Solar radiation and plasma diagnostics

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• **Radiation field in the solar atmosphere**

  – Amount of radiant energy flowing through unit area per unit time per unit frequency and per unit solid angle: intensity $I_\nu$

  – If radiation field is in thermal equilibrium with surroundings (a closed cavity at temperature $T$): blackbody radiation

  \[
  I_\nu = \frac{2\pi h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \equiv B_\nu(T) \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1}
  \]

  – Deep in the solar atmosphere, local thermodynamic equilibrium holds, and mean free path of photons is short (a few km): photons within a small volume can be considered to be contained in a cavity where the temperature is ~ constant.
The interaction of the radiation field with the plasma is described by the Radiative Transfer Equation

- Medium absorbs radiant energy $k_\lambda$ is the linear absorption coefficient in cm$^{-1}$

- $\tau = k_\lambda \, l$ is the optical depth at wavelength $\lambda$ of a uniform slab of linear thickness $l$.
  E.g. $k_\lambda = 10^{-6}$ cm$^{-1}$ around 5000 Å

- More generally: $\tau = \int k_\lambda \, dl$
• The interaction of the radiation field with the plasma is described by the Radiative Transfer Equation

– Medium emits radiant energy at rate $\varepsilon_\lambda \text{ erg cm}^{-3} \text{ s}^{-1} \text{ sr}^{-1} \text{ Å}^{-1}$

– Radiation propagating through the slab along OA varies between $h$ and $h + dh$ due to absorption and emission:

$$I_\lambda(h + dh, \Psi) - I_\lambda(h, \Psi) = \varepsilon_\lambda(h) dh \sec \Psi - I_\lambda(h, \Psi) k_\lambda dh \sec \Psi$$

– In the limit where $dh \to 0$, we get

$$\mu \frac{dI_\lambda}{dh} = \varepsilon_\lambda - k_\lambda I_\lambda$$
• The interaction of the radiation field with the plasma is described by the Radiative Transfer Equation

\[ \mu \frac{dI_\lambda}{dh} = \epsilon_\lambda - k_\lambda I_\lambda \]

– Finally, in the solar atmosphere, the optical depth at height \( h' \) is

\[ \tau_\lambda(h') = \int_{\infty}^{h'} k_\lambda dh \]

– The radiative transfer equation is then

\[ \mu \frac{dI_\lambda}{d\tau_\lambda} = I_\lambda - S_\lambda \] \[ \text{RTE} \]

with the source function \( S_\lambda = \epsilon_\lambda / k_\lambda \)
Solutions to the Radiative Transfer Equation

The intensity of radiation flowing through the upper atmosphere (relative to the point where the optical depth is \( \tau \)) is given by

\[
I(\tau, \mu+) = -e^{\tau/\mu} \int_{\infty}^{\tau} \frac{S(t)}{\mu} e^{-t/\mu} dt
\]

If \( \tau \to 0 \) then

\[
I(0, \mu+) = \int_{0}^{\infty} \frac{S(t)}{\mu} e^{-t/\mu} dt
\]

If \( S \) is constant at all depths: \( I(0, \mu+) = S \)

If \( S \) is constant in only a small slab of optical thickness \( \tau' \): \( I(0, \mu+) = S(1 - e^{-\tau'/\mu}) \)

Emergent intensity not as large as \( S \); reduced by optical depth term. If \( \tau' \) is very small, then \( I(0, \mu+) = S\tau'/\mu \)

In the case of constant source function, the emergent intensity from a slab cannot be greater than \( S \), but may be much smaller than \( S \) if the optical depth is small.
• **Solutions to the Radiative Transfer Equation**
  
  ● If $S$ is not constant at all depths: taking $S(\tau) = a + b\tau$
    one finds $I(0, \mu+) = a + b\mu$

  This solution matches the limb darkening of the Sun!

  ● This particular form of the source function is actually a natural
    consequence of the assumption of a Gray atmosphere, where
    the opacity is independent of wavelength.

  ● This results in the Eddington-Barbier relationship:
    the intensity observed at any value of $\mu$ equals the source
    function at the level where the local optical depth has the
    value $\tau = \mu$.

  It means that you see deeper in the atmosphere as you look
  towards the centre ($\mu=1$) than towards the limb ($\mu \to 0$).

  ● Limb darkening and EB also imply that $T$ increases with $\tau$
How do we detect solar radiation?

• The photosphere (in short)
  – Take advantage of photons that have optical depth unity at the surface of the Sun
  – This happens in the visible around 5000 Å
  – Many absorption lines (dark) superimposed on continuum signal presence of atoms / ions in solar atmosphere absorbing radiation coming from below.
  – The line strengths depend on the column densities of these atoms / ions which contain electrons in the lower state of the transition
  – Local Thermodynamic Equilibrium holds
  – $T \approx 4000-6000 \, \text{K}$, $n_H \approx 10^{15} - 10^{17} \, \text{cm}^{-3}$, $n_e \approx 10^{11} - 10^{13} \, \text{cm}^{-3}$
• The chromosphere: most poorly understood layer
  – Don’t wait for an eclipse!
  – Tune your instrument to detect photons for which $\tau \sim 1$ about 1000-2000 km above the photosphere
  – This means looking at
    – the core of lines such as $H\alpha$ or Ca II K, or
    – submillimetre and millimetre continua
  – No limb darkening: rather, limb brightening! $T$ decreases with $\tau$
  – $T$ rises to $\sim 20000$ K, decrease of $n_H$, $n_e \sim 10^{10}$ cm$^{-3}$
  – Plasma mostly out of LTE; optically thick at some wavelengths
• The corona (in short)
  – Optical forbidden lines tell us it’s hot ~ 1-2 MK and tenuous (less than $10^9$ cm$^{-3}$)
  See Edlen (1945) on Fe X 6375 Å and Fe XIV 5303 Å
  – Most of radiated energy is in EUV

- Out of LTE
- Soft X-ray spectrum shows strong emission lines and no obvious sign of continuum
What do we (I) mean by *plasma diagnostics*?

An empirical derivation of:

- Temperatures
- Densities
- Mass flow velocities
- Pressure
- Chemical abundances

in a specific (observed) region of the solar atmosphere at a certain time.

What for?

- E.g., energy and momentum balance and transport
• **Direct inversion of spectral data**
  – For optically thin plasma (all emitted photons leave freely without interaction)
  – Yields spatially averaged values

• **Forward approach**
  – Necessary for optically thick plasma
  – Semi-empirical models
    ● Start with given spatial distribution of $T$, $p$, $n$
    ● Solve excitation and ionisation balance for all species
    ● Determines opacities and emissivities
    ● Solve RTE to get the emergent spectrum
    ● Compare with observed spectrum ... and adjust model to start over again
• Optically thin plasma emitting Gaussian-shaped line
  – Line width yields ion temperature $T$ and non-thermal (or microturbulent) velocity $\xi$
    \[
    \Delta \lambda_D = \frac{\lambda_0}{c} \left( \frac{2kT}{m} + \xi^2 \right)^{1/2}
    \]
  – Observations of different lines give an idea of variation of $T$ and $\xi$, and so of
distribution of energy in different layers
    "The isotropic and small-scale nature of the nonthermal motions appear to be suited for
    MHD turbulence."
• **Optically thin plasma emitting Gaussian-shaped line**
  – Electron density estimated by, e.g.
    ● Stark broadening (generally yields upper limits)
    ● Emission measure methods
    ● Line ratios

  – Neutral and ion densities; abundances
    ● Line strengths, or absorption of radiation
    ● Often requires good photometric calibration and accurate atomic data

  – Gas pressure
    ● Derived from density and temperature measurements
    ● Using pressure-sensitive lines (or line intensity ratios)
• **Application to optically thin XUV / EUV / UV lines**
  – A lot of data (not even looking at the pre-SOHO era!): SOHO/SUMER, SOHO/CDS, SOHO/UVCS, Hinode/EIS, SDO/EVE, IRIS
  
  – Techniques described now applicable to plasma with $n_e < 10^{13}$ cm$^{-3}$ in ionization equilibrium
  
  – See work of Feldman et al (1977), Mariska (1992), Mason and Monsignori Fossi (1994), ...
• Line emission from optically thin plasma

  – Emissivity of b-b transition

  – Under the coronal approximation, only the ground level \((g)\) and excited level \((j)\) are responsible for the emitted radiation. The statistical equilibrium reduces to:

    \[
    n_e n_g C_{gj} = n_j A_{jg}
    \]

  – Balance excitation from ground level with spontaneous radiative decay

    \[
    I(\lambda_{jg}) = \frac{hc}{4\pi \lambda_{jg} A} \int_V n_e n_g C_{gj} dV \quad [\text{erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]
    \]

  – Now the population of the \(g\) level can be written as:

    \[
    n_g = \left( \frac{n_g}{N_{\text{ion}}} \right) \left( \frac{N_{\text{ion}}}{N_{\text{el}}} \right) \left( \frac{N_{\text{el}}}{N_H} \right) \left( \frac{N_H}{n_e} \right) n_e
    \]

    Abundance of element with respect to H

    \[\sim 1\]

    \[\sim 0.8\]
Direct spectral inversion

Carole Jordan’s work
Line emission from optically thin plasma

- Collisional excitation coef: (assuming Maxwellian velocity distribution)

\[ C_{gj} = \frac{8.63 \times 10^{-6} \gamma_{gj}(T)}{\omega_g} T^{-1/2} \exp \left( -\frac{hc}{\lambda_{jg} kT} \right) \]

Statistical weight Collision strength

- Finally...

\[ I(\lambda_{jg}) = \frac{1}{4\pi A} \int_V A b G(T) n_e^2 dV \]

where we have introduced the contribution function \( G(T) \)

\[ G(T) = \frac{8.63 \times 10^{-6} \gamma_{gj}(T)}{\omega_g} \frac{N_{\text{ion}}}{N_{\text{el}}} \frac{N_H}{n_e} T^{-1/2} \exp \left( -\frac{hc}{\lambda_{jg} kT} \right) \frac{hc}{\lambda_{jg}} \]
Direct spectral inversion

Contribution functions for lines belonging to O III – O VI ions, CHIANTI v.5.1

www.chantidatabase.org
• **Electron temperature**
  
  – Emission measure: yields amount of plasma emissivity along LOS

  ● Use the fact that contribution function is peaked to write

  \[ I(\lambda_{jg}) = \frac{1}{4\pi} Ab \langle EM \rangle \langle G(T) \rangle, \text{ with } \langle EM \rangle = \int n_e^2 dh \ [\text{cm}^{-5}] \]

  ● EM can be directly inferred from the observation of spectral lines

  ● It may be defined also as \( EM = n_e^2 V_c \ [\text{cm}^{-3}] \), with \( V_c \) the coronal volume emitting the line

  ● EM also yields the electron density
Direct spectral inversion

- **Electron temperature**
  - Differential Emission Measure:
    yields distribution in temperature of plasma along LOS

\[
DEM(T) = n_e^2 \frac{dh}{dT} \text{ [cm}^{-5} \text{ K}^{-1}] \text{ and thus } I(\lambda_{jg}) = \frac{1}{4\pi} Ab \int_T G(T)DEM(T)dT
\]

- The DEM contains information on the processes at the origin of the temperature distribution, **BUT**
- The inversion is tricky, using observed line intensities, through calculating \( G(T) \), assuming elemental abundances, and is sensitive to uncertain atomic data (see Hannah & Kontar, A&A 539, 146, 2012)
• **Electron density from line ratios**

  – Allowed transitions have \( I \propto n_e^2 \)

  – Forbidden and intersystem transitions, with a metastable (long lifetime) upper state \( m \), can be collisionally de-excited towards level \( k \)

  – For such a pair of lines from the same ion:

\[
\frac{I(\lambda_{jg})}{I(\lambda_{mk})} = \frac{n_g}{n_m} \frac{C_{gj}}{C_{mk}} \frac{\lambda_{mk}}{\lambda_{jg}}, \quad \text{so} \quad \frac{I(\lambda_{jg})}{I(\lambda_{mk})} \propto \frac{n_e}{F(T, n_e)}
\]

  This is because of the density dependence of the population of level \( m \)

  – Intensity ratio yields \( n_e \) averaged along LOS at line formation temperature
• An Atomic Database for Spectroscopic Diagnostics of Astrophysical Plasmas
  – critically evaluated set of atomic data (energy levels, wavelengths, radiative transition probabilities and excitation data) for a large number of ions
  – Spectral analysis and plasma diagnostics programs written in IDL (stand-alone or included in SSW) and Python (ChiantiPy)
  – Allows you to
    • Calculate line and/or continuum intensities
    • Create synthetic spectrum

– Examples from User guide written by the Del Zanna and the CHIANTI team...
Ionization equilibrium for Mg — mazzotta_etal
CHIANTI V. 7.1.3 O V 192.9039 (Å)/248.4608 (Å) T = 2.24e+05 (K)
Other spectroscopic diagnostics in corona

"Typical" Light Curve & X-ray Spectra

Courtesy I.G. Hannah

Some Heating
Hard Flat Non-thermal

Increased T & EM
Soft Steep Non-thermal

Lower T & Higher EM
No Non-thermal
Other spectroscopic diagnostics in corona

Non-thermal (Hard) X-ray Emission

- The bremsstrahlung free-free photon flux at the Earth $I(\varepsilon)$ is related to the source electron distribution $F(E)$ as:

$$I(\varepsilon) = \frac{1}{4\pi R^2} \int_\varepsilon^\infty \int_V n(r) F(E, r) Q(\varepsilon, E) dEd^3r$$

- Assume non-thermal emission from a power-law of electrons accelerated out of Maxwellian, spectral index $\delta$ above $E_c$

$$F(E) \propto E^{-\delta}$$

- Total Number of accelerated electrons s$^{-1}$ above $E_c$ [keV]

$$N(E > E_c) = \int_{E_c}^{\infty} F(E) dE$$

- Power in these electrons in erg s$^{-1}$

$$P(E > E_c) = \int_{E_c}^{\infty} F(E) E dE = 1.6 \times 10^{-9} \frac{\delta - 1}{\delta - 2} NE_c$$

- Non-thermal Energy in erg

$$U_N(E > E_c) = P(E > E_c) \Delta t$$
Other spectroscopic diagnostics in corona

If take simpler non-relativistic form of $Q(\varepsilon,E)$ find analytically $I(\varepsilon) \propto \varepsilon^{-\gamma}$

- Kramers or Non-relativistic Bethe-Heitler (see Brown 1971, Holman 2009)
• **Microwave emission from solar flare loops**
  
  – Primarily due to gyrosynchrotron emission from electrons moving in the local magnetic field with $E \sim m_e c^2$
  
  – Optically thin spectrum can be approximated at high $\nu$ by $k \nu^\alpha$
  
  – Spectral index $\alpha$ related to energy spectral index of accelerated electrons and pitch angle distribution
How to interpret the optically thick spectrum?

• The “bible”?

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**Structure of the Solar Chromosphere. III. Models of the EUV Brightness Components of the Quiet Sun**

J. E. Vernazza\(^1\), E. H. Avrett, and R. Loeser
Harvard-Smithsonian Center for Astrophysics
Received 1980 April 7; accepted 1980 October 20

• Plenty of more refined, and more successful models since then
How to interpret the optically thick spectrum?

Fig. 1.—The average quiet-Sun temperature distribution derived from the EUV continuum, the $\lambda \alpha$ line, and other observations. The approximate depths where the various continua and lines originate are indicated.
How to interpret the optically thick spectrum?

- VAL 3

Fig. 10.— Temperature as a function of height and of log $m$ for models A–F
VAL 3

- Start with given spatial distribution of $T$, $p$, $n$
- Solve excitation and ionisation balance for all species
- Determines opacities and emissivities
- Solve RTE to get the emergent spectrum
- Compare with observed spectrum ... and adjust model to start over again
IRIS observations – Mg II optically thick lines

- UV spectra and images with high resolution in space (0.33-0.4 arcsec) and time (1-2s) focused on the chromosphere and transition region
IRIS observations – Mg II optically thick lines

Spectral observable | Atmospheric property
--- | ---
$\Delta \nu_k$ or $\Delta \nu_{h3}$ | upper chromospheric velocity
$\Delta \nu_k$ or $\Delta \nu_{h2}$ | mid chromospheric velocity
$\Delta \nu_k - \Delta \nu_{h3}$ | upper chromospheric velocity gradient
k or h peak separation | mid chromospheric velocity gradient
k2 or h2 peak intensities | chromospheric temperature
$(I_{k2v} - I_{k2r})/(I_{k2v} + I_{k2r})$ | sign of velocity above $z(\tau = 1)$ of $k_2^+$
IRIS data analysis

Analysis

- Interpretation of Mg II h/k lines
  - Formation of IRIS diagnostics I, Leenaarts et al., 2013a
  - Formation of IRIS diagnostics II, Leenaarts et al., 2013b
  - Formation of IRIS diagnostics III, Pereira et al, 2013

- Invited talks from SDO-4/IRIS/Hinode meeting (2012)

- User Guide to Data Analysis

Documentation

ITN 26 - User Guide To Data Analysis
ITN 27 - Quicklook Tools Manual
ITN 28 - IRIS IDL Data Structure
ITN 29 - Deconvolution Approach
ITN 30 - 60 Day Observing Plan
ITN 37 - How to derive physical information from Mg II h/k lines
UVSP Database and SolarSoft Tree
IRIS data analysis

Download
- IRIS-related Bifrost Models (Oslo)

Radiative Transfer Codes
- Multi3d
- RH 1.5d (please acknowledge Han Uitenbroek and Tiago Pereira)

Documentation
- ITN 33 - General Overview of Numerical Simulations
- ITN 34 - Numerical Simulations Quicklook Tools
- ITN 35 - Numerical Simulations Synthetic Observables
- ITN 36 - RH 1.5 D Manual
- ITN 37 - How to Derive Physical Information from Mg II h/k
Formation of He II 304 in flare atmosphere

• RADYN code


Allred et al (2005)
• **Line profiles give us key information on plasma parameters**
  – Line width: thermal and non-thermal processes
  – Line position: Doppler shifts, mass flows
  – Line intensity: densities, temperature
  – Line profile shape: optical thickness

• **Issues**
  – It takes time to acquire spectra on rather limited field of views
  – Data analysis relies on complex atomic data with high uncertainties
  – Line identification and blends can cause headaches!
• Spectra are still useful even without detailed profiles
  – Integrated intensities should not be affected by instrumental profile

• Imaging
  – No detailed line profile, no Doppler shifts
  – High cadence, high temporal resolution
  – Narrow-band imaging getting close to spectroscopic imaging
    – Still issues about what lines contribute (and to what extent) to observed emission
Thermal structure of a hot non-flaring corona

We find that, whereas the cool region has a flat and featureless distribution that drops at temperature \( \log T \geq 6.3 \), the distribution of the hot region shows a well-defined peak at \( \log T = 6.6 \) and gradually decreasing trends on both sides, thus supporting the very hot nature of the hot component diagnosed with imagers.

Where can I look to learn more about solar radiation and plasma diagnostics?

- ADS
- Nuggets (UKSP, EIS, RHESSI, ...)
- Online notes, e.g. Rob Rutten’s lectures: [www.staff.science.uu.nl/~rutte101/Astronomy_course.html](http://www.staff.science.uu.nl/~rutte101/Astronomy_course.html)
• **Plasma diagnostics in the solar wind acceleration region**
  – Uses ratio of collisional and radiative components of pairs of strong resonance lines (e.g., O VI 1032/1037; Ne VIII 770/780; Mg X 610/625; Si XII 499/521; Fe XVI 335/361)
  – Kinetic temperatures and deviations from Maxwellian distributions can be determined from line shapes and widths (mass or charge-to-mass dependent processes)
  – Mass-independent broadening can also be produced by bulk motions of coronal plasma
  – Measurements provide key tests for models
    
    See Kohl & Withbroe (1982); Withbroe et al. (1982); UVCS papers
• **Plasma diagnostics in the solar wind acceleration region**
  – Solar wind velocities by the Doppler dimming effect (Hyder & Lites 1970)
  ● Intensity of resonantly scattered component of spectral line depends on

$$\int_{-\infty}^{\infty} J(\nu) \phi(\nu - \nu_w) d\nu$$

- Mean intensity of disk radiation
- Normalised absorption profile
- Doppler shift introduced by wind velocity
Arbitrary selection of research papers

Kohl & Withbroe 1982

DOPPLER DIMMING

I(νw)/I(ν = 0)

VELOCITY (km/sec)

O XVI λ1032
Si XII λ499
He II λ304
HI λ1216

Kohl & Withbroe 1982
Arbitrary selection of research papers


- V=0 km s\(^{-1}\)
- V=80 km s\(^{-1}\)
  - T = 8000 K
  - T = 15000 K
- V=200 km s\(^{-1}\)
- V=400 km s\(^{-1}\)


**Température vs. altitude**

- Ly-\(\beta\)
- Ly-\(\alpha\)

*streamer*  
*couronne ouverte*

**Ly-\(\alpha\) (SOHO/UVCS)**
• **The TR and coronal downflows**
  – Net redshift in all TR emission lines, peaking at log T=5, explained by material draining down on both sides of TR loops towards footpoints (Brekke et al., 1997; Dammash et al., 2008).
  – Similar observations in coronal lines (e.g. EIS: del Zanna 2008, Tripathi et al 2009)
  – Also observed in optically thick Lyman lines by SOHO/SUMER (see Curdt et al., 2011)

• **Lyman-α is one of the most important lines**
  – 1216 Å
  – Transition between atomic levels 1 and 2 of hydrogen
  – Key role in radiative energy transport in solar atmosphere
Arbitrary selection of research papers

Correspondence between asymmetry and downflows
Correspondence between line reversals and magnetic field

Flatter profiles (reduced opacity) cluster along the network lane
• Plasma diagnostics in the flaring solar chromosphere (Graham et al., 2011)
  – Combined EIS, RHESSI, XRT and TRACE data covering a wide range of temperatures
  – Evidence for T~7 MK in footpoints from XRT
  – and $n_e \sim$ a few $10^{10}$ cm$^{-3}$ at T~1.5-2 MK
  – Small downflows at T<1.6MK; upflows up to 140 km s$^{-1}$ above
Arbitrary selection of research papers

- Graham et al., 2011
Solar prominence diagnostics with Hinode (Labrosse et al., 2011)

- Used EIS data covering a wide range of temperatures
- Evidence for absorption and volume blocking
- Used optically thick He II 256 Å line and non-LTE models
- Infer H column density of $10^{20}$ cm$^{-2}$
Labrosse et al., 2011

- Prominence plasma parameters obtained by comparison between inferred intensities and computed intensity at 256 Å

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central temperature</td>
<td>8700 K</td>
</tr>
<tr>
<td>Surface temperature</td>
<td>96500 K</td>
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<tr>
<td>Central pressure</td>
<td>0.33 dyn cm⁻²</td>
</tr>
<tr>
<td>Surface pressure</td>
<td>0.22 dyn cm⁻²</td>
</tr>
<tr>
<td>Column mass</td>
<td>2.5 × 10⁻⁴ g cm⁻²</td>
</tr>
<tr>
<td>Hydrogen column density</td>
<td>10²⁰ cm⁻²</td>
</tr>
<tr>
<td>Intensity of the 256 Å line</td>
<td>200 erg s⁻¹ cm⁻² sr⁻¹</td>
</tr>
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