMIC FIBRILS

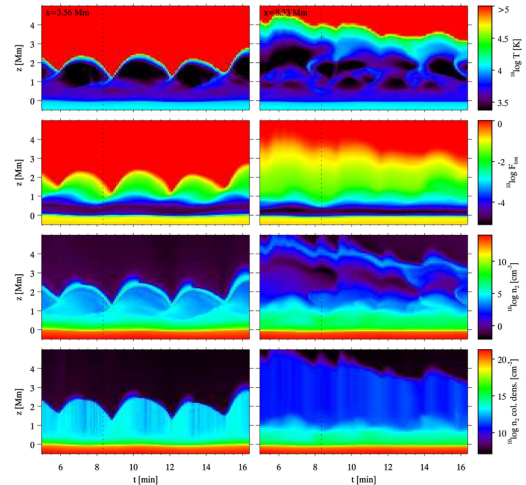
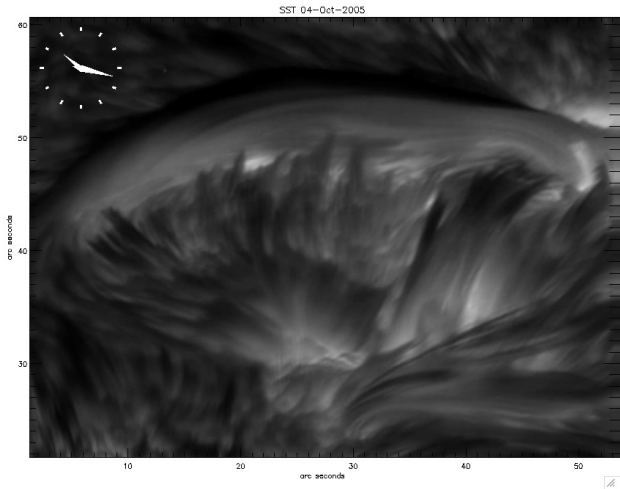
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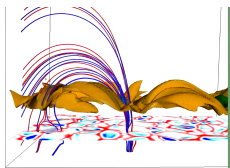
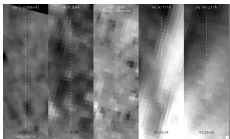
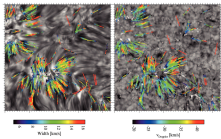
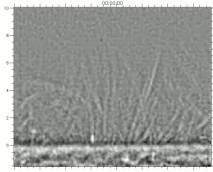
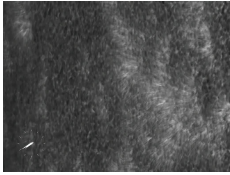
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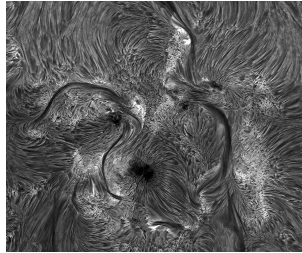
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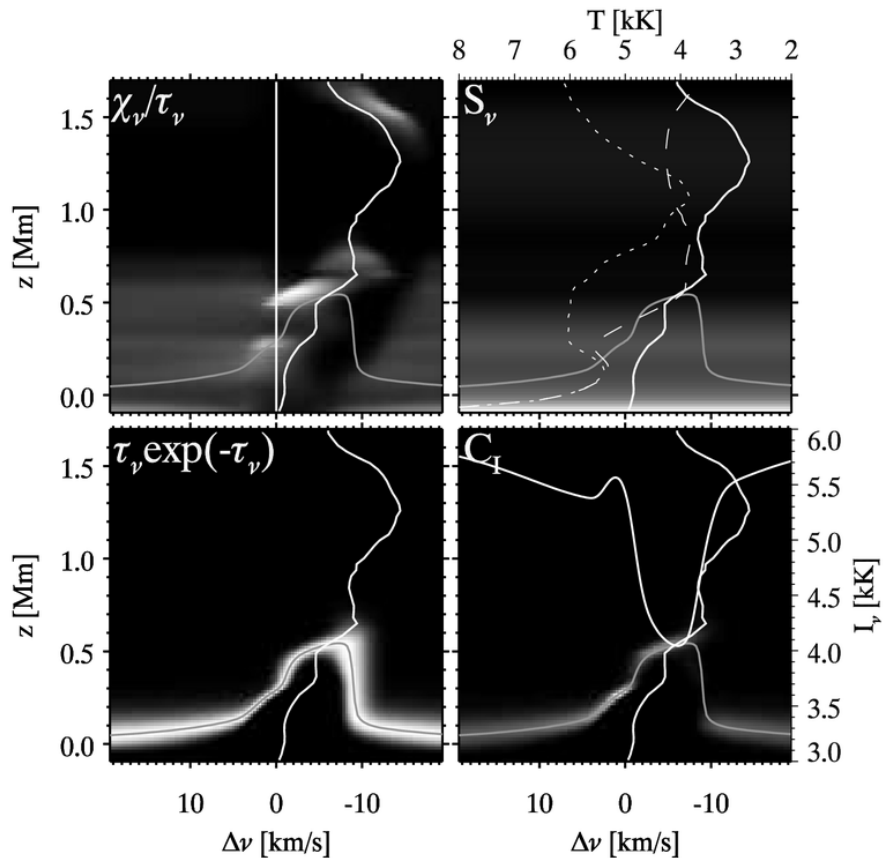
FIBRIL-FIELD ALIGNMENT FOR NLFFF LOWER BOUNDARY



- *NLFFF tests with chromospheric boundary*
 - Na I D₁: Metcalf et al. [1995ApJ...439..474M](#) [2005ApJ...623L..53M](#)
 - H α : Bobra & van Ballegoijen [2008ApJ...672.1209B](#) Wiegelmann et al. [2008SoPh..247..249W](#)
- *good alignment*
 - Aschwanden et al. [2016ApJ...826...61A](#)
- *partial alignment*
 - de la Cruz Rodríguez & Socas-Navarro [2011A&A...527L...8D](#)
 - Leenaarts et al. [2015ApJ...802..136L](#)
 - Martínez-Sykora et al. [2016ApJ...831L...1M](#)
 - Asensio Ramos et al. [2016arXiv161206088A](#)
- ¿ non-E alignment only at H ionization in propagating heating events?

Na I D₁ IN A MAGNETIC CONCENTRATION

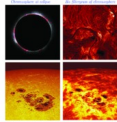
Leenaarts et al. 2010ApJ...709.1362L



CHROMOSPHERE OBSERVATIONS & DIAGNOSTICS

Rob Rutten

line formation displays: lectures on my website (google my name)
brief tutorial: 2016aKrV100309P => proceedings IAU 337 Cartagena



1858 - 1970: chromosphere = off-limb flash spectrum
1960 - 2010: chromosphere = transition plateau in static ID NLTE-SE models
2000 - present: chromosphere = sum small dynamic magnetics leading the corona
conjecture: chromosphere = propagating heating events and aftermath contrasts?

1

CHROMOSPHERE NAMING

Abstract of Norman Lockyer's paper read Nov. 26, 1868. Proc. Royal Society of London, 17, 131
1868RSPS...17..131L = full report

Details are given of the observations made by the new instrument, which was received incomplete on the 16th of October. These observations include the discovery, and exact determination of the lines, of the prominence-spectrum on the 20th of October, and of the fact that the prominence are usually local aggregations of a general medium which uniformly envelopes the sun. The term Chromosphere is suggested for this envelope, in order to distinguish it from the cool absorbing atmosphere on the one hand, and from the white-light-giving photosphere on the other. The possibility of variation in the thickness of this envelope is suggested, and the phenomena presented by the star in Corona are referred to.

Two of the lines correspond with Fraunhofer's C and F, another line B' or B'' (of Kirchhoff's scale) from Daws's E. There is another bright line, which occasionally makes its appearance near C, but slightly less refrangible than that line. It is remarked that the line near D has no corresponding line ordinarily visible in the solar spectrum. The author has

Fraunhofer's 'C' is H α , 'H' is 'H', the non-Fraunhofer line near 'D' (Na1D, + Na1D β) is He I, and the occasional 'less refrangible' line near H α is He I 6674. A.

4

ANNOTATION IN SACRAMENTO PEAK OBSERVATORY LIBRARY COPY

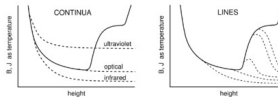
attention reader

see Dr Jager's comments on this book in Z. Astrophysik; v. 55; p 44 (1962)

(rather damaging!)

7

SUMMARY 1D SCATTERING SOURCE FUNCTIONS

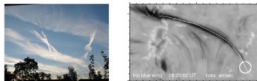


- continua
 - optical: $S \approx B$ for radiative equilibrium
 - ultraviolet: $S \approx J - B \rightarrow$ overionization of minority neutrals
 - infrared: $J < B$ but doesn't matter since $H\alpha$ and $H\beta$ have $S = B$
- lines
 - $\approx B(B + \kappa_B/\kappa_{\text{res}})^{-1}$ much less steep, so closer to isothermal $S = \sqrt{E}$
 - for stronger lines S sees more of the model chromosphere
 - FRD lines have frequency-dependent core-to-wing S curves like these

10

LONG H α FIBRIL AS CONTRAIL AFTER PROPAGATING HEATING EVENT

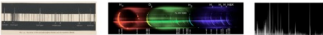
Rutten & Rouppe van der Voort 2016aKrV160076169 @ A&A



- H α : blue wing: faint tail with slender extending dark thread = wide bluehatched core
- propagating heating event extending in IRIS 1400 Å (SIV), AIA 304. 371, 193 Å
- three-four minutes later dark H α core fibril, retracting with increasing redshift
- Ca II IS42 Å shows only start of heating event and finish of redshifted contraction
- H α : fibril - contrail: not representing cool present but much hotter precursor past
 - ↳ RBE-like but more horizontal trajectory?
 - ↳ line-lying by H α ionization: contrail outlines precursor faster?
 - ↳ more such? Yes! Are all long H α fibrils contrails? Maybe...

2

SOLAR FLASH SPECTRUM



- chromosphere naming = definition (Lockyer 1869 outside eclipse)
 - strong: H I Balmer lines, He I D α , Ca II H&K
 - weaker: Mg Ib, Na I D, Sr II, Ba II
- chromosphere research = flash spectroscopy
 - Menzel thesis = 1898-1908 Campbell (1909)LoKo.17...1M (602 pp. on ADS)
 - Thomas & Athay book = 1952 HAO 1961spec.book...A (422 pp. not on ADS)
 - Dunn et al. = 1962 HAO 1968gasp...15..275D (275 pp. on ADS; RIR digitized)
- chromosphere = ergium
 - flash spectrum \neq reversed disk spectrum
 - both hot (He I D α) and cool (Na I D, & D) lines
 - spatial extent exceeds radiative-equilibrium scale height

5

De Jager's review (1962ZA...55...66T + 1962ZA...55...70W)

Besprechungen

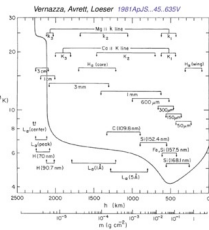
Thomas, R. N., and B. D. AVRETT: Physik der Sonne (Chromosphäre, X + 422 Seiten. Interscience Publishers, Inc., New York 1961. Geh. \$ 15.90.

Der Titel des Buches verspricht mehr, als der Inhalt gibt. Jeder, der schon einmal durch ein He-Filter oder durch ein Spektroskop die beobachtete Struktur der Chromosphärenoberfläche gesehen oder das Profil des Sonnenrands beobachtet hat, wird - sobald er den Titel 'Physik der Chromosphäre' liest - an eine Erklärung der Dynamik dieser Gasmassen denken. Er wird ein Problem der Schall-, Stoß- und Gravitationswellen und an die Description von deren Energieformen. Valentić wird er sich fragen, was die Autoren von der Rolle halten, die Magnetfelder und magnetohydrodynamische Wellen spielen und in welchem Maße von ihnen die verschiedenen Strukturen der ruhigen bzw. gestörten Gebiete dieses merkwürdigen Teiles der Sonne bestimmt werden. Von allem dem wird er aber in diesem Buche nichts finden: Die betreffenden Probleme werden kaum erwähnt, geschweige denn besprochen. und so weiter... four pages more

Ughot: the book treats the derivation of a model atmosphere from the spectrograms taken by the 1952 HAO eclipse expedition but ignores the inhomogeneity and dynamics of the chromosphere such as sound, shock, gravity and MHD waves, as well as magnetic fields.

8

VALIIC MODEL



11

NORMAN LOCKYER

wikipedia



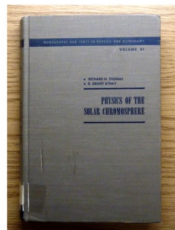
Sir Joseph Norman Lockyer, FRS (17 May 1836 – 16 August 1920), known simply as Norman Lockyer, was an English scientist and astronomer. Along with the French scientist Pierre Janssen he is credited with discovering the gas helium.

In 1855 he became the world's first professor of astronomical physics at the Royal College of Science, South Kensington, now part of Imperial College. At the college, the Solar Physics Observatory was built for him and here he directed research until 1913.

To facilitate the transmission of ideas between scientific disciplines, Lockyer established the general science journal Nature in 1869. He remained its editor until shortly before his death.

3

ECLIPSE WISDOM



- line formation theory
 - flash spectrum @ Harvard, Boulder = Mihalas 1970, 1978: summary
 - static 1D 'standard' models: VALIIC more Avrett, hydrogen exans
 - non-E: detailed balancing 1D RayStn 2D Slaggar 3D Bilout
- chromosphere diagnostics
 - Na I D, Mg Ib, Ly α +H α He I D α He II 4542 Å Ca II H&K-Mg b h&k
 - SIV He I He II
- chromospheric & coronal heating ingredients
 - gravity waves
 - acoustic waves
 - Alfvénic waves
 - reconnection
- fine structure
 - sketched: Noyes 1979 Gabriel 1979 Wedemeyer 2016 Rutten 2016
 - observed and explained: Ca II ground dynamic fibrils
 - observed but not explained: streamers/spicules/BBS-E/BBS-R/E
 - fibril-fibril alignment for NLFFF: yes partly \neq only at launch?

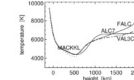
6

CHROMOSPHERE POTPOURRI

- line formation theory
 - flash spectrum @ Harvard, Boulder = Mihalas 1970, 1978: summary
 - static 1D 'standard' models: VALIIC more Avrett, hydrogen exans
 - non-E: detailed balancing 1D RayStn 2D Slaggar 3D Bilout
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 - Na I D, Mg Ib, Ly α +H α He I D α He II 4542 Å Ca II H&K-Mg b h&k
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 - observed and explained: Ca II ground dynamic fibrils
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 - fibril-fibril alignment for NLFFF: yes partly \neq only at launch?

9

AVRETT SOLAR-ANALOG STARS



- VALIIC = Vernazza, Avrett, Losser 1981ApJS...45..635V; best fit to UV continua
- MACKUL = Malby et al. 1986ApJ...306..284M; less steep upper photosphere
- FALC = Fontana, Avrett, Losser 1993ApJ...406..319F; ambipolar diffusion
- ALC? = Avrett & Losser 2008ApJS...175..253A; UV line fits; updates 2016ApJ...811..274 (J) The result may be interpreted as holding for a compositionally varying star called VALIIC (J). This star is remarkably like the Sun in its temporally and spatially averaged continuum spectral distribution, but in contrast to the Sun it does obey hydrostatic equilibrium and static plane-parallel geometry, and it contains only those atoms, ions and electrons that were specified in the Avrett code, but mainly with just the corresponding cross sections. Its modeling is exact! The advantage of analyzing the star VALIIC rather than the star Sun is that the physics of VALIIC radiation is fully understandable. Also, it keeps adhering to these course notes ad infinitum while solar physics evolves to more complexity. Rutten "Radiative Transfer in Stellar Atmospheres"

12

13

EXPLAIN EVERYTHING – INCLUDING SIMILARITIES AND DIFFERENCES
ALCT: 2008ApJ...178.229A **FOHHT**: 2008ApJ...707.482P **FALP**: 1993ApJ...436.310P

ALCT **T** **FOHHT** **FALP**

ALCT **H1** **FOHHT** **H1** **FALP**

ALCT **H2** **FOHHT** **H2** **FALP**

ALCT **H3** **FOHHT** **H3** **FALP**

14

CHROMOSPHERE POTPOURRI

- line formation theory
 - flash spectrum @ Harvard; Boulder = Mihalas (1970, 1978): summary
 - static 1D “standard” models: VALIIC more Arnett hydrogen exam
 - non-E: detailed balancing 1D Radvj 2D Staggar 3D Bfrost
- chromosphere diagnostics
 - Na I D + Mg b₂ Ly α H α Ca II 8542 Å Ca II H & K Mg II h & k
 - SIV mm He I+He II
- chromospheric & coronal heating ingredients
 - gravity waves
 - acoustic waves
 - Alfvénic waves
 - reconnection
- line structure
 - sketched: Hoyes 1979 Gabriel 1976 Wedemeyer 2016 Rutten 2016
 - observed and explained: Ca II g lines dynamic chromosphere
 - observed but not explained: straws/picules H RBEs/FREs long H α fibrils
 - fibril-field alignment for NLFFF: use partly μ only at launch?

15

DETAILED BALANCING

Hydrogen ionization/recombination relaxation timescale throughout the solar-like shocked Rayleigh atmosphere. The timescale for getting 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 is partially ionized.
 Carlsson & Stein 2002ApJ...572.626C

net radiative and collisional downward rates (Wien approximation)
 $n_e n_H - n_H n_e = n_e^2 \frac{h\nu_{Ly\alpha}}{kT} \left(\frac{A_{Ly\alpha}}{A_{He I}} - \frac{A_{He I}}{A_{Ly\alpha}} \right)$ for $z \gg 1$, no heating/cooling
 $n_e n_e - n_e n_e = n_e^2 \left(\frac{h\nu_{Ly\alpha}}{kT} - 1 \right) = n_e^2 \left(\frac{h\nu_{Ly\alpha}}{kT} - 1 \right) \left(1 + \frac{h\nu_{Ly\alpha}}{kT} \right)$ zero for $h\nu_{Ly\alpha} = kT$, LTE S'

dicke approximation for atom collisions with electrons (Van Regenmortel 1982)
 $C_{Ly\alpha} \approx 2.16 \left(\frac{h\nu_{Ly\alpha}}{kT} \right)^2 T^{-1/2} n_e N_H$

Einstein relation
 $C_{Ly\alpha} = C_{He I} = C_{Ly\alpha} A T$

$C_{Ly\alpha}$ is not very temperature sensitive (any collision will do); $C_{He I}$ has Boltzmann sensitivity

16

NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS
 Carlsson & Stein 2002ApJ...572.626C

- RADN code: 1D hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed supersonic piston driven acoustic waves in hot shock near $v \approx 100$ km
- Ly α scatterers in radiative balance and coronas ≈ 2 . Within shocks $S \approx 1$ saturates to β from radiation lock-in (increased from partial hydrogen ionization) so that $h\nu_{Ly\alpha} \approx \beta$
- collisional Ly α balancing has Boltzmann temperature sensitivity: fast (seconds) in hot gas, slow (minutes) in cool gas, resulting in retention: post-shock cooling gas maintains the high $h\nu_{Ly\alpha}$ shock value as increasing β during minutes, up to huge overpopulation ($n_e \approx 10^{17}$)
- ionization from ≈ 3 in the 2-D radiative-like hydrogen trap in an instantaneous statistical-equilibrium balance driven by Balmer continuum g , β and cooled by cascade recombination with $\lambda_{Ly\alpha} \approx 10^{11}$ s and 10^{11} s in cool gas, adding to the retained $h\nu_{Ly\alpha}$
- between shocks Ly α remains highly overionized versus SE and LTE predictions

17

NON-E HYDROGEN IONIZATION IN 2D MHD SHOCKS
 Leenarts et al. 2007A&A...473.659L

- in shocks Ly α has $S \approx \beta$ from high β (fast balancing) and Ly α (10% H ionization)
- related collisional balancing in Ly α : $h\nu_{Ly\alpha}$ hangs near high shock value $n_e \approx n_H^{1/2}$
- glow/plastic post-shock $\rightarrow 2$ overpopulations versus LTE ($S \approx \beta$ underionization)
- μ large post-shock overionization from hydrogen log Balmer balancing
- no Lyman RT: green arches artifacts, no lateral μ boost from Ly α scattering

18

BIFROST SOLAR-ANALOG STAR

- Bifrost: a Modular Python/C++ Framework for Development of High-Resolution Data Analysis Pipelines 2017AAS...2392305C
- Vertical crustal motion observed in the BIFROST project 2003Geo...35.425S
- BIFROST project: 3-D crustal deformation rates derived from GPS confirm post-solar rebound in Ferrisarcadia 2017EAS...61.205Z
- “SPACE” 2013-2015: ASGARid Balloon and BIFROST Parabolic Flights: Latest Developments in Hands On Space Education Projects for Secondary School Students 2015ESAO726.620Z
- BIFROST: conference hotel in Iceland (not on ADS)
- Bifrost: computational star in Carlissarcandia, remarkably like the Sun in its spectral characteristics and likewise non-plane-parallel, inconstant, and inconsistent, with the virtue of showing much spatio-temporal fine structure similar to solar fine structure:
 - granules and intergranules
 - acoustic box modes similar to solar \rightarrow smooth interference patterns
 - non-diposited internal gravity waves
 - diposited internetwork shocks
 - magnetic network concentrations
 - dynamic fibrils
 - Eternum reconnection bursts
 - but lacking spicules/H α component/reconnection? Alfvénic (branon?) wave bursts?
- Bifrost analogs in chromosphere-formation stage: COSBOLL MURAM Mancha

19

BIFROST

code

- Gudknecht et al. 2014AA...531A.194D Bifrost description
- Carlsson & Leenarts 2012A&A...558A.39C cooling + heating approximations
- Leenarts et al. 2012A&A...560A.106K fast angle-dependent PRD
- Martinez-Sykora et al. 2012ApJ...763.141M ionization diffusion
- Perera et al. 2013AA...354A.118P 3D simulation better than standard 1D models
- Olin et al. 2013AJ...145.720J non-E 3-D shock
- Goding et al. 2014ApJ...784.203 JH H α ionization
- Carlsson et al. 2014AA...565A.4C publicly available snapshot
- Sakurovich & Leenarts 2014AA...597A.46E PRD in 3D simulations

warnings

- no Ly α RT, so no μ boosting from Ly α around scattering around hot structures
- for H α RT: μ still ≈ 0.2 in MILD of Leenarts & Carlsson 2009ASPC...416...57L, not column-wise as RH1.5D of Perera & Ueberroth 2015AA...574...3P
- for H α and He I features RT: must be time-dependent, not snapshot-wise SE

morals

- When analog star lines match solar lines one still has to find out how they came about in the analog star. This task is non-trivial. When analog star lines do not match solar lines, one should not simply blame the solar observations but appreciate the mismatch as potentially informative.

20

BIFROST VERSUS 1D STANDARD MODELS

- Bifrost = state-of-the-art: 3D, 1D, non-E, SE, SEP populations but NE for H Leenarts, Carlsson & Rosser van der Voort 2014ApJ...746.136L
- ALCT = Ly α 1D static, no μ in μ microturbulence, SE populations
- Arnett & Luvier 2008ApJ...175.229A
- FOHHT + OSSE: 1D static, no μ , E-imposed acceleration, SE populations
- Fontenla, Curti, Haberman, Harder & Tan 2003ApJ...701.420P

The J and H α behaviors seem generally similar. However, the coronal differences between plane-parallel static hydrostatic equilibrium modeling and 3D MHD simulation are enormous. The T(4) stratifications in the simulation vary tremendously, with shocks propagating upwards and downwards and the increase to coronal temperature depending up and down in height. Bifrost has no “temperature minimum” or “transition region”!

21

BIFROST ANALYSES – SOFAR

Hayek et al. 2016AA...517A.49H solar-type stars

Martinez-Sykora et al. 2016AJ...172J.481 EUV line asymmetries

Leenarts et al. 2016ApJ...749.136L 3D H α formation

Stapan et al. 2016ApJ...820.105L Ly α formation

de la Cruz Rodriguez et al. 2016A&A...568A.34D Ca II 8542 Å inversion test

Clun et al. 2016ApJ...787.402J non-E UV rays

Martinez-Sykora et al. 2016ApJ...817.109V Ca II and H α from a spicule-II

Leenarts et al. 2016ApJ...772.902J Mg II h & k for IRS I

Leenarts et al. 2016ApJ...772.902J Mg II h & k for IRS II

Perera et al. 2016ApJ...822.108 H α reconnection strong field simulation

Hartmann & Anthonis 2016ApJ...822.108 H α reconnection strong field simulation

Clun et al. 2016ApJ...822.108 optically thin emission lines

Leenarts et al. 2016ApJ...822.108 H α fibrils versus field

Stapan et al. 2016ApJ...822.108 Ly α formation

Perera et al. 2016ApJ...822.108 Ly α formation

Carlsson et al. 2015ApJ...808L.300J Mg II k from page

Hansen et al. 2015ApJ...811.106J Ly α heating from topmost braiding

Rathore et al. 2015ApJ...811.106J IRIS C II formation

Guerrero et al. 2015ApJ...817.404J quiet-Sun heating events

Martinez-Sykora et al. 2016ApJ...817.404J non-E SIV/O V ratios

Goding et al. 2016ApJ...817.404J H α ionization

Noberge-Silverio et al. 2016ApJ...822.108 H α surge

Kato et al. 2016ApJ...822.108 waves from magnetic pumping

de la Cruz Rodriguez et al. 2016ApJ...830.202J Mg II h & k Mg II triplet inversions

Schweizer-Scherrer 2016ApJ...831.108J IRIS Si IV internetwork versus IRS

Martinez-Sykora et al. 2016ApJ...831.108J Si IV 2.65 ampolar misalignment fibrils-field

Leenarts et al. 2016AA...594A.46E spatial structure in the hot 10000

Goding et al. 2016ApJ...819.100250J He resonance lines

22

Na I D AND Mg b₂

- similar NLTE formation = heavy two-level scattering
- core intensities do not sense ALCT chromosphere
- narrow Na I D, fibrils reverse reversed granulation
- non-E1 minority stage: recombination n_e \times Ly α Ly α settling and scattering
- SST: Dopplergrams = unignited fluxube magnetograms (Na I D formation)
- μ non-E enhanced in cooling/recombining downflows? (SE = Bifrost snapshot OK)

23

Ly α and H α

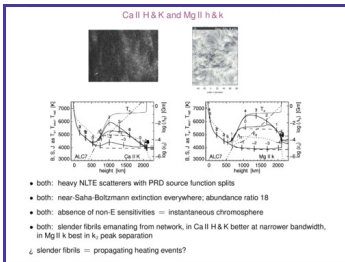
- both: heavy NLTE scatterers with $S \approx \beta$
- Ly α : boosted by enormous extinction \rightarrow radiative thermalization: $S \approx \beta$ in shocks (in ALCT chromospheric optical thermalization); $h\nu_{Ly\alpha} \approx \beta$ in cool gas surrounding hot structures; Ly α scattering in post-hot cool gas slow $S \approx \beta$ thermalization with $h\nu_{Ly\alpha} \approx \beta$: S' memory of hot past
- H α : photons created in granulation; scatter 3D across upper chromosphere opacity gap and through chromosphere in shocks etc. Boltzmann Ly α $h\nu_{Ly\alpha}$; post-hot cool gas $h\nu_{Ly\alpha} \approx \beta$: extinction memory of hot past
- Ly α scores: heating events bright; down-thrust, cooling: cooling: cooling: dark from scattering H α score: RBE/RRE heating events, cooling: cooling: dark from non-E opacity

24

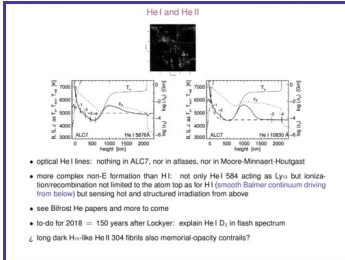
H α and Ca II 8542 Å

- both: heavy NLTE scatterers with $S \approx \beta$ sampled at similar ≈ 1 heights
- both: SaHa-Boltzmann or larger extinction in shocks and ALCT
- core widths: both decrease away from network \rightarrow decreasing temperature
- H α : fibrils extend further, contradicting SaHa-Boltzmann extinction sensitivities
- fibril opacity in Ca II 8542 Å instantaneous, in H α : post-hot non-E?

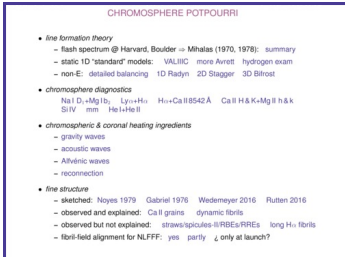
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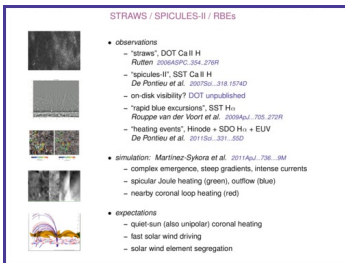
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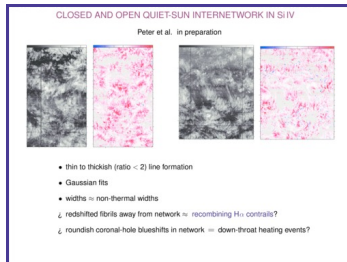
31



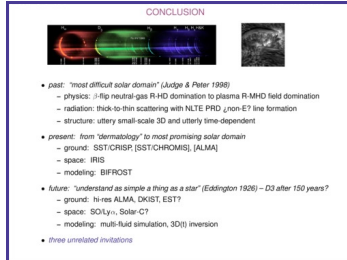
34



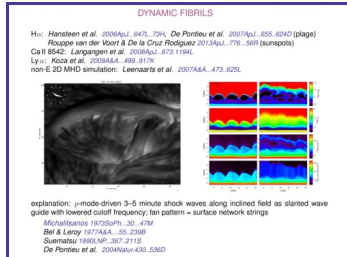
26



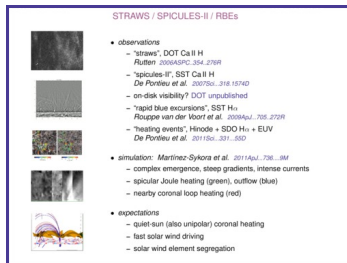
29



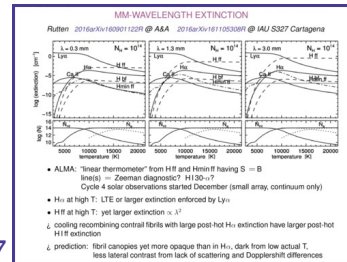
32



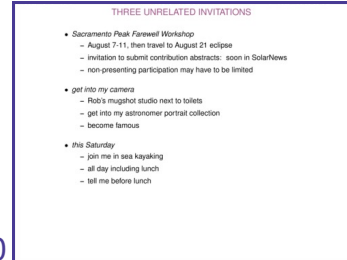
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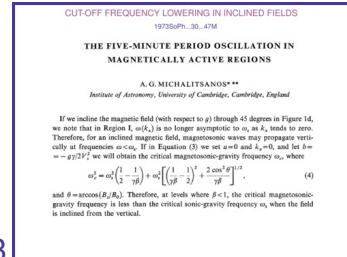
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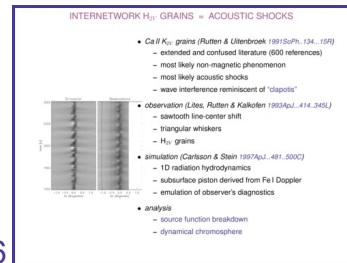
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33

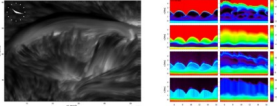


36



DYNAMIC FIBRILS

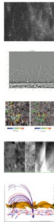
Hic: *Hansteen et al. 2009ApJ...693L..73H*, *De Pontieu et al. 2007ApJ...655L..624D* (plage)
Rosseel van der Voort & De la Cruz Rodriguez 2013ApJ...776L..569R (sunspots)
 Cai li (S45): *Langangen et al. 2009ApJ...672L..154L*
 Lyric: *Koca et al. 2009A&A...499B..977K*
 non-E 2D MHD simulation: *Leenaarts et al. 2007A&A...473L..620L*



explanation: p -mode-driven 3-5 minute shock waves along inclined field as slanted wave guide with lowered cutoff frequency; fan pattern = surface network strings
Michalasiunas 1975S&Ph...30L..41M
Bel & Leroy 1977A&A...55L..238B
Sunstein 1990ApJ...367L..111G
De Pontieu et al. 2004Natur...430L..530D

37

STRAWS / SPICULES-II / RBES



- observations
 - "straws", DOT Ca II H
 - *Rutan 2006ASPC...354L..279R*
 - "spicules II", SST Ca II H
 - *De Pontieu et al. 2007So...318L..1574D*
 - on disk visibility? DOT unpublished
 - "rapid blue excursions", SST H α
 - *Rosseel van der Voort et al. 2009ApJ...705L..270R*
 - "heating events", Hinode + SDO H α + EUV
 - *De Pontieu et al. 2011So...331L..58D*
- simulation: *Martinez-Sykora et al. 2011ApJ...736L..38M*
 - complex emergence, steep gradients, intense currents
 - spicular arcade heating (green), outflow (blue)
 - nearby coronal loop heating (red)
- expectations
 - quiet sun (also unipolar) coronal heating
 - fast solar wind driving
 - solar wind element segregation

38

FIBRIL-FIELD ALIGNMENT FOR NLFFF LOWER BOUNDARY

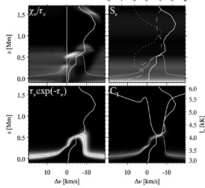


- NLFFF tests with chromospheric boundary
 - *Nai D., Metcalfe et al. 1995ApJ...430L..474M*, *2005ApJ...623L..53M*
 - *Hic: Ebra & van Ballegoijen 2008ApJ...672L..109B*, *Wiegmann et al. 2008SoPh...247L..249W*
- good alignment
 - *Achewenden et al. 2016ApJ...826L..61A*
- partial alignment
 - *de la Cruz Rodriguez & Socas-Navarro 2011A&A...537L..8D*
 - *Leenaarts et al. 2015ApJ...802L..136L*
 - *Martinez-Sykora et al. 2016ApJ...821L..11M*
 - *Aerospo Ramos et al. 2016ApJ...819L..209B8A*
- \perp non-E alignment only at H ionization in propagating heating events?

39

Na I D λ IN A MAGNETIC CONCENTRATION

Leenaarts et al. 2010ApJ...709L..136L



40



41

thumbs/thumb-.jpg

42