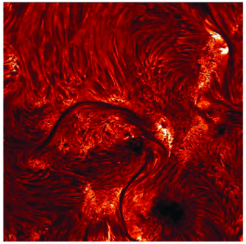
CHROMOSPHERE OBSERVATIONS & DIAGNOSTICS

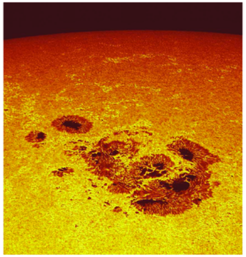
Rob Rutten

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

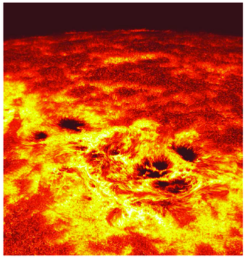
Chromosphere at eclipse

Hα filtergram of chromosphere





Photospheric spots & bright points

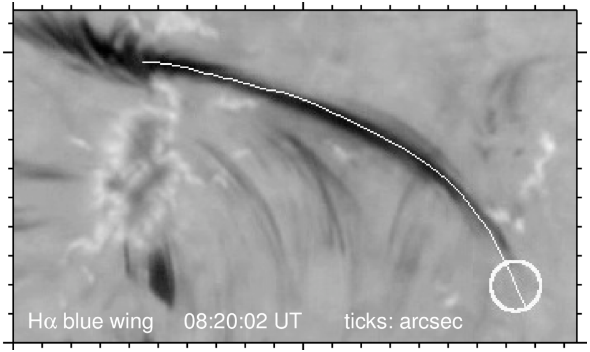


Same area in chromospheric Ca^+

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 Hα FIBRIL AS CONTRAIL AFTER PROPAGATING HEATING EVENT

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



- Hα blue wing: fantail with slender extending dark thread = wide blueshifted core
- propagating heating event extending in IRIS 1400 Å (Si IV), AIA 304, 171, 193 Å
- three-four minutes later dark Hα core fibril, retracting with increasing redshift
- Ca II 8542 Å shows only start of heating event and finish of redshifted contraction
- Hα fibril ~ contrail: not representing cool present but much hotter precursor past

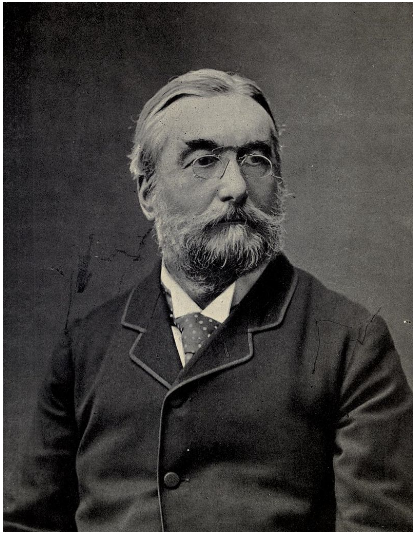
¿ RBE-like but more horizontal trajectory?

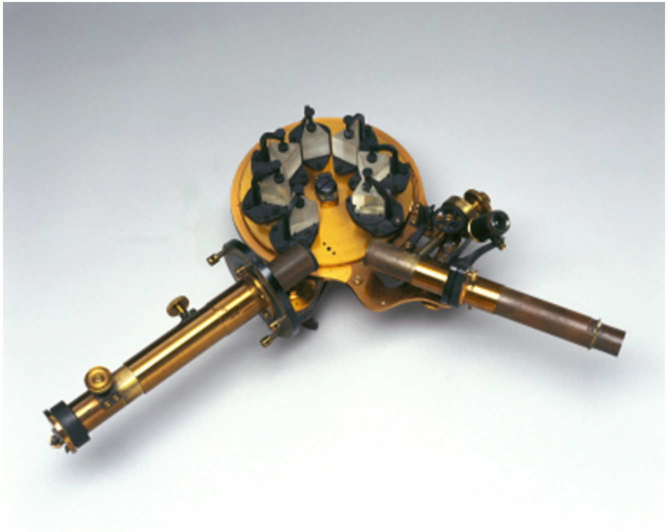
¿ line-tying by H ionization: contrail outlines precursor field?

¿ more such? Yes! Are all long Hα 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.

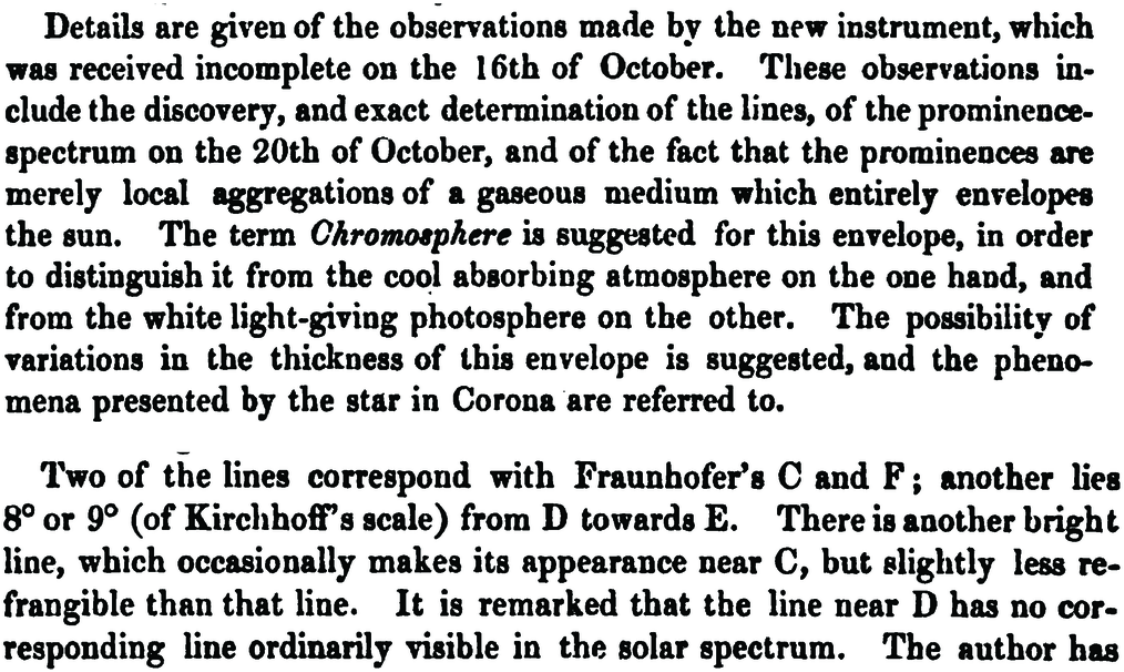
In 1885 he became the world's first professor of astronomical physics at the Royal College of Science, South Kensington, now part of Imperial College. At the college, the Solar Physics Observatory was built for him and here he directed research until 1913.

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 Hα, "F" is Hβ, 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 Hα is He I 6678 Å.

SOLAR FLASH SPECTRUM

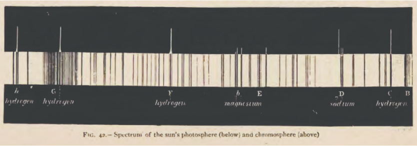
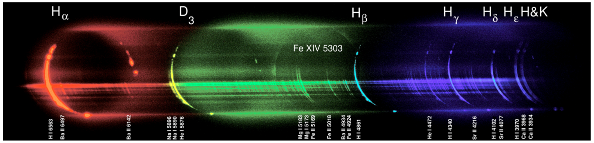
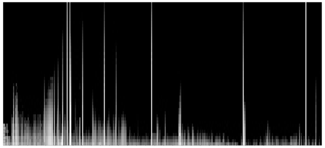


Fig. 42.– Spectrum of the sun's photosphere (below) and chromosphere (above)



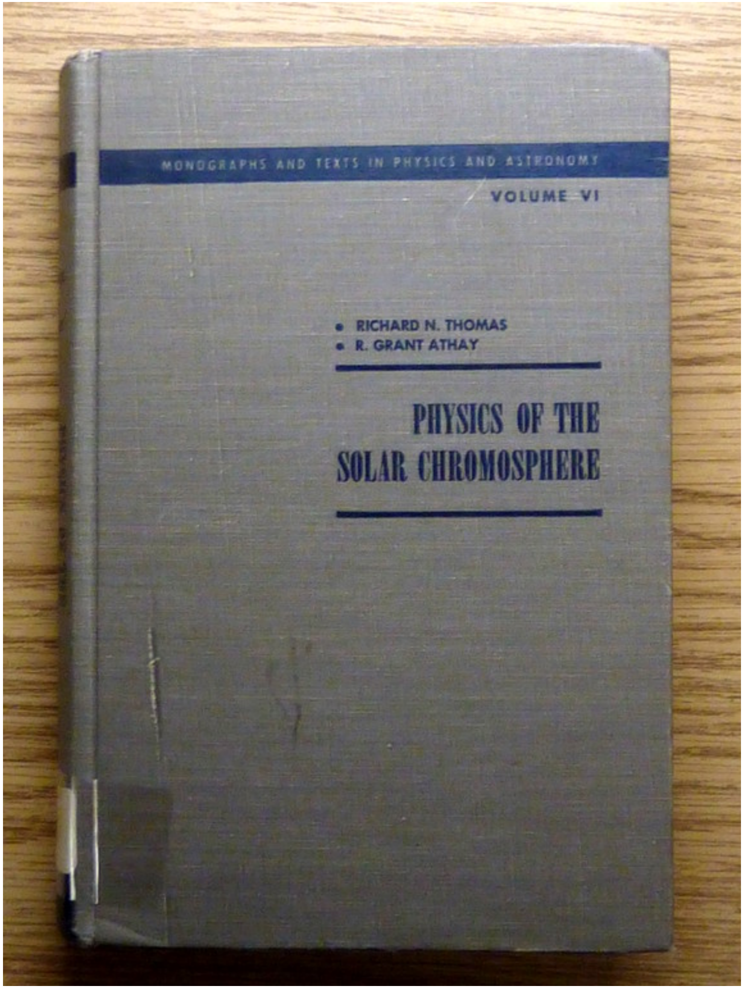


- *chromosphere naming $=$ definition (Lockyer 1868 outside eclipse)*
  - strong: H I Balmer lines, He I D_3, Ca II H & K
  - weaker: Mg I b, Na I D, Sr II, Ba II

- *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-equilibrum scale height

ECLIPSE WISDOM



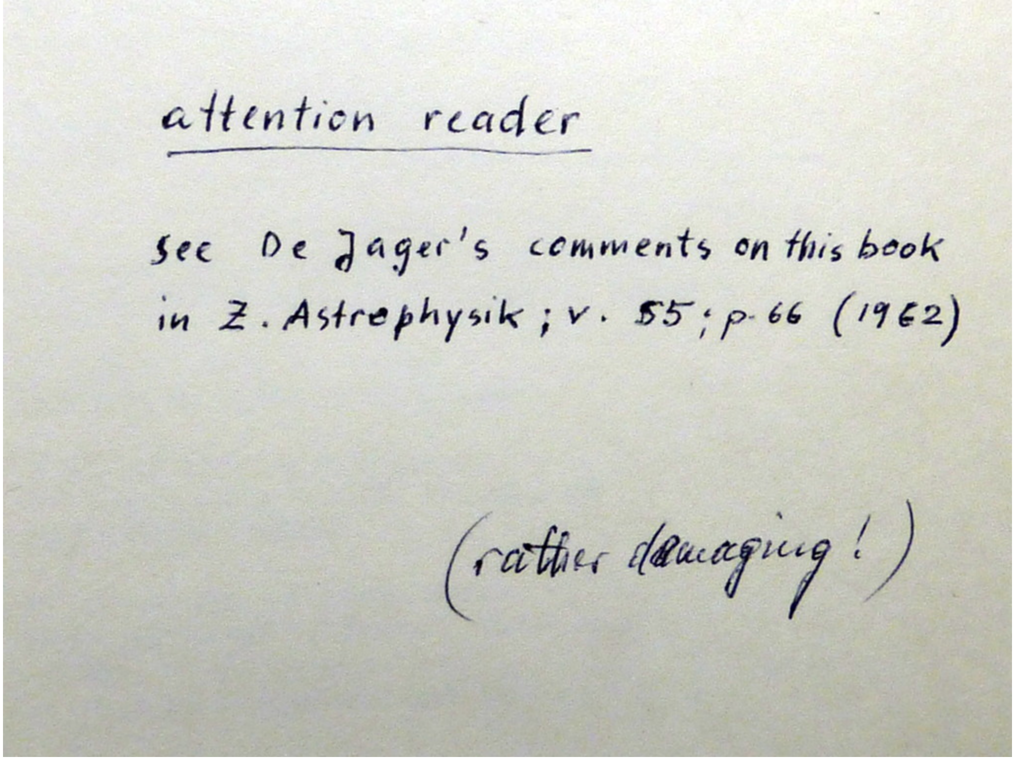
MONOGRAPHS AND TEXTS IN PHYSICS AND ASTRONOMY

VOLUME VI

- RICHARD N. THOMAS
- R. GRANT ATHAY

PHYSICS OF THE
SOLAR CHROMOSPHERE

ANNOTATION IN SACRAMENTO PEAK OBSERVATORY LIBRARY COPY

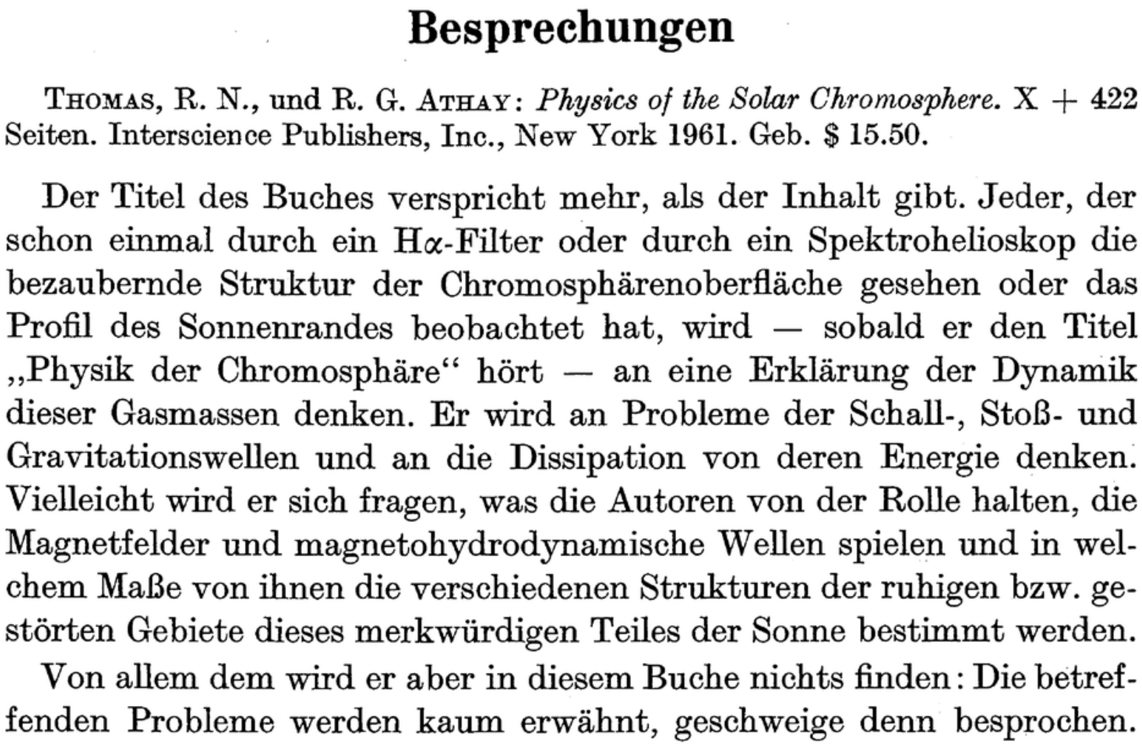


attention reader

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

(rather damaging!)

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



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 Hα-Filter oder durch ein Spektroheliokop 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

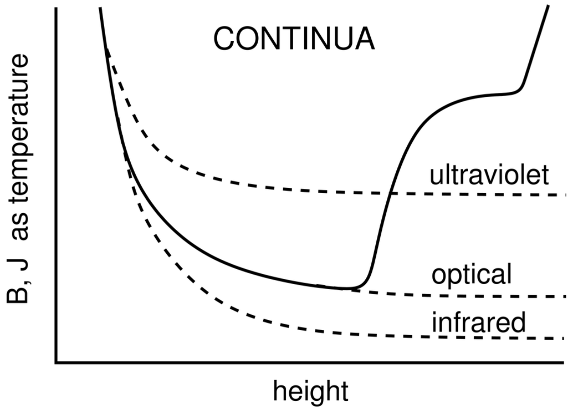
Upshot: the book treats the derivation of a model atmosphere from the spectrograms taken by the 1952 HAO eclipse expedition but ignores the inhomogeneity and dynamics of the chromosphere such as sound, shock, gravity and MHD waves, as well as magnetic fields.

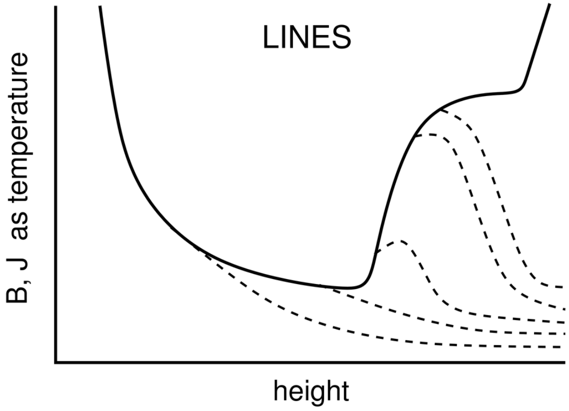
CHROMOSPHERE POTPOURRI

- *line formation theory*
  - flash spectrum @ Harvard, Boulder ⇒ Mihalas (1970, 1978): summary
  - static 1D “standard” models: VALIIIC more Avrett hydrogen exam
  - non-E: detailed balancing 1D Radyn 2D Stagger 3D Bifrost
- *chromosphere diagnostics*

  Na I D_1+Mg I b_2 Lyα+Hα Hα+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 Hα fibrils
  - fibril-field alignment for NLFFF: yes partly ¿ only at launch?

SUMMARY 1D SCATTERING SOURCE FUNCTIONS

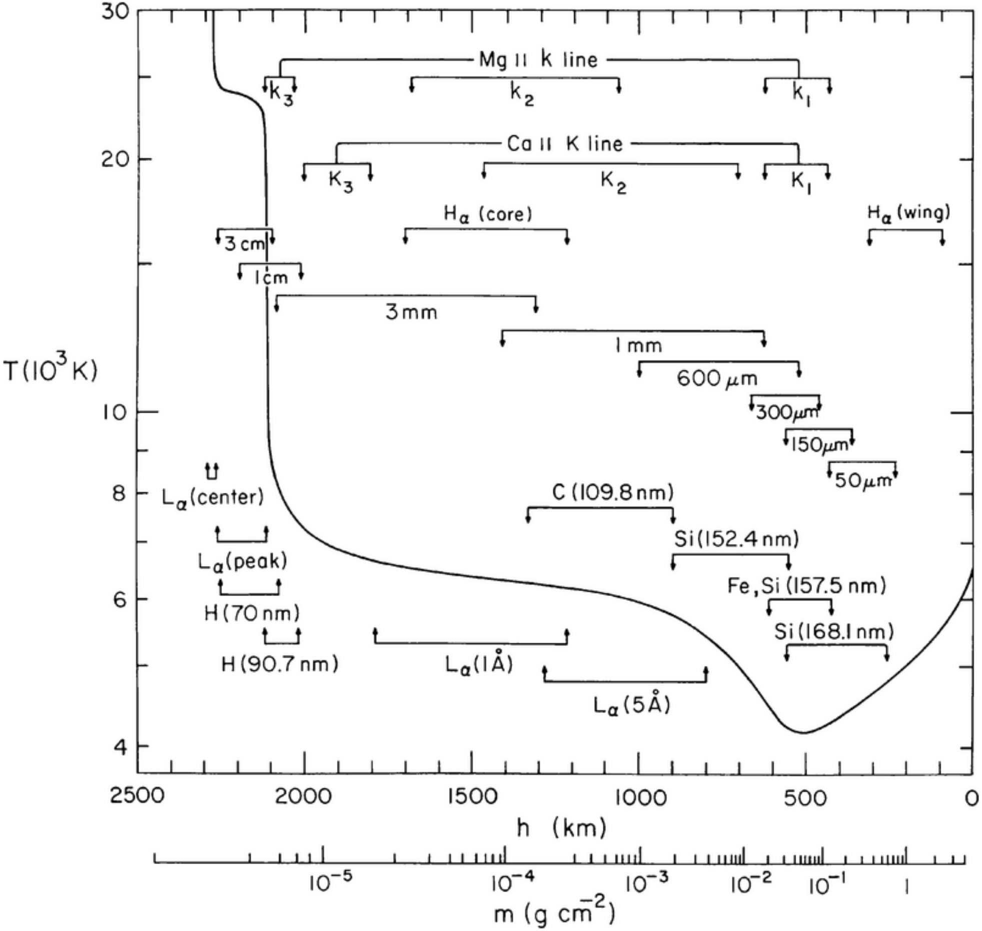




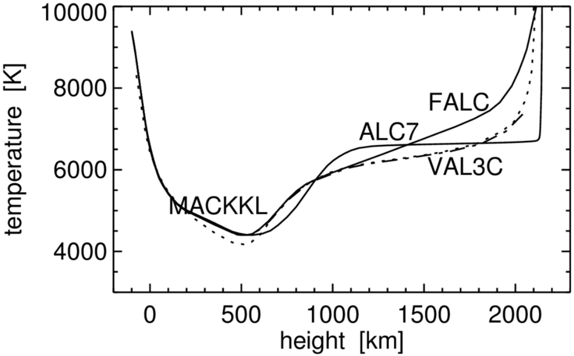
- *continua*
  - optical: $J \approx B$ for radiative equilibrium
  - ultraviolet: $S \approx J > B \rightarrow$ overionization of minority neutrals
  - infrared: $J < B$ but J doesn't matter since $\mathrm{H}^-_{\mathrm{ff}}$ and H_{ff} have $S = B$
- *lines*
  - $\mathrm{d}B/\mathrm{d}\tau = \mathrm{d}B/\mathrm{d}(\tau^c + \tau^l)$ much less steep, so closer to isothermal $S \approx \sqrt{\varepsilon}\, B$
  - for stronger lines S sees more of the model chromosphere
  - PRD lines have frequency-dependent core-to-wing S curves like these

VALIIIC MODEL

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



AVRETT SOLAR-ANALOG STARS



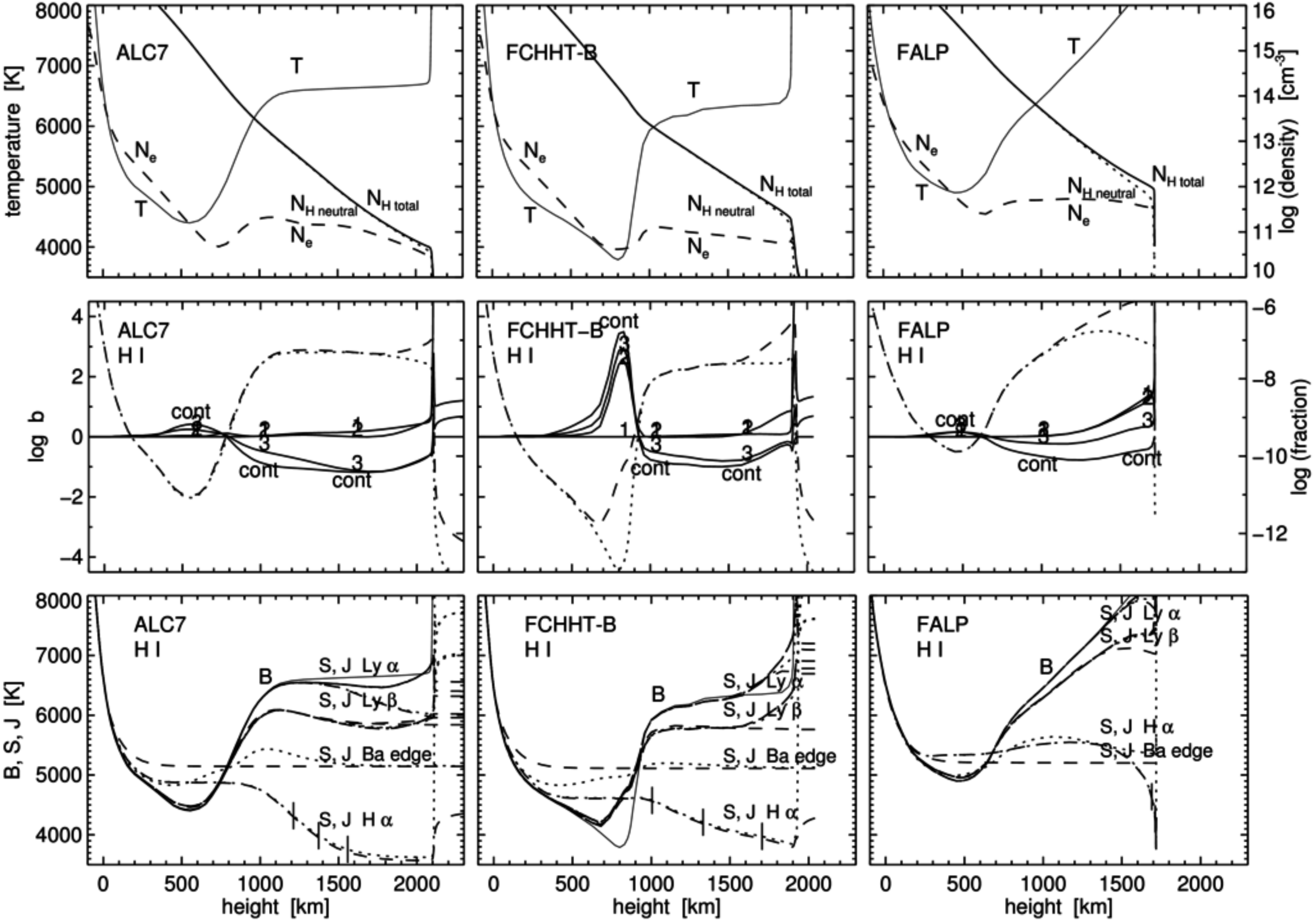
- VAL3C = Vernazza, Avrett, Loeser 1981ApJS...45..635V: best-fit to UV continua
- MACKKL = Maltby et al. 1986ApJ...306..284M: less steep upper photosphere
- FALC = Fontenla, Avrett, Loeser 1993ApJ...406..319F: ambipolar diffusion
- ALC7 = Avrett & Loeser 2008ApJS..175..229A: UV-line fit; update 2015ApJ...811...87A

[. . .] 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 Amospheres”

EXPLAIN EVERYTHING – INCLUDING SIMILARITIES AND DIFFERENCES

ALC7: *2008ApJS..175..229A* *FCHHT-B:* *2009ApJ...707..482F* *FALP:* *1993ApJ...406..319F*



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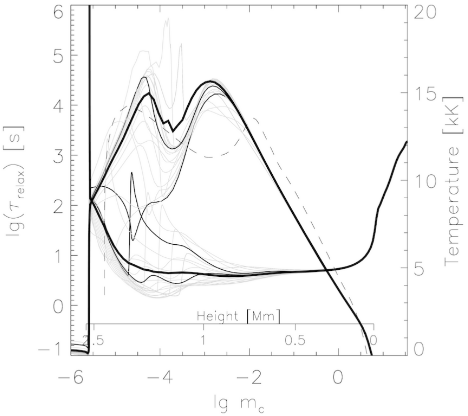
DETAILED BALANCING



Hydrogen ionization/recombination relaxation timescale throughout the solar-like shocked Radyn atmosphere. The timescale for settling to equilibrium at the local temperature is very long, 15–150 min, in the chromosphere but much shorter, only seconds, in shocks in which hydrogen partially ionizes.

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

net radiative and collisional downward rates (Wien approximation)

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

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

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

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

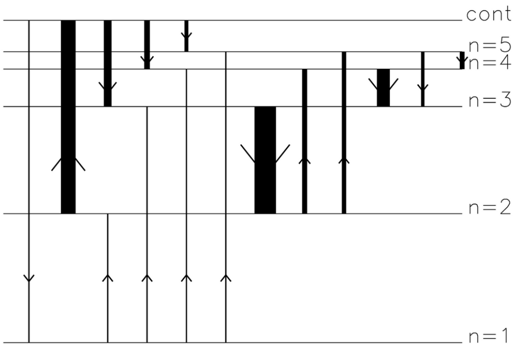
Einstein relation

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

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

NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

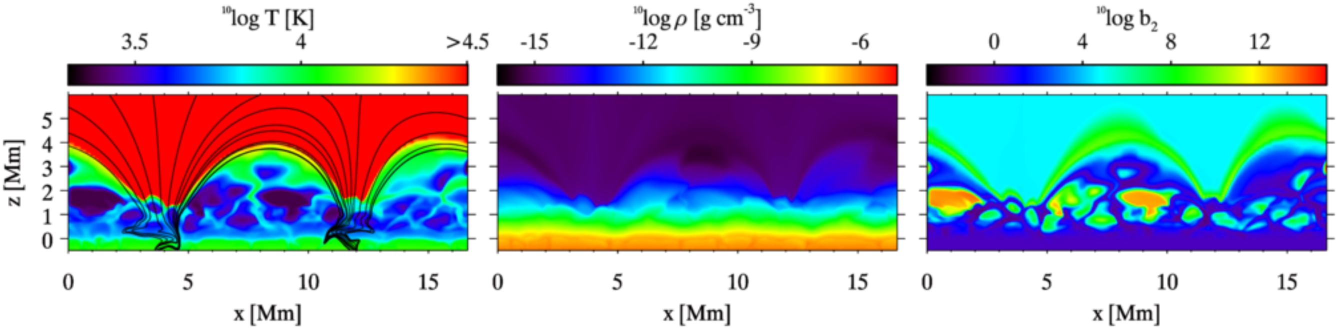
Carlsson & Stein *2002ApJ...572..626C*

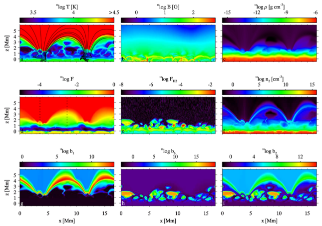


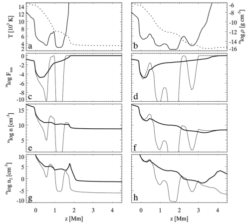
- RADYN code: 1D(t) hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed subphotosphere piston drives acoustic waves up that shock near $h = 1000$ km
- Lyα scatters in radiative balance and controls $n = 2$. Within shocks $S \approx J$ saturates to B from radiation lock-in (increased 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 $n_2 \approx n_2^{\mathrm{LTE}}$
- gigantic post-shock $n = 2$ overpopulations versus LTE (“S-B underestimates”)
- yet larger post-shock overionization from hydrogen-top Balmer balancing
- no Lyman RT: green arches artifacts, no lateral N_{e} boost from Lyα scattering

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
- *"SP.ACE" 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

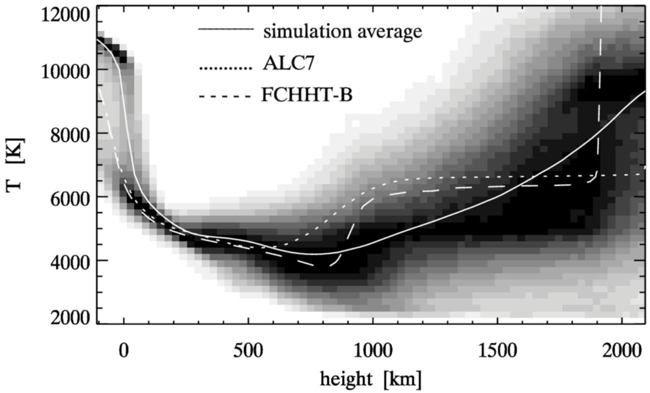
- *code*
  - Gudiksen et al. 2011A&A...531A.154G Bifrost description
  - Carlsson & Leenaarts 2012A&A...539A..39C cooling + heating approximations
  - Leenaarts et al. 2012A&A...543A.109L fast angle-dependent PRD
  - Martinez-Sykora et al. 2012ApJ...753..161M ambipolar diffusion
  - Pereira et al. 2013A&A...554A.118P 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

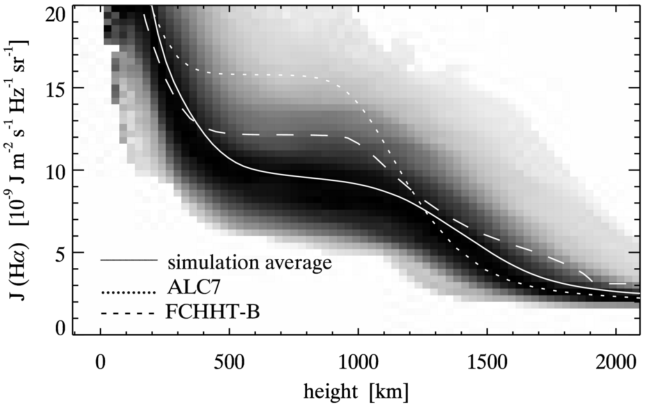
- *warnings*
  - no Lyα RT, so no $N_{\rm e}$ boosting from Lyα surround scattering around hot structures
  - for Hα RT must be 3D as in MULTI3D of Leenaarts & Carlsson 2009ASPC..415...87L, not column-wise as in RH1.5D of Pereira & Uitenbroek 2015A&A...574A...3P
  - for H and He features RT must be time-dependent, 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





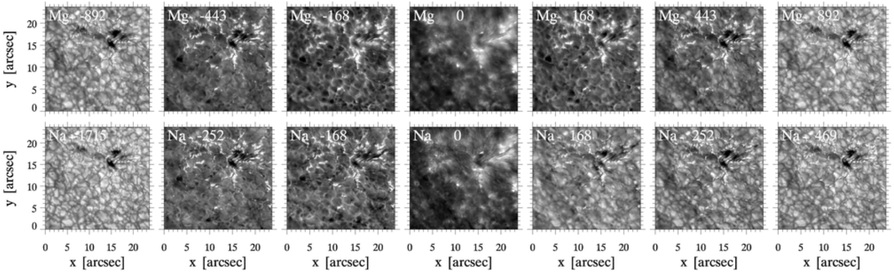
- Bifrost $=$ state-of-the-art: 3D(t), $\vec{B}$, non-HE, SE populations but NE for H
  Leenaarts, Carlsson & Rouppe van der Voort *2012ApJ...749..136L*
- ALC7 $=$ UV fit: 1D static, no $\vec{B}$, HE + microturbulence, SE populations
  Avrett & Loeser *2008ApJS..175..229A*
- FCHHT-B $=$ UV fit: 1D static,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

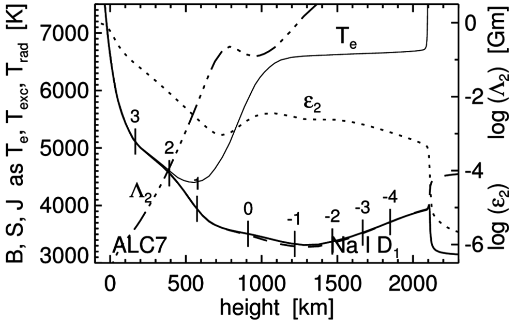
The T and J_ν(Hα) behaviors seem arguably similar. However, the conceptual differences between plane-parallel static hydrostatic-equilibrium modeling and 3D(t) MHD simulation are enormous. The $T(h)$ stratifications in the simulation vary tremendously, with shocks propagating upwards and sideways and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

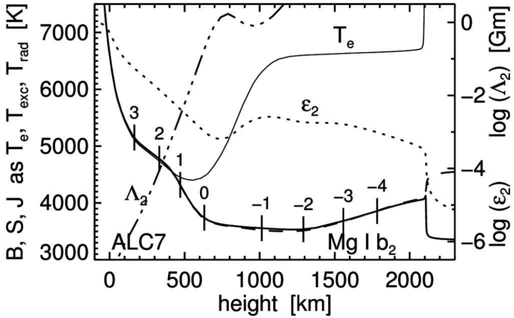
BIFROST ANALYSES – SOFAR

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 Hα formation
Stepán et al. 2012ApJ...758L..43S Lyα 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 Hα 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 Hα fibrils versus field
Stepán et al. 2015ApJ...803...65S scattering polarization Lyα
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 Hα 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 D$_1$ AND Mg I b$_2$

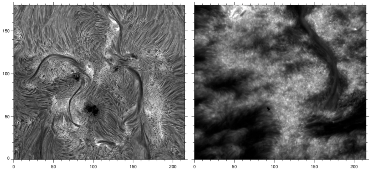


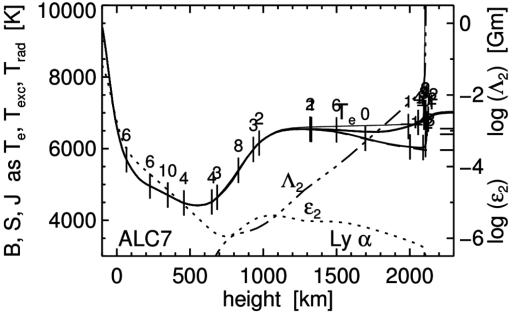


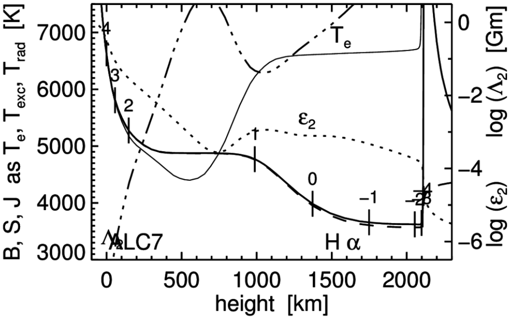


- similar NLTE formation $=$ heavy two-level scattering
- core intensities do not sense ALC7 chromosphere
- narrow Na I D$_1$ flanks reverse reversed granulation
- ¿ non-E? minority stages: recombination $\propto N_{\rm e}$ senses Lyα settling and scattering
- SST: Dopplergrams $\approx$ unsigned fluxtube magnetograms (Na I D$_1$ formation)
  ¿ non-E enhanced in cooling recombining downflows? (SE $=$ Bifrost snapshot OK)

Lyα and Hα







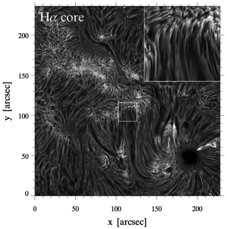
- both: heavy NLTE scatterers with $S \approx J$

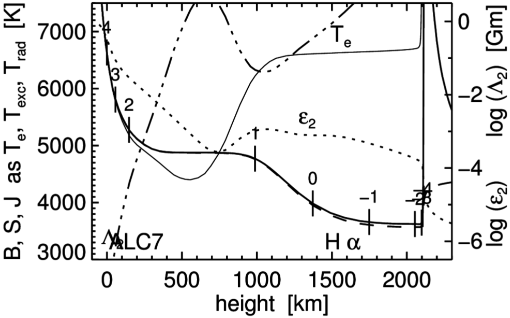
- Lyα: boxed-in by enormous extinction $\Rightarrow$ radiative detailed balance: $S = J$
  in shocks ($\approx$ ALC7 chromosphere) collisional thermalization: $b_2 \approx b_1$
  in cool gas surroundng hot structures $b_2 \gg 1$ from Lyα surround scattering
  in post-hot cool gas slow $S \approx J$ thermalization with $b_2 \gg 1$: S^l memory of hot past

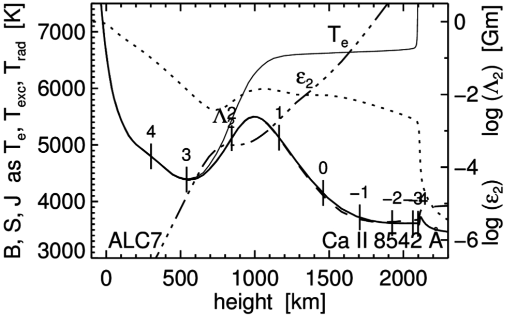
- Hα: photons created in granulation
  scatter 3D across upper-photosphere opacity gap and through chromosphere
  in shocks etc. Boltzmann extinction $b_2 \approx b_1$
  in post-hot cool gas $b_2 \gg 1$: extinction memory of hot past

¿ Lyα scene: heating events bright down-throat, cooling contrails dark from scattering
Hα scene: RBE/RRE heating events, cooling contrails dark from non-E opacity

Hα and Ca II 8542 Å



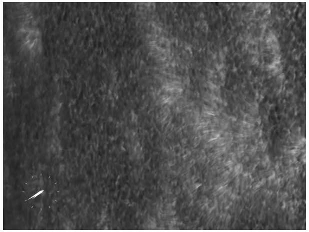


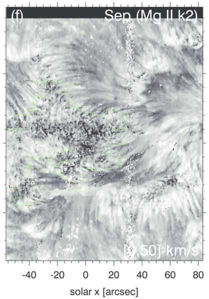


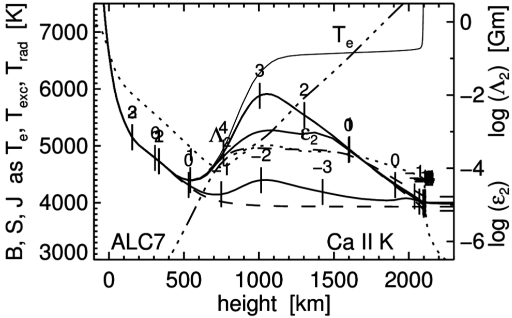
- both: heavy NLTE scatterers with $S \approx J$ sampled at similar $\tau = 1$ heights
- both: Saha-Boltzmann or larger extinction in shocks and ALC7
- core widths: both decrease away from network $=$ decreasing temperature
- Hα fibrils extend further, contradicting Saha-Boltzmann extinction sensitivities

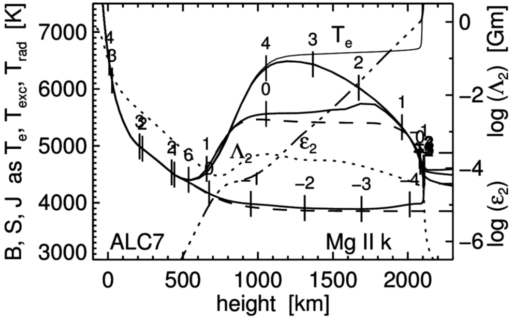
¿ fibril opacity in Ca II 8542 Å instantenous, in Hα post-hot non-E?

Ca II H & K and Mg II h & k







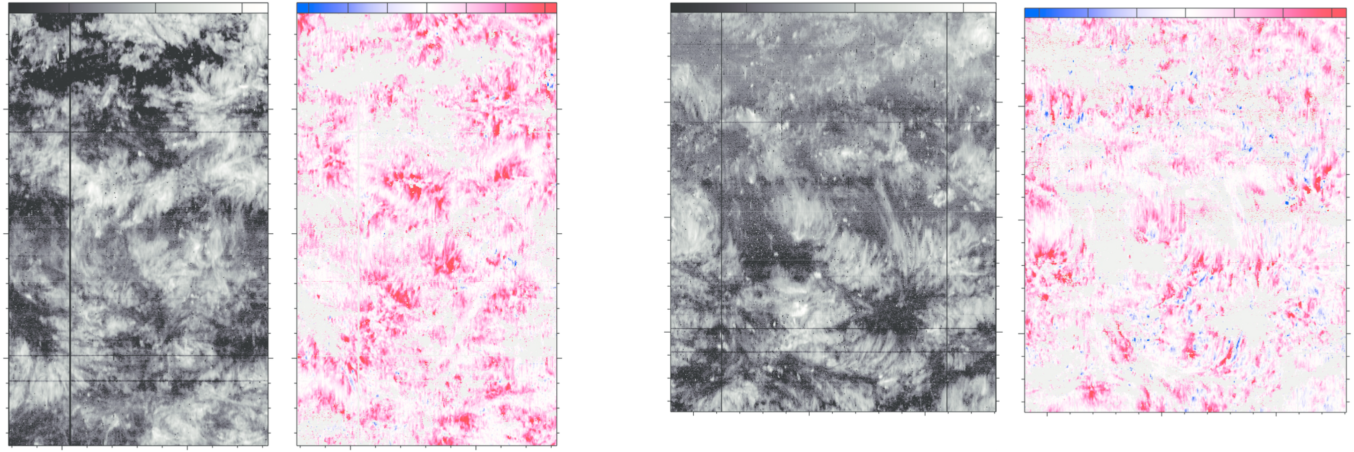


- both: heavy NLTE scatterers with PRD source function splits
- both: near-Saha-Boltzmann extinction everywhere; abundance ratio 18
- both: absence of non-E sensitivities = instantaneous chromosphere
- both: slender fibrils emanating from network, in Ca II H & K better at narrower bandwidth, in Mg II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



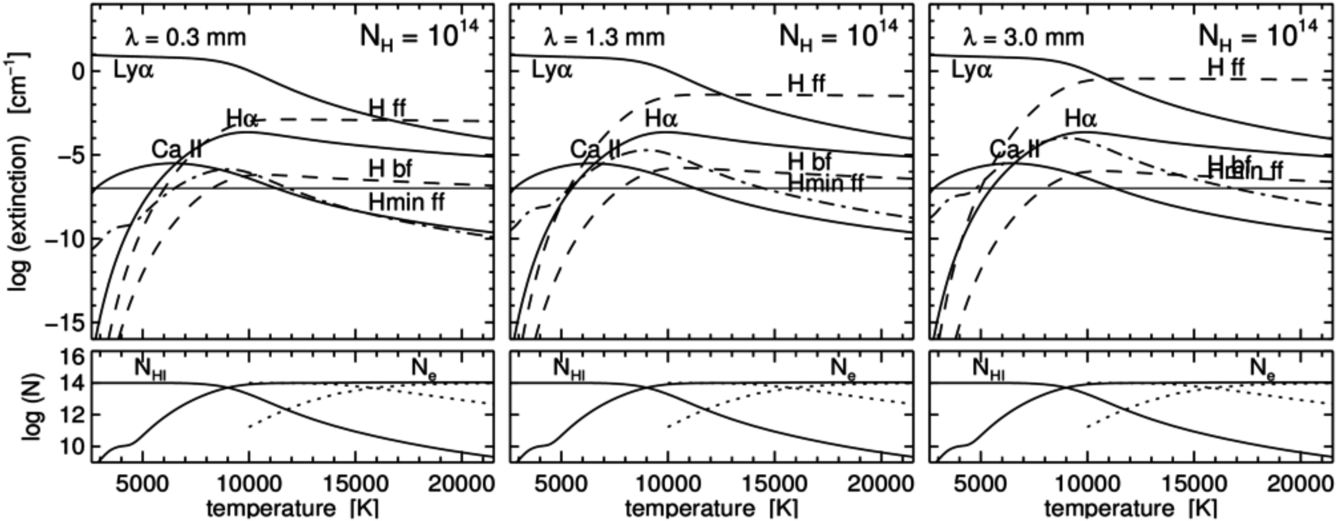
- thin to thickish (ratio $<$ 2) line formation
- Gaussian fits
- widths $\approx$ non-thermal widths

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

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

MM-WAVELENGTH EXTINCTION

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

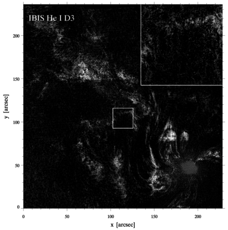


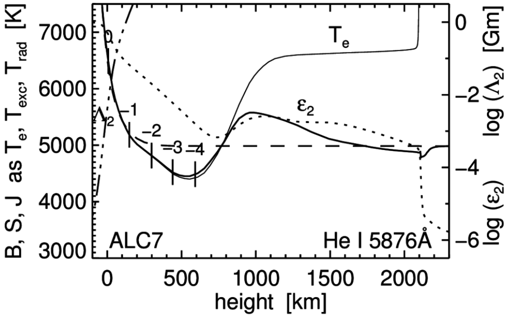
- ALMA: “linear thermometer” from H ff and Hmin ff having S $=$ B
  line(s) $=$ Zeeman diagnostic? H I 30-α?
  Cycle 4 solar observations started December (small array, continuum only)
- Hα at high T: LTE or larger extinction enforced by Lyα
- H ff at high T: yet larger extinction $\propto \lambda^2$

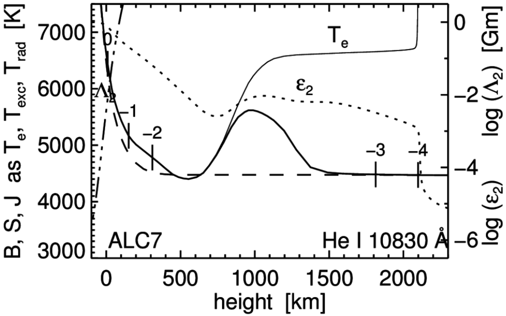
¿ cooling recombining contrail fibrils with large post-hot Hα extinction have larger post-hot H I ff extinction

¿ prediction: fibril canopies yet more opaque than in Hα, dark from low actual T,
less lateral contrast from lack of scattering and Dopplershift differences

He I and He II



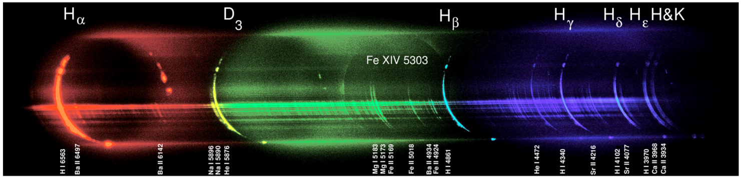


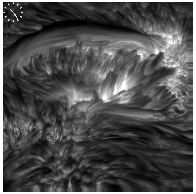


- optical He I lines: nothing in ALC7, nor in atlases, nor in Moore-Minnaert-Houtgast
- more complex non-E formation than H I: not only He I 584 acting as Lyα but ionization/recombination not limited to the atom top as for H I (smooth Balmer continuum driving from below) but sensing hot and structured irradiation from above
- see Bifrost He papers and more to come
- to-do for 2018 $=$ 150 years after Lockyer: explain He I D$_3$ in flash spectrum

¿ long dark Hα-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 ¿non-E? line formation
  - structure: uttery 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/Lyα, 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

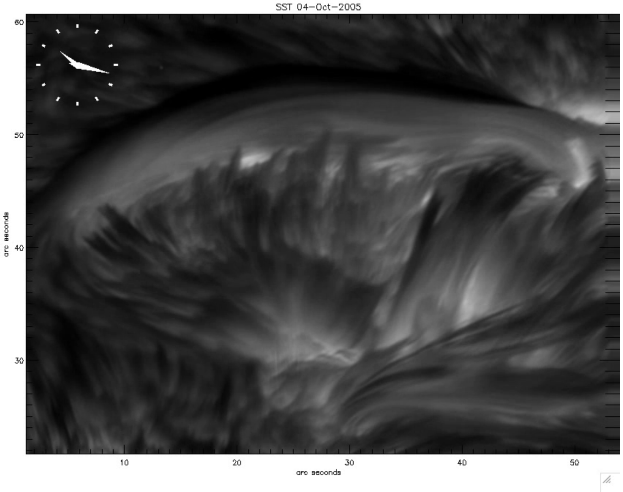
CHROMOSPHERE POTPOURRI

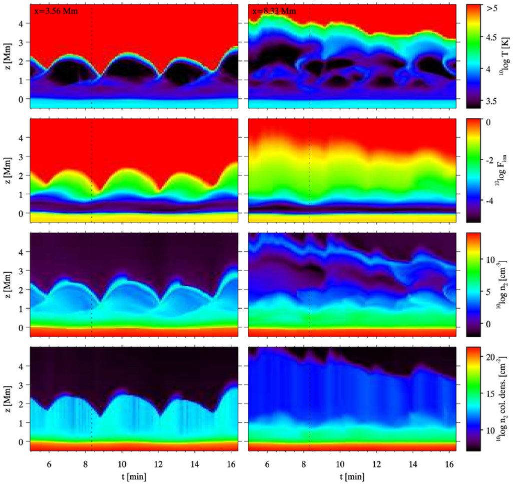
- *line formation theory*
  - flash spectrum @ Harvard, Boulder ⇒ Mihalas (1970, 1978): summary
  - static 1D “standard” models: VALIIIC more Avrett hydrogen exam
  - non-E: detailed balancing 1D Radyn 2D Stagger 3D Bifrost
- *chromosphere diagnostics*

  Na I D_1+Mg I b_2 Lyα+Hα Hα+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 Hα fibrils
  - fibril-field alignment for NLFFF: yes partly ¿ only at launch?

DYNAMIC FIBRILS

Hα: *Hansteen et al.* *2006ApJ...647L..73H*, *De Pontieu et al.* *2007ApJ...655..624D* (plage)
Rouppe van der Voort & De la Cruz Rodiguez *2013ApJ...776...56R* (sunspots)
Ca II 8542: *Langangen et al.* *2008ApJ...673.1194L*
Ly α: *Koza et al.* *2009A&A...499..917K*
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*

CUT-OFF FREQUENCY LOWERING IN INCLINED FIELDS

1973SoPh...30...47M

THE FIVE-MINUTE PERIOD OSCILLATION IN MAGNETICALLY ACTIVE REGIONS

A. G. MICHALITSANOS* **

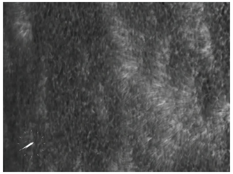
Institute of Astronomy, University of Cambridge, Cambridge, England

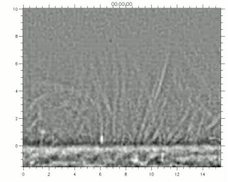
If we incline the magnetic field (with respect to g) through 45 degrees in Figure 1d, we note that in Region I, $\omega(k_x)$ is no longer asymptotic to ω_s as k_x tends to zero. Therefore, for an inclined magnetic field, magnetosonic waves may propagate vertically at frequencies $\omega < \omega_s$. 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

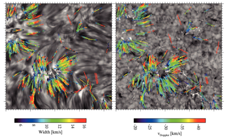
$$\omega_c^2 = \omega_s^2\left(\frac{1}{2} - \frac{1}{\gamma\beta}\right) + \omega_s^2\left[\left(\frac{1}{\gamma\beta} - \frac{1}{2}\right)^2 + \frac{2\cos^2\theta}{\gamma\beta}\right]^{1/2}, \qquad (4)$$

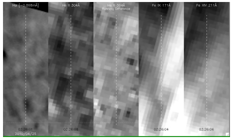
and $\theta = \arccos(B_z/B_0)$. Therefore, at levels where $\beta < 1$, the critical magnetosonic-gravity frequency is less than the critical sonic-gravity frequency ω_s when the field is inclined from the vertical.

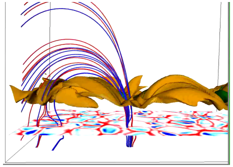
STRAWS / SPICULES-II / RBEs











- *observations*
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  - fast solar wind driving
  - solar wind element segregation

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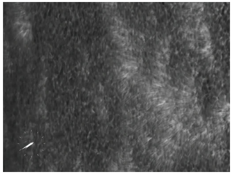

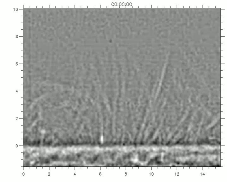

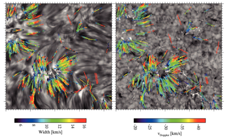

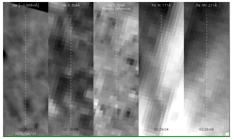

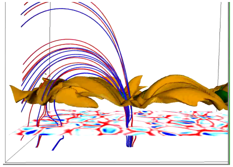

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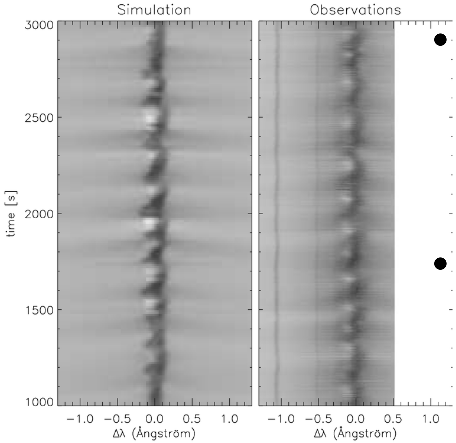
INTERNETWORK H_{2V} GRAINS = ACOUSTIC SHOCKS



- *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

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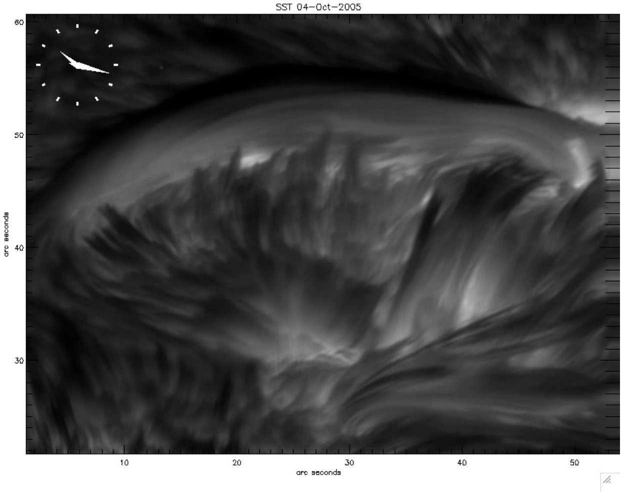

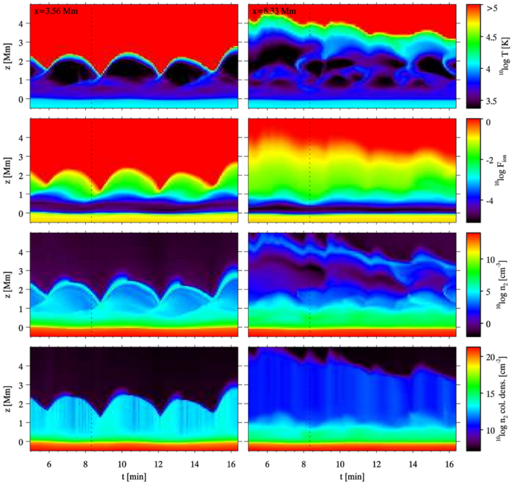

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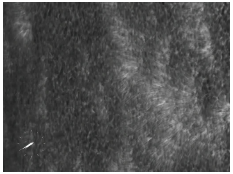

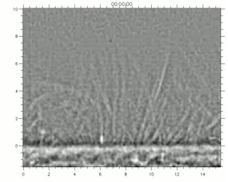

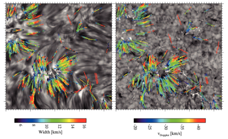

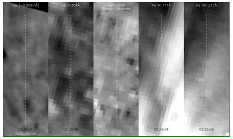

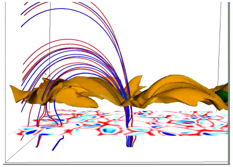

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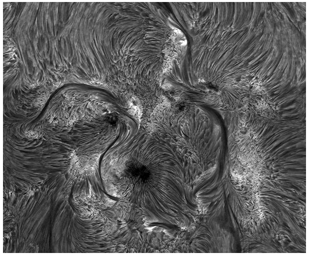
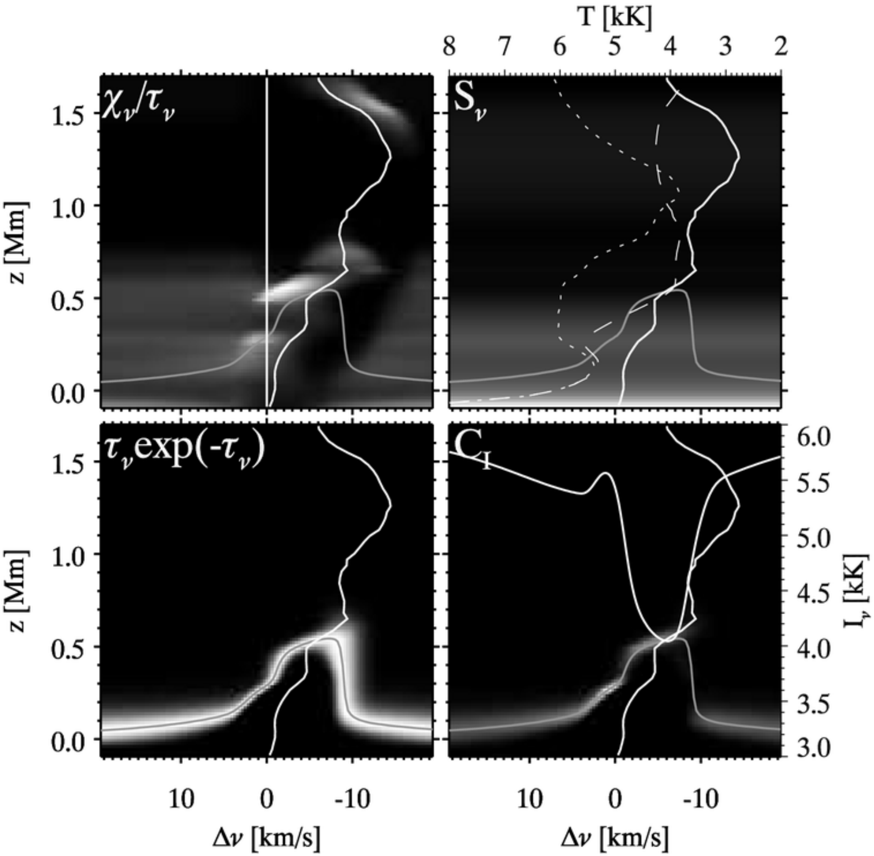
FIBRIL–FIELD ALIGNMENT FOR NLFFF LOWER BOUNDARY

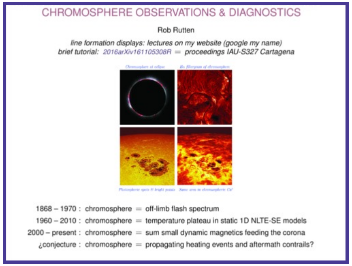


- *NLFFF tests with chromospheric boundary*
  - Na I D_1: Metcalf et al. 1995ApJ...439..474M 2005ApJ...623L..53M
  - Hα: Bobra & van Ballegooijen 2008ApJ...672.1209B Wiegelmann et al. 2008SoPh..247..249W
- *good alignment*
  - Aschwanden et al. 2016ApJ...826...61A
- *partial alignment*
  - de la Cruz Rodríiguez & 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 D_1 IN A MAGNETIC CONCENTRATION

Leenaarts et al. *2010ApJ...709.1362L*



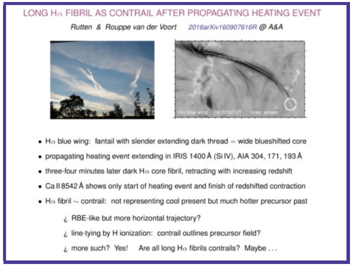


CHROMOSPHERE OBSERVATIONS & DIAGNOSTICS

Rob Rutten

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

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?

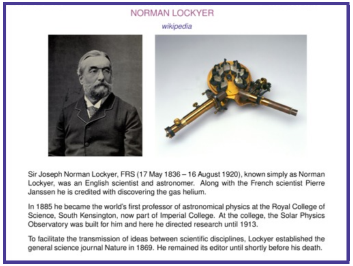


LONG Hα FIBRIL AS CONTRAIL AFTER PROPAGATING HEATING EVENT

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

- Hα blue wing: fantail with slender extending dark thread = wide blueshifted core
- propagating heating event extending in IRIS 1400 Å (Si IV), AIA 304, 171, 193 Å
- three-four minutes later dark Hα core fibril, retracting with increasing redshift
- Ca II 8542 Å shows only start of heating event and finish of redshifted contraction
- Hα fibril ~ 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 Hα fibrils contrails? Maybe . . .



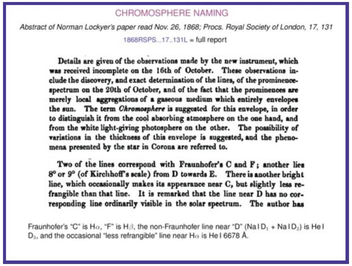
NORMAN LOCKYER

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

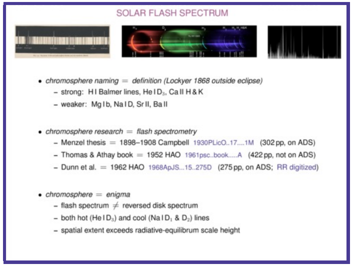
Abstract of Norman Lockyer's paper read Nov. 26, 1868; Procs. Royal Society of London, 17, 131

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.

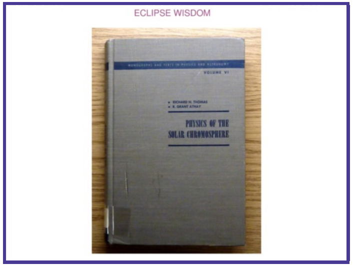
Two of the lines correspond with Fraunhofer's C and F; another lies 8° or 9° (of Kirchhoff's scale) from D towards E. There is another bright line, which occasionally makes its appearance near C, but slightly less refrangible than that line. It is remarked that the line near D has no corresponding line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

Fraunhofer's "C" is Hα, "F" is Hβ, 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 Hα is He I 6678 Å.

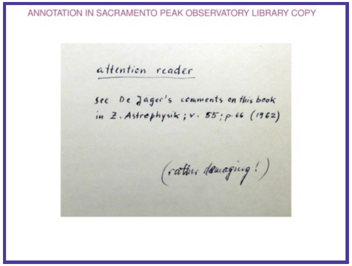


SOLAR FLASH SPECTRUM

- *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 ≠ reversed disk spectrum
  - both hot (He I D$_3$) and cool (Na I D$_1$ & D$_2$) lines
  - spatial extent exceeds radiative-equilibrum scale height



ECLIPSE WISDOM

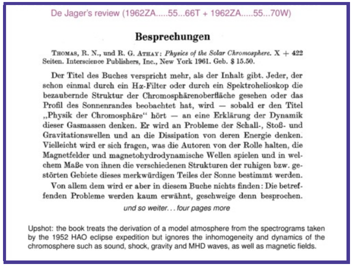


ANNOTATION IN SACRAMENTO PEAK OBSERVATORY LIBRARY COPY

attention reader

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

(rather damaging!)



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

Besprechungen

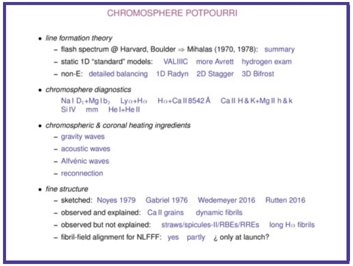
Thomas, R. N., und R. G. Athay: *Physics of the Solar Chromosphere.* X + 422 Seiten. Interscience Publishers, Inc., New York 1961. Geb. $ 15.50.

Der Titel des Buches verspricht mehr, als der Inhalt gibt. Jeder, der schon einmal durch ein Hα-Filter oder durch ein Spektroheliokop 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.

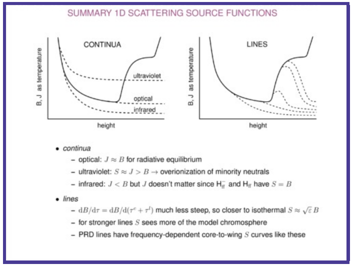
und so weiter. . . four pages more

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.



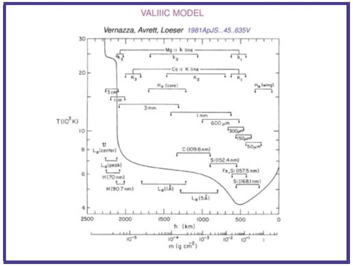
CHROMOSPHERE POTPOURRI

- *line formation theory*
  - flash spectrum @ Harvard, Boulder ⇒ Mihalas (1970, 1978): summary
  - static 1D "standard" models: VALIIIC more Avrett hydrogen exam
  - non-E: detailed balancing 1D Radyn 2D Stagger 3D Bifrost
- *chromosphere diagnostics*
  Na I D$_1$+Mg I b$_2$ Lyα+Hα Hα+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 Hα fibrils
  - fibril-field alignment for NLFFF: yes partly ¿ only at launch?



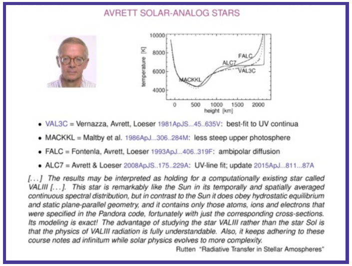
SUMMARY 1D SCATTERING SOURCE FUNCTIONS

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



VALIIIC MODEL

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

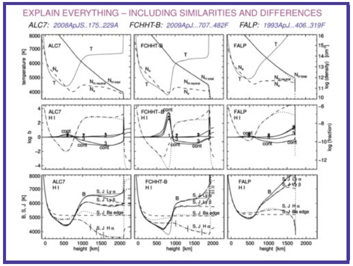


AVRETT SOLAR-ANALOG STARS

- 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

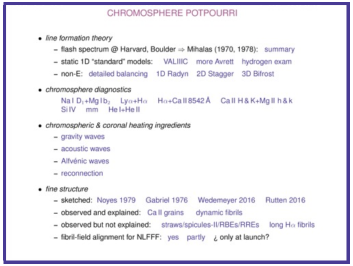
[. . .] The results may be interpreted as holding for a computationally existing star called VALIII [. . .]. This star is remarkably like the Sun in its temporally and spatially averaged continuous spectral distribution, but in contrast to the Sun it does obey hydrostatic equilibrium and static plane-parallel 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 Amospheres"



EXPLAIN EVERYTHING – INCLUDING SIMILARITIES AND DIFFERENCES

ALC7: *2008ApJS..175..229A* *FCHHT-B:* *2009ApJ...707..482F* *FALP:* *1993ApJ...406..319F*



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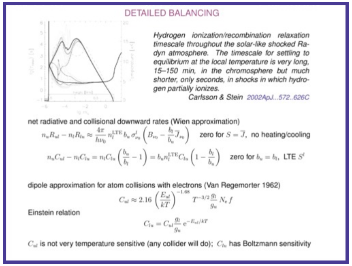


DETAILED BALANCING

Hydrogen ionization/recombination relaxation timescale throughout the solar-like shocked Radyn atmosphere. The timescale for settling to equilibrium at the local temperature is very long, 15–150 min, in the chromosphere but much shorter, only seconds, in shocks in which hydrogen partially ionizes.
Carlsson & Stein *2002ApJ...572..626C*

net radiative and collisional downward rates (Wien approximation)

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

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

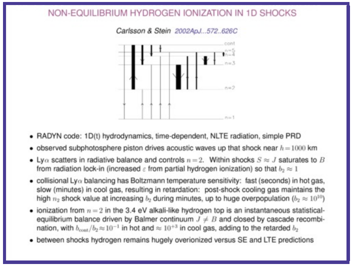
dipole approximation for atom collisions with electrons (Van Regemorter 1962)

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

Einstein relation

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

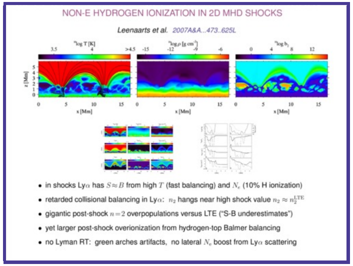
C_{ul} is not very temperature sensitive (any collider will do); C_{lu} has Boltzmann sensitivity



NON-EQUILIBRIUM HYDROGEN IONIZATION IN 1D SHOCKS

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

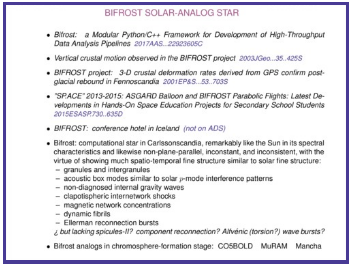
- RADYN code: 1D(t) hydrodynamics, time-dependent, NLTE radiation, simple PRD
- observed subphotosphere piston drives acoustic waves up that shock near $h = 1000$ km
- Lyα scatters in radiative balance and controls $n = 2$. Within shocks $S \approx J$ saturates to B from radiation lock-in (increased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

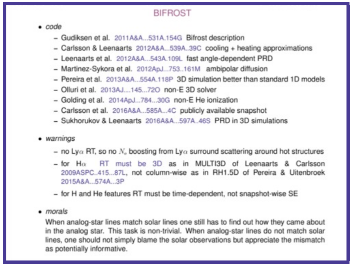
- in shocks Lyα has $S \approx B$ from high T (fast balancing) and N_e (10% H ionization)
- retarded collisional balancing in Lyα: n_2 hangs near high shock value $n_2 \approx n_2^{\rm LTE}$
- gigantic post-shock $n = 2$ overpopulations versus LTE ("S-B underestimates")
- yet larger post-shock overionization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

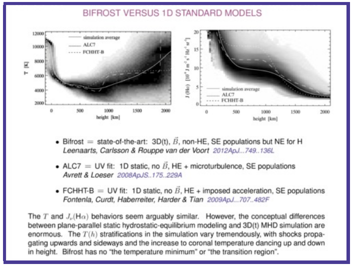
  ¿ but lacking spicules-II? component reconnection? Alfvénic (torsion?) wave bursts?
- Bifrost analogs in chromosphere-formation stage: CO5BOLD MuRAM Mancha



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 Lyα RT, so no N_e boosting from Lyα surround scattering around hot structures
  - for Hα 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*

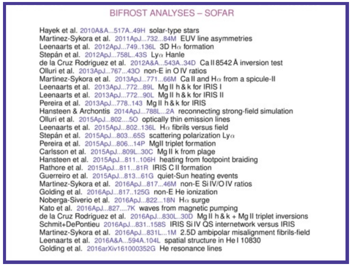
  When analog-star lines match solar lines one still has to find out how they came about in the analog star. This task is non-trivial. When analog-star lines do not match solar lines, one should not simply blame the solar observations but appreciate the mismatch as potentially informative.



BIFROST VERSUS 1D STANDARD MODELS

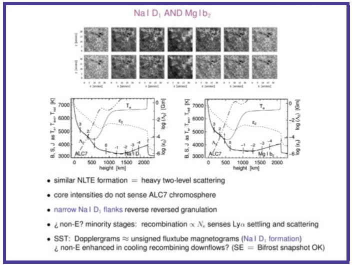
- Bifrost = state-of-the-art: 3D(t), $\vec{B}$, non-HE, SE populations but NE for H
  Leenaarts, Carlsson & Rouppe van der Voort *2012ApJ...749..136L*
- ALC7 = UV fit: 1D static, no $\vec{B}$, HE + microturbulence, SE populations
  Avrett & Loeser *2008ApJS..175..229A*
- FCHHT-B = UV fit: 1D static,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

The T and J_ν(Hα) 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".



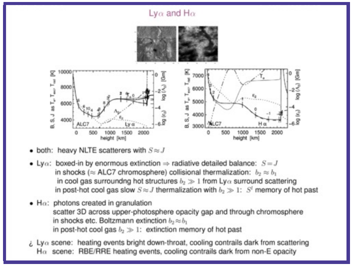
BIFROST ANALYSES – SOFAR

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 Hα formation
Stepán et al. 2012ApJ...758L..43S Lyα 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 Hα 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 Hα fibrils versus field
Stepán et al. 2015ApJ...803...65S scattering polarization Lyα
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 Hα 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 D_1 AND Mg I b_2

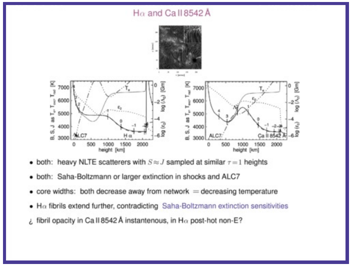
- similar NLTE formation = heavy two-level scattering
- core intensities do not sense ALC7 chromosphere
- narrow Na I D_1 flanks reverse reversed granulation
- ¿ non-E? minority stages: recombination $\propto N_e$ senses Lyα settling and scattering
- SST: Dopplergrams ≈ unsigned fluxtube magnetograms (Na I D_1 formation)
  ¿ non-E enhanced in cooling recombining downflows? (SE = Bifrost snapshot OK)



Lyα and Hα

- both: heavy NLTE scatterers with $S \approx J$
- Lyα: boxed-in by enormous extinction ⇒ radiative detailed balance: $S = J$
  in shocks (≈ ALC7 chromosphere) collisional thermalization: $b_2 \approx b_1$
  in cool gas surroundng hot structures $b_2 \gg 1$ from Lyα surround scattering
  in post-hot cool gas slow $S \approx J$ thermalization with $b_2 \gg 1$: S^l memory of hot past
- Hα: 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

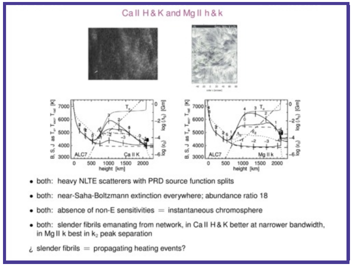
¿ Lyα scene: heating events bright down-throat, cooling contrails dark from scattering
Hα scene: RBE/RRE heating events, cooling contrails dark from non-E opacity



Hα 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
- Hα fibrils extend further, contradicting Saha-Boltzmann extinction sensitivities

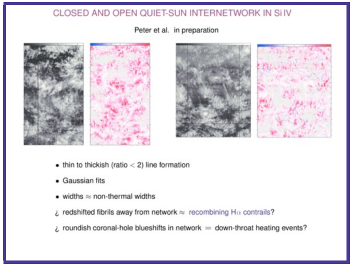
¿ fibril opacity in Ca II 8542 Å instantenous, in Hα post-hot non-E?



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?



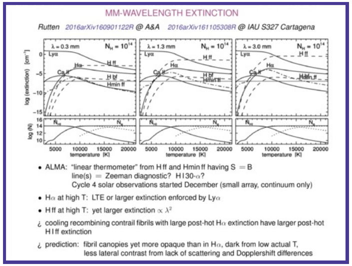
CLOSED AND OPEN QUIET-SUN INTERNETWORK IN Si IV

Peter et al. in preparation

- thin to thickish (ratio < 2) line formation
- Gaussian fits
- widths ≈ non-thermal widths

¿ redshifted fibrils away from network ≈ recombining Hα contrails?

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



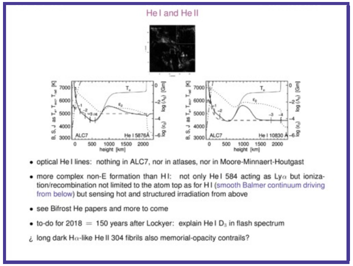
MM-WAVELENGTH EXTINCTION

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

- ALMA: "linear thermometer" from H ff and Hmin ff having S = B
  line(s) = Zeeman diagnostic? H I 30-α?
  Cycle 4 solar observations started December (small array, continuum only)
- Hα at high T: LTE or larger extinction enforced by Lyα
- H ff at high T: yet larger extinction $\propto \lambda^2$

¿ cooling recombining contrail fibrils with large post-hot Hα extinction have larger post-hot H I ff extinction

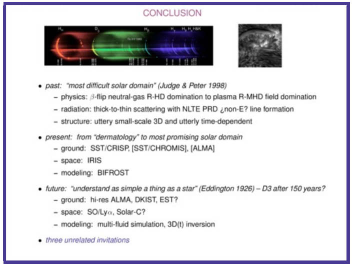
¿ prediction: fibril canopies yet more opaque than in Hα, dark from low actual T,
less lateral contrast from lack of scattering and Dopplershift differences



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 Lyα 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 D_3 in flash spectrum

¿ long dark Hα-like He II 304 fibrils also memorial-opacity contrails?



CONCLUSION

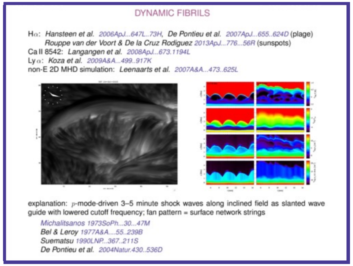
- *past: "most difficult solar domain" (Judge & Peter 1998)*
  - physics: β-flip neutral-gas R-HD domination to plasma R-MHD field domination
  - radiation: thick-to-thin scattering with NLTE PRD ¿non-E? line formation
  - structure: uttery small-scale 3D and utterly time-dependent
- *present: from "dermatology" 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/Lyα, 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 ⇒ Mihalas (1970, 1978): summary
  - static 1D "standard" models: VALIIIC more Avrett hydrogen exam
  - non-E: detailed balancing 1D Radyn 2D Stagger 3D Bifrost
- *chromosphere diagnostics*
  Na I D_1+Mg I b_2 Lyα+Hα Hα+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 Hα fibrils
  - fibril-field alignment for NLFFF: yes partly ¿ only at launch?



DYNAMIC FIBRILS

Hα: *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
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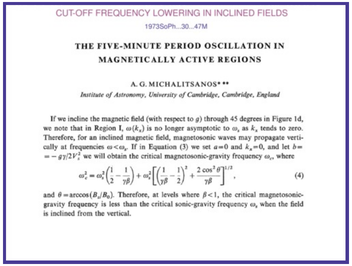


CUT-OFF FREQUENCY LOWERING IN INCLINED FIELDS

1973SoPh...30...47M

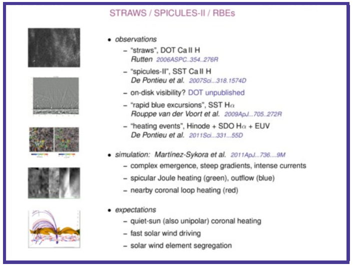
THE FIVE-MINUTE PERIOD OSCILLATION IN
MAGNETICALLY ACTIVE REGIONS

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

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

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
    De Pontieu et al. 2007Sci...318.1574D
  - on-disk visibility? DOT unpublished
  - "rapid blue excursions", SST Hα
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- *simulation: Martínez-Sykora et al.* 2011ApJ...736....9M
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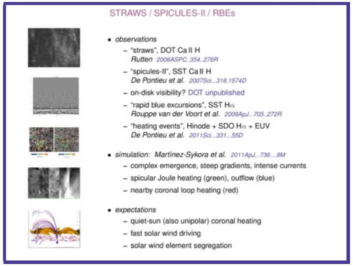
  - spicular Joule heating (green), outflow (blue)
  - nearby coronal loop heating (red)
- *expectations*
  - quiet-sun (also unipolar) coronal heating
  - fast solar wind driving
  - solar wind element segregation



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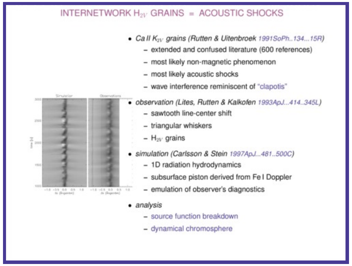
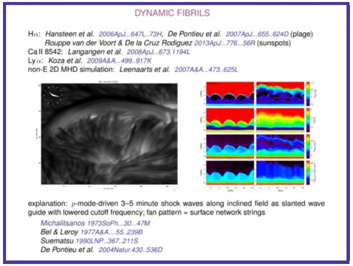


INTERNETWORK H_{2V} GRAINS = ACOUSTIC SHOCKS

- *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



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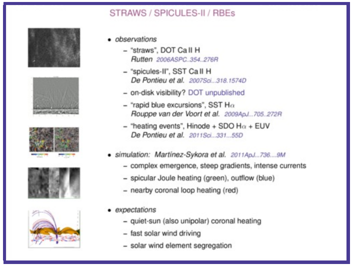

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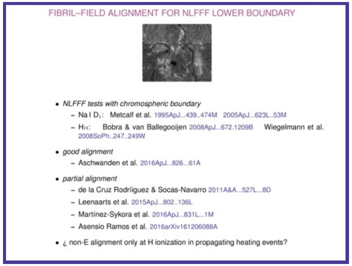

FIBRIL–FIELD ALIGNMENT FOR NLFFF LOWER BOUNDARY

- *NLFFF tests with chromospheric boundary*
  - Na I D$_1$: Metcalf et al. 1995ApJ...439..474M 2005ApJ...623L..53M
  - Hα: Bobra & van Ballegooijen 2008ApJ...672.1209B Wiegelmann et al. 2008SoPh..247..249W
- *good alignment*
  - Aschwanden et al. 2016ApJ...826...61A
- *partial alignment*
  - de la Cruz Rodríiguez & 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?

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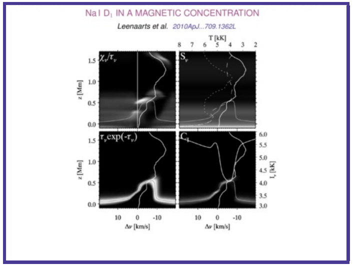

Na I D$_1$ IN A MAGNETIC CONCENTRATION

Leenaarts et al. *2010ApJ...709.1362L*

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