physics of the solar chromosphere

Philip Judge, HAO, NCAR
Thermosphere-Ionosphere vs chromosphere
broad commonalities

• “Earth’s upper atmosphere can be categorized as a gravitationally bound partially ionized, fluid”
  – (spans ~15 scale heights; chromosphere: ~10)
  – $p$ is a natural vertical coordinate ($p=mg$ in chromosphere)

• “Quasi-hydrostatic balance” (subsonic vertical motions)
  – ($V/C_s \sim 0.1$; chromosphere* $\sim 0.3-1$)

• $T$ increases with height (divergence of external energy flux)

• incomplete mixing ($z >$ turbopause, 110 km)

• “magnetized” ions

*Bulk of chromosphere: not “spicules”*
### gross differences

<table>
<thead>
<tr>
<th>Thermosphere-Ionosphere</th>
<th>Chromosphere</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Potential</strong> $\mathbf{B}$: $\delta \mathbf{B} &lt; 1%$ from ion. $\mathbf{j}$ (B from $\oplus$ interior, m-sphere)</td>
<td><strong>Non-potential</strong> $\mathbf{B}$, fields tied to sub-photosphere</td>
</tr>
<tr>
<td>$\mathbf{E} = \nabla \varphi$</td>
<td>$\mathbf{E}_/= 0$</td>
</tr>
<tr>
<td>$\mathbf{E}, \mathbf{\sigma}$ “electrodynamics”, $\mathbf{B}$ “fixed” $\mathbf{j}$ determined by $\mathbf{E}, \mathbf{\sigma}$</td>
<td>$\mathbf{v}, \mathbf{B}, \mathbf{\sigma}$ full MHD (coupled fluid and induction equations), “frozen field” $\mathbf{j}$ determined by $\mathbf{j} \times \mathbf{B} - \nabla \mathbf{p} + ..$</td>
</tr>
<tr>
<td>Heating mechanisms largely known</td>
<td>Electrodynamic heating: unknown</td>
</tr>
<tr>
<td>Horizontal scales $\gg$ vertical $\partial f/\partial x, \partial f/\partial y \ll \partial f/\partial z$, $\sim$ geostrophic balance</td>
<td>Vertical scales $\geq$ horizontal Photospheric flux concentrations $\partial f/\partial x, \partial f/\partial y \geq \partial f/\partial z$</td>
</tr>
</tbody>
</table>
why study the chromosphere?
The chromosphere: gateway to the corona?

...Or the purgatory of solar physics?

P.G. Judge

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Abstract. I argue that one should attempt to understand the solar chromosphere not only for its own sake, but also if one is interested in the physics of: the corona; astrophysical dynamos; space weather; partially ionized plasmas; heliospheric UV radiation; the transition region. I outline curious observations which I personally find puzzling and deserving of attention.

Key words. Sun:chromosphere
energization of the mesosphere/thermosphere/ionosphere

**Fig. 3.** A 0.06 s exposure obtained with the TRC at Lyα, showing the filamentary looplike structure of active regions. The image is truncated due to offset pointing of the XSST from disk center. The Ca II K spectroheliogram obtained at Meudon Observatory 8 hours prior to launch is shown for comparison.

Bonnet *et al.* (see page L48)

Reversed color table
Strongest line in astrophysics
H Lyman alpha... (D layer)

VAULT
Ly-alpha
121.5 nm

10" tick marks
Big Questions...

- what, physically, is the fine structure?
- what heats the chromosphere?
- what drives the dynamics?
- does it influence the magnetic field emerging through it?
  - boundary conditions for the corona/heliosphere
The IRIS observing programs

• Observe the region where most of the non-thermal energy is deposited and the temperature rise begins - the chromosphere and transition region - together with the region that is directly impacted - the corona.

• Collect data with spectral, spatial, and temporal resolution sufficient to reveal a range of physical processes.
A short history
Young (1881, 1892,...)

• "...this outer envelope... seems to be made up not of overlying strata... but rather of flames, beams and streamers, as transient as those of our own aurora borealis."

• "the outer portion... is chiefly due to the `corona'"

• "At its base... is what resembles a sheet of scarlet fire... This is the `chromosphere', a name first proposed by Frankland and Lockyer in 1869... in allusion to the vivid redness of the stratum... It was called the `sierra' by Airy in 1842."

• "Stannyan 1709... the emersion of the sun was preceded by a blood-red streak of light... for six or seven seconds" ("flash")

• Young's (1871 eclipse) visual observations of flash spectrum: "reversal" of Fraunhofer's lines

• 1893 first photograph (cf. corona 1860), "flash"
the Sun’s chromosphere

- boring sun:
  - convection, turbulence, atmospheric waves
  - global (p-) modes
  - weak, stochastic chromosphere
  - no corona (almost)

figure: Durrant 1987
the Sun’s chromosphere

• **boring sun:** Hale 1903
  – convection, turbulence, atmospheric waves
  – global (p-) modes
  – weak, stochastic chromosphere
  – no corona (almost)

• interesting, magnetic Sun

\[ \frac{\lambda}{\Delta \lambda} \geq 40,000 \]
Hale 1903: Ca II H 396.8 nm

\( H_1 \) - low chromosphere
\( H_2 \) - high chromosphere
Leighton & colleagues ca. 1959

- Network cell, boundary ⇔ supergranular flow
- Boundary has magnetic concentrations
- Ca II emission ⇔ boundaries ⇔ magnetic concentrations

Fig. 7c.—Magnetic fields and Ca II emission around a spot group near the north meridian of the sun on September 16, 1958
A brief guide to spectrum formation


Essential radiative transfer

- Photons interact only with atoms, ions, electrons (low E)
  - absorption and emission coefficients $\alpha_\nu, j_\nu$

- transport equation ($I=$distribution function for photons):
  $$\frac{dI_\nu}{ds} = I_\nu(s + ds) - I_\nu(s) = j_\nu(s)\, ds - \alpha_\nu(s)I_\nu(s)\, ds$$

$$\frac{dI_\nu}{\alpha_\nu\, ds} = S_\nu - I_\nu,$$
Essential radiative transfer

- Photons interact only with atoms, ions, electrons (low E)
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- transport equation (I=distribution function for photons):

\[
\frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu
\]

\[
\frac{dI_\nu}{\alpha_\nu \, ds} = S_\nu - I_\nu,
\]

Standard form (1D, \( \mu = \cos \vartheta \))

\[
\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu.
\]
Solutions to

\[ \mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu. \]
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\[ \mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu. \]

Given \( S \),

\[ I_\nu^+(\tau_\nu = 0, \mu) = \int_0^{\infty} S_\nu(t_\nu) e^{-t_\nu/\mu} \, dt_\nu/\mu. \]
Solutions to \( \mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu. \)

Given \( S, \) \( I_\nu^+(\tau_\nu = 0, \mu) = \int_0^\infty S_\nu(t_\nu) e^{-t_\nu/\mu} \, dt_\nu/\mu. \)

Eddington-Barbier, \( I_\nu^+(\tau_\nu = 0, \mu) \approx S_\nu(\tau_\nu = \mu) \)
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LTE (high densities and/or optical depths):
\[ S_\nu = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \equiv B_\nu(T). \]
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non LTE (chromosphere)

\[ S_\nu = (1 - \varepsilon_\nu)J_\nu + \varepsilon_\nu B_\nu. \]
Solutions to

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\[ S_{\nu} = (1 - \varepsilon_{\nu}) J_{\nu} + \varepsilon_{\nu} B_{\nu}. \]

Lambda operator (integral)

\[ J_{\nu}(\tau_{\nu}) = \Lambda_{\nu}[S_{\nu}] \]
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non LTE: coupled integro-differential equation
One more ingredient:
absorption and emission coefficients \( \alpha, j \)

Continua
(b-f, f-f)

Figure 8.1: The continuous extinction coefficient in the photosphere of the Sun.
One more ingredient: absorption and emission coefficients $\alpha_\nu, j_\nu$

Lines and elastic scattering (Rayleigh)
The optically thin case

Transition region and corona

\[ \frac{dI_\nu}{ds} = j_\nu - \alpha_\nu I_\nu \]

“Thin” means \( \alpha_\nu \, ds \ll 1 \), then with \( I(s=\infty) = I_0 \),
The optically thin case

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“Thin” means \( \alpha_\nu ds \ll 1 \), then with \( I(s=\infty) = I_0 \),

\[ I_\nu(0) - I_0 = \int_\infty^0 j_\nu ds \]

\[ j_\nu ds \propto N_e^2 G(T) \frac{ds}{dT} dT \]

\[ I_\nu(0) - I_0 = \int_0^\infty \left( N_e^2 \frac{ds}{dT} \right) G(T) dT = \int_0^\infty \xi(T) G(T) dT \]

\( \xi(T) \): “emission measure”
Low density, optically thin case

SDO/IRIS: ions with 2 or more electrons removed are best considered as a function of electron temperature

2-body collisions: no detailed balance, no Saha equilibrium
Examples relevant to the IRIS mission


160 nm (like SDO/AIA)
Examples relevant to the IRIS mission

![Spectrum graph showing peaks labeled IRIS at wavelengths 1400 Å and 1500 Å.](image)

**Wavelength** Å

**SUMER QS intensities**

**Monday, May 7, 2012**
Examples relevant to the IRIS mission

- Quiet Sun
- $\alpha$ Cen A G2 V

Wavelength $\text{Å}$
Why must chromospheres exist?

- For *any reasonable* heating mechanism, the Sun must produce a *partially ionized stratified upper atmosphere* (subject to \( j \times B \) forces) because of
  
  - \( \nabla p + \rho g \sim 0 \),
  
  - (\( \sim \) subsonic)
  
  - energy balance

\[ \nabla \cdot F_{EM} \sim F/2000 \text{ km} \]

\[ F \sim \text{observed } 10^7 \text{ erg/cm}^2/\text{s} \]
Why must chromospheres exist?

- For any reasonable* heating mechanism, the Sun must produce a partially ionized stratified upper atmosphere (subject to \( j \times B \) forces) because of

\[
\begin{align*}
\nabla p + \rho g & \sim 0, \\
\text{(\sim subsonic)} \quad \nabla \cdot \mathbf{v}(\epsilon + p) & = \nabla \cdot F_{EM} - Q_R. \\
\end{align*}
\]

\[
\epsilon = \frac{3p}{2} + \chi_H n_e
\]

\[
p = (n_H + n_e + ... )kT, \quad \chi_H = 13.6 \text{ V} \gg kT/e
\]

\[
\frac{dQ_R}{dT} \sim \exp(-T/T_0)
\]

while \( n_e/n_H < 1 \) (partially ionized)

*\( \nabla \cdot F_{EM} \sim F/2000 \text{ km} \)

\( F \sim \text{observed } 10^7 \text{ erg/cm}^2/\text{s} \)

\[
\frac{dn_e}{dT} \sim n_H \exp(-T/T_1)
\]
“disk chromosphere”

- UV/EUV: HSRA, VAL, FAL,...
- hydrostatic
  - much called into question
- consider-
  - eclipse data (flash)
  - subsonic motions
  - oscillation data
  - ...
- gross stratification is sound
  - \( P(\text{corona}) = 10^{-5} P(\text{photosphere}) \)
  - type I spicule models

chromosphere spans 1.5-2 Mm
Magnetic structure, associated dynamics
magnetic fields at the chromospheric base
Berger et al 2004 A&A: network/plage

- SST data:
  - A. G-band
  - B. Ca II H 3Å
  - C. magnetogram
  - D. Ni I doppler
The awkward $\beta \geq 1$ transition occurs within the chromosphere

Gold (1964).

stratification makes this transition geometrically thin that is not the whole story...

yet the chromosphere is often so-treated
magnetism and dynamics: IBIS Ca II IR triplet
QS chromosphere

- Cauzzi et al 2007
- $\lambda/\Delta \lambda \approx 100,000$
- line core
- network vs internetwork
magnetism and dynamics: Spicules

- Hinode data (radial filter to enhance spicules, M. Carlsson)
- Fast dynamics (de Pontieu et al. 2007), connects to corona?

spicules arise from within the chromosphere

Lifetimes 1 min

stratified VAL chromosphere 1.5Mm only
magnetism and dynamics: On disk “spicules”

- SST data Rouppe v.d Voort et al 2009
What role do Alfvenic waves play in energizing the solar atmosphere?

Alfvenic waves ubiquitous and strong in chromosphere/TR/corona (Hinode/SDO-AIA), but generation, power spectrum, propagation, damping and dissipation poorly known.

3D MHD simulations show Alfvenic waves with similar properties.
What role do Alfvenic waves play in energizing the solar atmosphere?

Alfvenic waves ubiquitous and strong in chromosphere/TR/corona (Hinode/SDO-AIA), but generation, power spectrum, propagation, damping and dissipation poorly known.

Thermal coverage and resolution of IRIS will provide insight in how much power is reflected/dissipated/mode-coupled throughout the interface region, and what remains for the corona - B. de Pontieu
What IRIS might see..

HRTS (Dere et al 2003)

Fig. 2.—HRTS 3 profiles of C I and the near simultaneous Hα – 0.6 Å spectroheliograms obtained by the Sacramento Peak Observatory. Also shown are the net line-of-sight Doppler velocities derived from the C I λ1560.7 and λ1561.4 lines according to eq. (1). The dashed lines denoted the zero and 3 σ velocity values. The positions of chromospheric jets are marked and numbered, with tick marks to the left indicating blueshifts and tick marks to the right, redshifts.

Dere et al. (see page L65)
What IRIS might see..
HRTS (Dere et al 2003)

Fig. 1.—HRTS 1 profiles of Si II, C IV, and C I with the positions of the chromospheric jets marked and numbered, with tick marks to the left indicating blueshifts and tick marks to the right, redshifts.

Dere et al. (see page L65)
What IRIS might see..
HRTS (Dere et al 2003)

**TABLE 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Chromospheric Jets</th>
<th>Visible Spicules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (km s(^{-1}))</td>
<td>(\leq 20)</td>
<td>25</td>
</tr>
<tr>
<td>Dimensions (arcsec)</td>
<td>1–4 (along slit)</td>
<td>diameter = 1, length = 10</td>
</tr>
<tr>
<td>Birthrate (cm(^{-2}) s(^{-1}))</td>
<td>(3 \times 10^{-20})</td>
<td>(5.5 \times 10^{-20})</td>
</tr>
<tr>
<td>Lifetime</td>
<td>40 s</td>
<td>5 min.</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>(1.6 \times 10^4)</td>
<td>(1.7 \times 10^4) at 4000 km</td>
</tr>
<tr>
<td>Density (cm(^{-3}))</td>
<td>(1 \times 10^{11})</td>
<td>(1.5 \times 10^{11}) at 4000 km</td>
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</table>
Alfvén Waves are Easy: Mode Conversion in Magnetic Regions

P. S. Cally\textsuperscript{1,2*}

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\textsuperscript{2}High Altitude Observatory, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA\textsuperscript{†}

Received 7th June 2011

Abstract. Alfvén waves are shown to be readily generated by mode conversion from fast MHD waves reflecting off the steep atmospheric Alfvén speed gradient in active region atmospheres. A simple analytic description of this process in terms of an ‘interaction integral’ indicates that it is spread over many vertical scale heights, and indeed fills the whole active region chromosphere for waves of moderate helioseismic degree $\ell$, even up to $\ell = 1000$ or more. This suggests that active region chromospheres are Alfvén wave factories.
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Alfvén Waves are Easy: Mode Conversion in Magnetic Regions

P. S. Cally¹,²*

Although the fast wave reflects (roughly at the height where \( \omega = a k \), with \( a \) the Alfvén speed and \( k \) the horizontal wavenumber), it couples to the third MHD wave type, the Alfvén wave, provided that gravity \( g \), the magnetic field \( B \), and the wavevector \( k \) are not coplanar (Cally & Goossens 2008).

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the chromosphere as a partially ionized magnetic boundary layer
partially ionized plasma

- partial ioniz\(^n\)⇒ 3-fluid *frictional dissipation, heating*
- efficient damping by ion-neutral collisions
- Kinetic theory ([Braginskii 1965](#))
  - \(Q_{fr} = j \cdot E = j^2/\sigma + (\xi_n j \times B - G)^2/\alpha_n,\)
  - “ambipolar diffusion”/star formation (1950s Schlüter, Cowling)
- \(G = 0 \Rightarrow \text{“Cowling conductivity” } \sigma^*_\perp\)
  - \(Q_{fr} = j ||^2/\sigma + j^2/\sigma^*_\perp, \quad \sigma/\sigma^*_\perp = 1 + 2 \xi_n \omega e \tau_e \omega i \tau_i, \quad \gg 1\)
  - \(\Rightarrow \text{rapid dissipation of } j^\perp\)
  - Goodman & colleagues: wave heating
  - Arber & colleagues: flux emergence
Chromospheric dissipation of $j_\perp$

- Braginskii (1965): certain motions ($G...$) dissipate $j_\perp$
  - Alfvén, fast modes, dynamic situations where
    $\nabla p - \rho g + j \times B \neq 0$
- **Not** slow modes, slow dynamics (cf. Goodman 2000)
- So, at coronal lower boundary, chromosphere makes:
  - $j_\perp \sim 0$; $j \times B \sim 0$
  - weaker Alfvén/fast modes

**Flux emergence:** Arber, Haynes & Leake (2007) based upon Cowling’s conductivity ($G=0$):

Plot of the magnitude of $J_\perp$ as a function of height along the line $x = y = 0$ for all three resistivity models at $t = 160$.

...radical effect on $j$ and flux emergence process
partially ionized plasma II

- $\sigma_\perp^*$ is some steps removed from $\sigma$ (kinetic theory)
  - case $G \neq 0$: $\sigma_\perp^*$ incorrect!
  - one must consistently determine the nature of $j_\perp$ (cf. E-region electrojet) from the dynamics

- Fontenla (2005, 2008 A+A)
  - for length scales $>100$ km (few mHz waves),
  - $Q_{fr} = j.E$ too small, invokes instability (Farley-Buneman)
  - need neutral component velocity $> \text{ion acoustic velocity}$
The future
**IRIS mission**

- **UV slit-jaw Images**
  - Si IV (65,000K)
  - C II (30,000K)
  - Mg II h/k (10,000K)
  - Mg II h/k wing (6,000K)

- **UV Spectra**
  - Far-UV 12.5 mÅ pixels
  - Near-UV 25 mÅ pixels

- **Realistic Radiative 3D MHD models**
  - to guide interpretation

- **20 cm UV telescope**
  - 1/6 arcsec pixels
  - *multi-channel spectrograph*
    - far-UV: 1332-1358 Å, 1390-1406 Å,
      - 40 mÅ resolution, effective area 2.8 cm²
    - near-UV: 2785 - 2834 Å,
      - 80 mÅ resolution, effective area 0.3 cm²

- **slit-jaw imaging**
  - 1335 Å & 1400 Å with 40 Å bandpass each;
  - 2796 Å & 2831 Å with 4 Å bandpass each.

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Monday, May 7, 2012

P. Judge, June 2012
IBIS- Cavallini & colleagues

Also TESOS, CRISP, GFPI,...
Facility InfraRed Spectropolarimeter

Telescope: DST

Features: diffraction limited, dual beam, 4-slits for high cadence (20 min.) rasters

Wavelengths: simultaneous 6302, 15650 or 6302, 10830 and runs concurrently with IBIS 8542, G-band camera

Now available for general use!
Polarimetric measurements with sensitivity sufficient to measure magnetic fields in the chromosphere and in coronal plasma

FIRS data Judge et al. (in prep).