

Spectroscopy of the solar Transition Region and Corona

L. Teriaca

L. Teriaca, IMPRS Seminar, Lindau 08/12/04

The Solar Corona



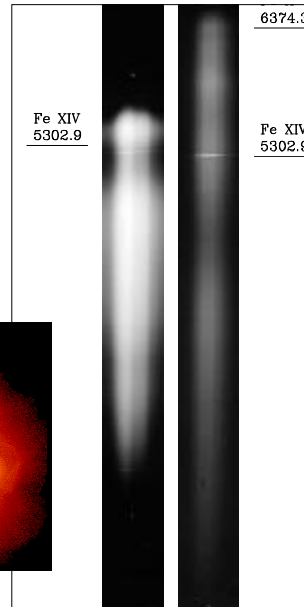
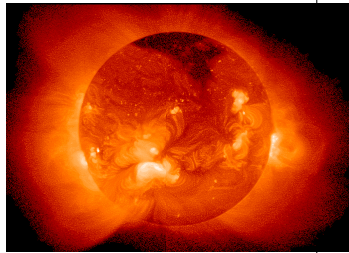
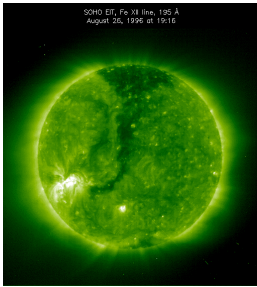
Composite photo of the August 11, 1999 total eclipse.
Lake Hazar, Turkey.

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The Solar Corona

Raw spectra obtained
on 19 June 1936 during
a total eclipse observed
from the former Soviet
Union.

$T_e = 1 - 2 \text{ MK}$



The Solar Chromosphere

$T_e = 10^4 \text{ K}$

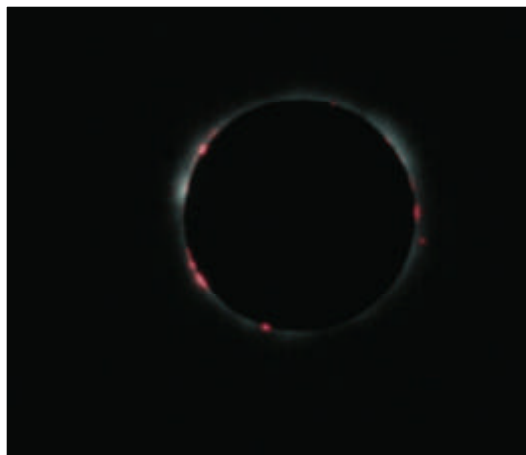
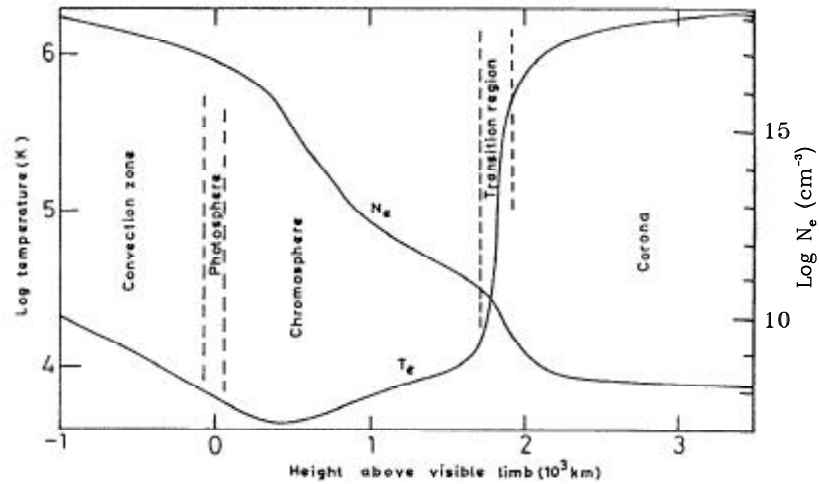


Photo of the August 11, 1999 total eclipse.
Kastamonu, Turkey.

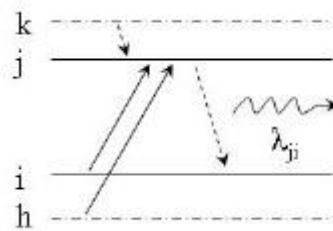
The Solar Transition Region



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Radiant power density

Optically thin plasma



Spectral radiant
power density:

$$P(I)_{ji} = \frac{hc}{I_{ji}} N_j A_{ji} \Psi(I) \quad (\text{erg s}^{-1} \text{cm}^{-3} \text{\AA}^{-1})$$

Radiant power density:

$$P_{ji} = \frac{hc}{I_{ji}} N_j A_{ji} \quad (\text{erg s}^{-1} \text{cm}^{-3})$$

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Radiant power density

$$P_{ji} = \frac{hc}{I_{ji}} \frac{N_j}{N_{ion}} \frac{N_{ion}}{N_{el}} \frac{N_{el}}{N_H} \frac{N_H}{N_e} N_e A_{ji} \quad (\text{erg s}^{-1}\text{cm}^{-3})$$

$\frac{N_j}{N_{ion}}$ is the fraction of ions in the upper level j . **Strong function of N_e**

$\frac{N_{ion}}{N_{el}}$ is the relative abundance of the ionic specie. **Strong function of T_e**

$\frac{N_{el}}{N_H}$ is the element abundance with respect to hydrogen.

$\frac{N_H}{N_e}$ is the hydrogen to electrons number density ratio. ≈ 0.85

Radiant power density

Normalised radiant power density

$$\mathbf{e}_{ji} = \frac{P_{ji}}{N_{ion}} = \frac{hc}{I_{ji}} \frac{N_j}{N_{ion}} A_{ji} \quad (\text{erg s}^{-1})$$

Contribution function

$$G(T_e, N_e, A_{el})_{ji} = \frac{\mathbf{e}_{ji}}{N_e} \frac{N_{ion}}{N_{el}} \frac{N_{el}}{N_H} \frac{N_H}{N_e} \quad (\text{erg s}^{-1}\text{cm}^3)$$

$$P_{ji} = G(T_e, N_e, A_{el})_{ji} N_e^2 \quad (\text{erg s}^{-1}\text{cm}^{-3})$$

Line radiance

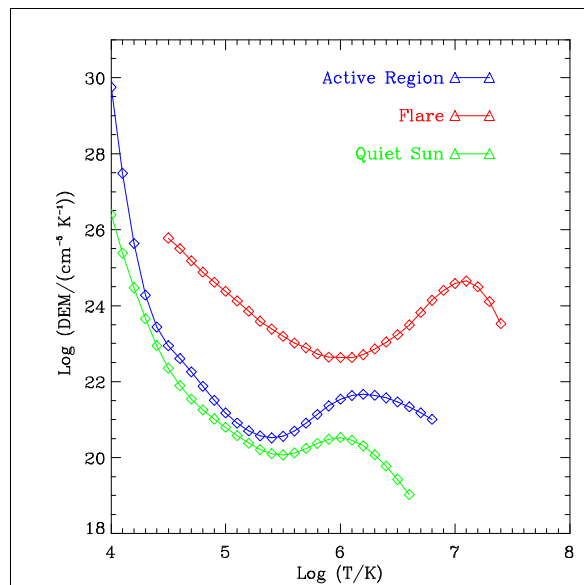
$$L_{ji} = \frac{1}{4\pi} \int_h G(T_e, N_e, A_{el})_{ji} N_e^2 dh \quad (\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1})$$

$$DEM(T) = N_e^2 \frac{dh}{dT} \quad (\text{cm}^{-5} \text{K}^{-1})$$

$$L_{ji} = \frac{1}{4\pi} \int_h G(T_e, N_e, A_{el})_{ji} DEM(T) dT \quad (\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1})$$

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Differential emission measure



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Atomic processes

Process	Rate ($\text{cm}^{-3} \text{s}^{-1}$)	Characteristic time (s)
Collisional excitation	$N_i N_e C_{ij}$	$2 \cdot 10^{-3}$
Collisional deexcitation	$N_j N_e C_{ji}$	$2 \cdot 10^{-3}$
Spontaneous radiative decay	$N_j A_{ji}$	$4 \cdot 10^{-9}$
Collisional ionization	$N_e N_{ion} q_{coll}$	107
Radiative recombination	$N_e N_{ion} \alpha_{rad}$	88

Characteristic times for the relevant atomic processes in the Transition region as calculated for the C IV line at 154.8 nm ($T_e=10^5$ K, $N_e=10^{10} \text{ cm}^{-3}$).

Thermal equilibrium

Te (K) \ Ne (cm^{-3})	5×10^8	10^{10}
	10^5	$t_{ee} = 10^{-3}$ $t_{pp} = 0.04$ $t_{ei} = 0.8$
10^6	$t_{ee} = 0.03$ $t_{pp} = 1.3$ $t_{ei} = 26$	$t_{ee} = 0.02$ $t_{pp} = 0.7$ $t_{ei} = 1.3$

Ionization ($N_{\text{ion}}/N_{\text{el}}$)

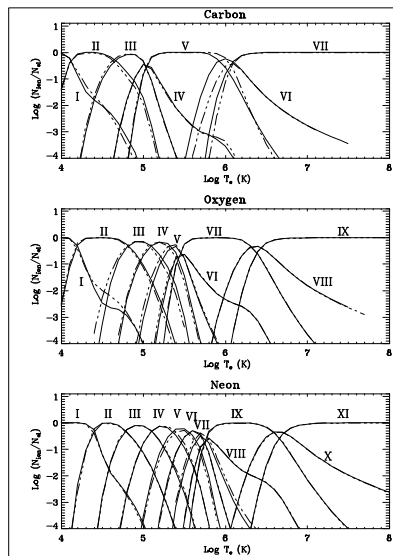
$$\frac{dN^z}{dt} = N_e (N^{z-1} q^{z-1} + N^{z+1} \alpha_r^{z+1} + N^{z+1} \alpha_d^{z+1}) - N_e N^z (q^z + \alpha_r^z + \alpha_d^z),$$

q collisional ionization
 α_r radiative recombination
 α_d dielectronic recombination

ionization equilibrium $\rightarrow \frac{dN^z}{dt} = 0$

$$\sum_{z=0}^Z N^z = N_{\text{el}}$$

Ionisation ($N_{\text{ion}}/N_{\text{el}}$)



Excitation (N_j/N_{ion})

$$\frac{dN_i}{dt} = \sum_{j \neq i} N_j N_e C_{ji} - \sum_{j \neq i} N_i N_e C_{ij} + \sum_{j > i} N_j A_{ji} - \sum_{j < i} N_i A_{ij},$$

statistical equilibrium $\rightarrow \frac{dN_i}{dt} = 0$

$$\sum_i N_i = N_{ion}$$

Collisional rate coefficients

$$C_{ij} = \int_{v_0}^{\infty} \mathbf{s}_{ij}(v) f(v) v \, dv \quad (\text{cm}^3 \text{ s}^{-1})$$

$$\sigma_{ij}(E) = \frac{\pi a_0^2 I_H \Omega_{ij}(E)}{\omega_i E},$$

$$\frac{dN(E)}{N_{Tot}} = \frac{2}{\sqrt{\pi}} (kT_e)^{-\frac{3}{2}} \sqrt{E} \exp\left(-\frac{E}{kT_e}\right) dE.$$

$$C_{ij} = \frac{8.63 \times 10^{-6}}{\omega_i k T_e^{\frac{3}{2}}} \int_{\Delta E_{ij}}^{\infty} \Omega_{ij}(E) \exp\left(-\frac{E}{kT_e}\right) dE,$$

$$C_{ij} = \frac{8.63 \times 10^{-6} \Omega_{ij}}{\omega_i T_e^{\frac{1}{2}}} \exp\left(-\frac{\Delta E_{ij}}{kT_e}\right).$$

Excitation (N_j/N_{ion})

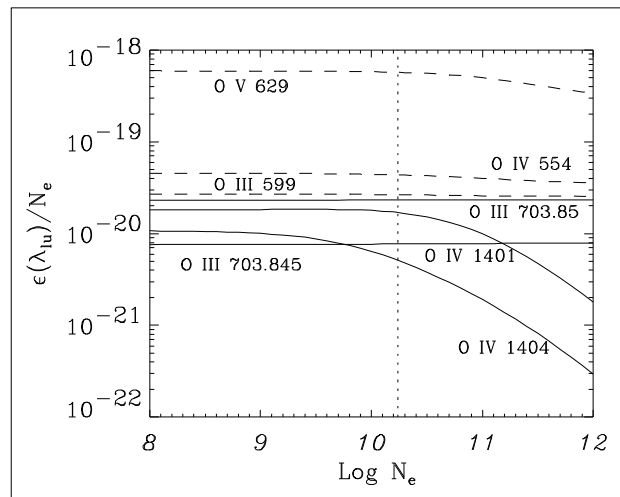
Allowed transition: $\frac{N_j}{N_{ion}} \propto N_e \Rightarrow \frac{e_{ij}}{N_e} = const$

Intersystem transition: $\frac{N_j}{N_{ion}} \propto N_e$ only if $N_e C_{ij} \ll A_{ji}$

$\frac{N_j}{N_{ion}} = const$ when $N_e C_{ij} \gg A_{ji}$

Excitation (N_j/N_{ion})

$$e_{ji} = \frac{hc}{I_{ji}} \frac{N_j}{N_{ion}} A_{ji}$$



CHIANTI atomic database: <http://www.solar.nrl.navy.mil/chianti.html>

Abundance (N_{el}/N_H)

Table 4.2: Photospheric (Grevesse & Sauval 1998) and coronal (Feldman et al. 1992) element abundances for the most abundant element on the Sun. First Ionization Potentials (FIP) values are from Martin & Wiese (1996).

Element	Z	Photospheric	Coronal	FIP (eV)
H	1	12.00	12.00	13.59
He	2	10.93*	10.90	24.59
C	6	8.52	8.59	11.26
N	7	7.92	8.00	14.53
O	8	8.83	8.89	13.62
Ne	10	8.08*	8.08	21.56
Na	11	6.33	6.93	5.14
Mg	12	7.58	8.15	7.65
Al	13	6.47	7.04	5.99
Si	14	7.55	8.10	8.15
S	16	7.33	7.27	10.36
Ar	18	6.40*	6.58	15.76
Ca	20	6.36	6.93	6.11
Fe	26	7.50	8.10	7.90
Ni	28	6.25	6.84	7.64

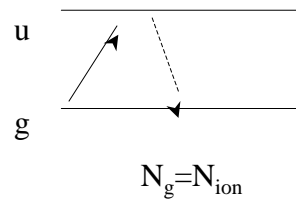
* These abundances were determined using coronal data. However the Ne value is fully consistent with the result of Widing (1997), who measured it in photosphere.

$$A_{el} = \log \frac{N_{el}}{N_H} + 12$$

Two – level atom

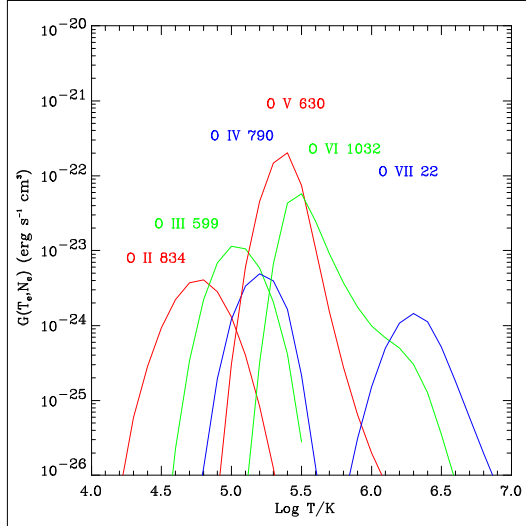
$$N_e N_g C_{gu} = N_u A_{ug}$$

$$G(T_e)_{gu} = \frac{hc}{\lambda_{ug}} \frac{N_{ion}}{N_{el}} \frac{N_{el}}{N_H} \frac{N_H}{N_e} C_{gu}$$

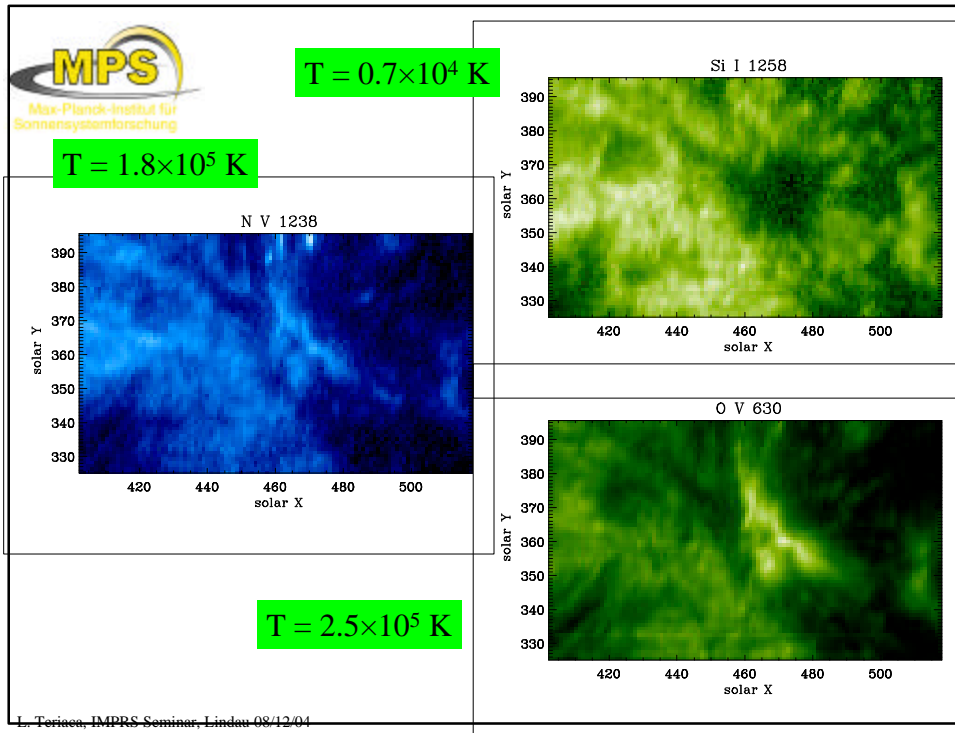


$$G(T_e)_{gu} = \frac{hc}{\lambda_{ug}} \frac{N_{ion}}{N_{el}} \frac{N_{el}}{N_H} \frac{N_H}{N_e} \frac{8.63 \times 10^{-6} \Omega_{ij}}{\omega_i T_e^{1/2}} \exp\left(-\frac{\Delta E_{ij}}{kT_e}\right)$$

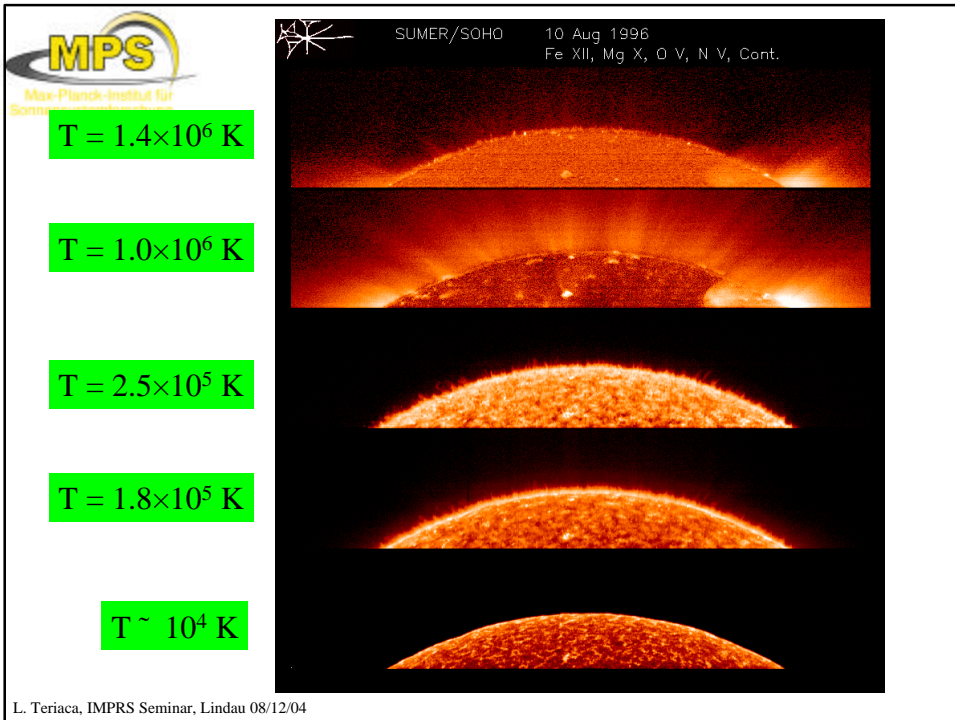
Formation temperature



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Emission Measure

$$L_{ji} = \frac{1}{4p} \int_h G(T_e)_{ji} N_e^2 dh \quad (\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1})$$

$$\langle G(T_e)_{ji} \rangle = \frac{1}{T_{\max}} \frac{\int_h G(T_e)_{ji} dh}{10^{(T_{\max}+0.15)} - 10^{(T_{\max}-0.15)}} \quad (\text{erg s}^{-1} \text{cm}^3)$$

$$L_{ji} = \frac{\langle G(T_e)_{ji} \rangle}{4p} \int_h N_e^2 dh \quad (\text{erg s}^{-1} \text{cm}^{-2} \text{sr}^{-1})$$

$$\text{EM}_c = \int_h N_e^2 dh \quad (\text{cm}^{-5})$$

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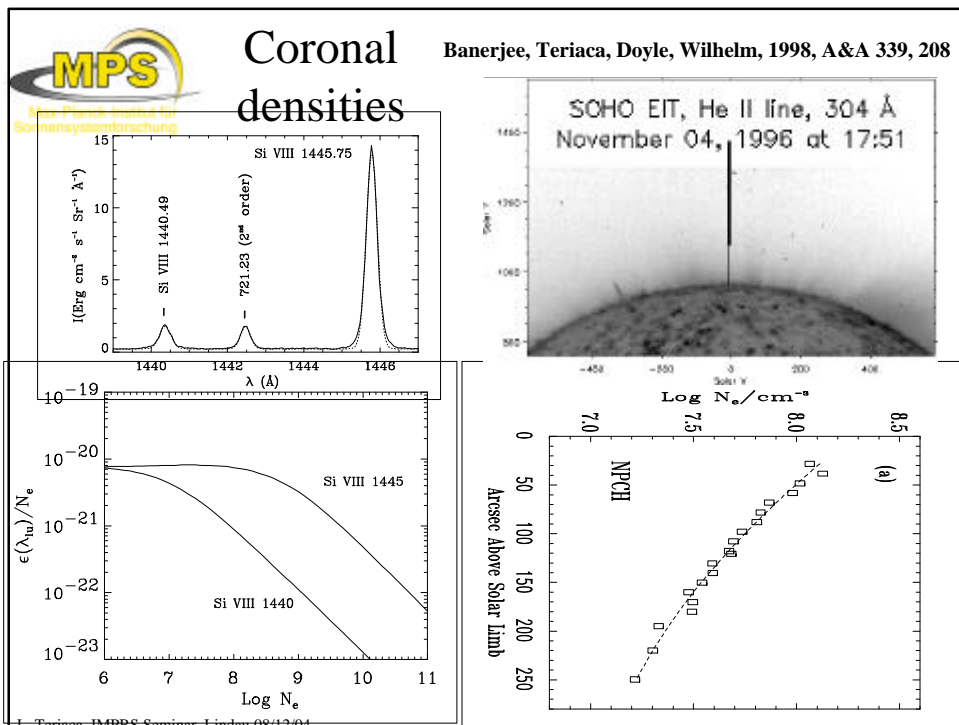
Electron density

$$EM_c = \int_h N_e^2 dh \quad (\text{cm}^{-5})$$

$$\langle N_e^2 \rangle = \frac{4pL}{\langle G(T) \rangle} \frac{1}{fh}$$

Density sensitive line radiance ratio

$$R = \frac{e_1}{e_2} = f(N_e) \quad ? \quad f=10^{-2} - 10^{-5}$$



Electron temperatures

If we consider an isothermal plasma, the ratio of two allowed transitions from adjacent ionization stages reduces to the ratio of their contribution functions.

If we consider two allowed transitions from the ground state of the same ion:

$$\frac{I_{gk}}{I_{gj}} = \frac{\Delta E_{gk} \Omega_{gk}}{\Delta E_{gj} \Omega_{gj}} \exp\left(\frac{\Delta E_{gj} - \Delta E_{gk}}{kT_e}\right),$$

sensitive to the temperature if:

$$(\Delta E_{gk} - \Delta E_{gi}) \gg kT_e$$

Line profile

$$\Psi(I) = \Psi(I)_{\text{NAT}} * \Psi(I)_{\text{COLL}} * \Psi(I)_{\text{Th}} * \Psi(I)_{\text{Nth}}$$

In the solar corona:

$$\Delta I_{\text{Th}} = \Delta I_{\text{NAT}} + \Delta I_{\text{COLL}}$$

Assuming that the ions follow a Maxwellian distribution:

$$\Psi(I)_{\text{Th}} = \frac{1}{\sqrt{p} \Delta I_{\text{Th}}} \exp\left(-\frac{(I - I_0)^2}{\Delta I_{\text{Th}}^2}\right)$$

where:

$$\Delta I_{\text{Th}} = \frac{I_0}{c} v = \frac{I_0}{c} \left(\frac{2kT}{m_{\text{ion}}}\right)^{1/2}$$

Line profile

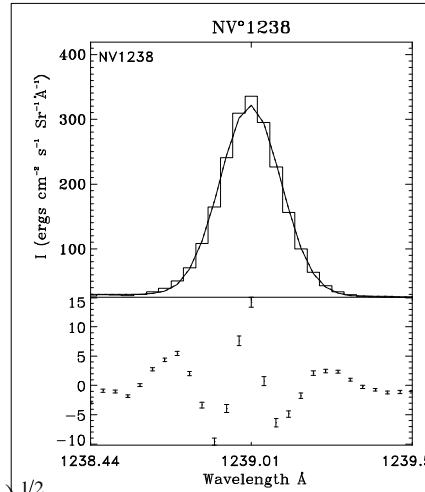
As an example, for N V 123.8 nm,
($T_e = 1.8 \times 10^5$ K),

$$\Delta I_{Th} = 0.061 \text{ \AA} = 14.9 \text{ km s}^{-1}$$

However, we observe:

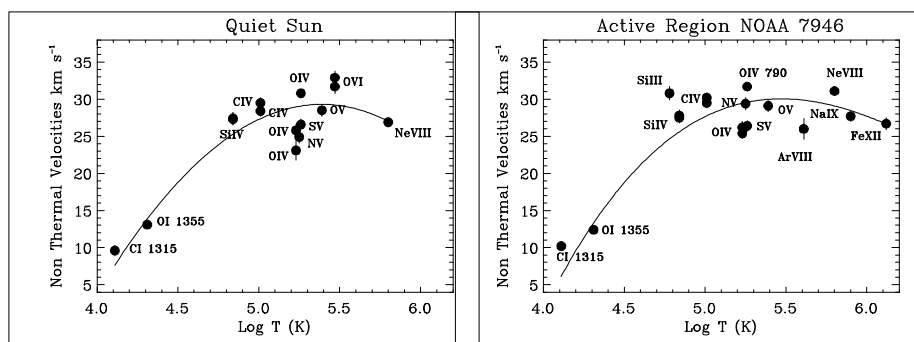
$$\Delta I_{Obs} = 0.1438 \text{ \AA} = 34.8 \text{ km s}^{-1}$$

$$\Delta I_{Sun} = \frac{I_0}{c} \left(\frac{2kT_e}{m_{ion}} + x^2 \right)^{1/2} = \frac{I_0}{c} \left(\frac{2kT_{eff}}{m_{ion}} \right)^{1/2}$$



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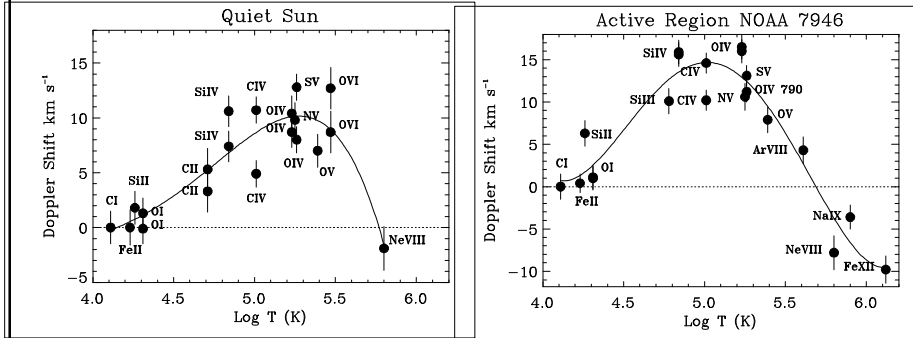
Non-thermal velocity



Teriaca, Banerjee, Doyle, 1999, A&A, 349, 636

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Doppler shift



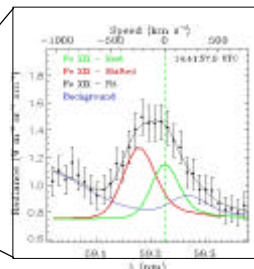
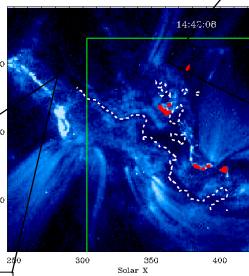
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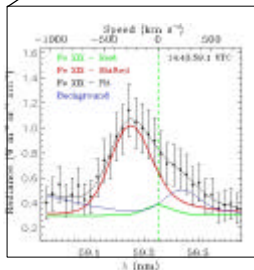
Chromospheric evaporation in flares

L. Teriaca et al.

Large upflows in
CDS Fe XIX line
at the footpoints
of the flaring loop
system during the
impulsive phase.

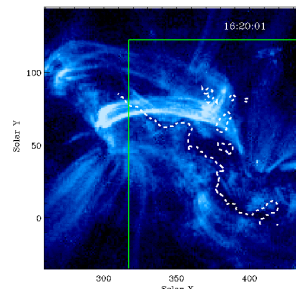


Red contours indicate Ha
downflows of $\sim 10 \text{ km s}^{-1}$



RHESSI data, starting at
14:50 UT, shows non
thermal emission still
present at the right footpoint

One hour later the flaring
loops start to appear in the
TRACE 17.1 nm band and
are fully visible around
16:20 UT



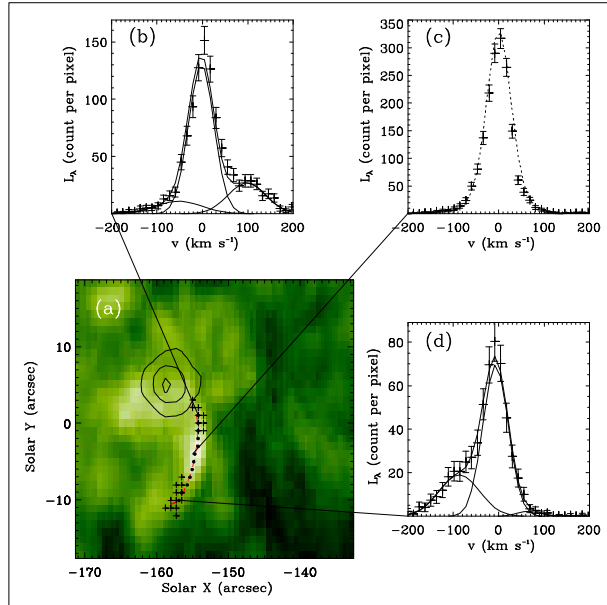
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Supersonic flows in a Quiet Sun loop

L. Teriaca et al. 2004, A&A 427, 1065

a) O VI SUMER raster of a small QS area. Black contours show magnetic flux of -10, -25, -40 G. Black + indicate the locations of strong non-Gaussian line profiles. The dashed red line indicates the projection on the plane of the sky of a semicircular loop with a diameter of 13". The black dots show the position of the observed loop.

b, d) Profiles on the legs of the loop with the results of a 3 component Gaussian fitting.
c) Profile at loop top. The dotted line shows the average QS profile times 4.9.
Observed speeds are consistent with the LOS component of a supersonic siphon-like flow of $\sim 130 \text{ km s}^{-1}$ along the loop.



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