

MPS
Max Planck Institut für Sonnensystemforschung


Spectroscopy of the solar Transition Region and Corona

L. Teriaca

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

MPS
Max Planck Institut für Sonnensystemforschung

The Solar Corona



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

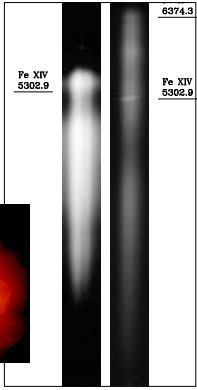
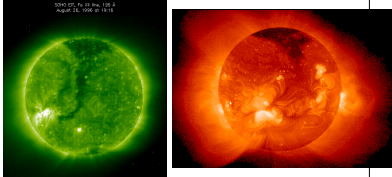
L. Teriaca, IMPRS Seminar, Lindau 08/12/04

MPS
Max Planck Institut für Sonnensystemforschung

The Solar Corona

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

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

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

MPS
Max Planck Institut für Sonnensystemforschung

The Solar Chromosphere

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


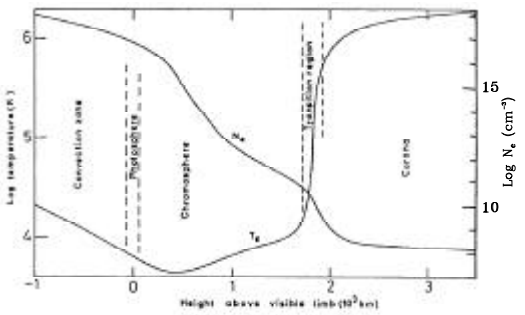


Photo of the August 11, 1999 total eclipse. Kastamonu, Turkey.

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

MPS
Max Planck Institut für Sonnensystemforschung

The Solar Transition Region

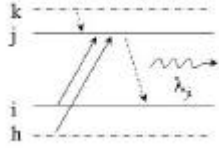


L. Teriaca, IMPRS Seminar, Lindau 08/12/04

MPS
Max Planck Institut für Sonnensystemforschung

Radiant power density

Optically thin plasma



Spectral radiant power density: $P(I)_{ji} = \frac{hc}{I_{ji}} N_j A_{ji} \Psi(I)$ (erg s⁻¹ cm⁻³ Å⁻¹)

Radiant power density: $P_{ji} = \frac{hc}{I_{ji}} N_j A_{ji}$ (erg s⁻¹ cm⁻³)

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

MPS
Max-Planck-Institut für Sonnensystemforschung

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

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

MPS
Max-Planck-Institut für Sonnensystemforschung

Radiant power density

Normalised radiant power density

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

Contribution function

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

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

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

MPS
Max-Planck-Institut für Sonnensystemforschung

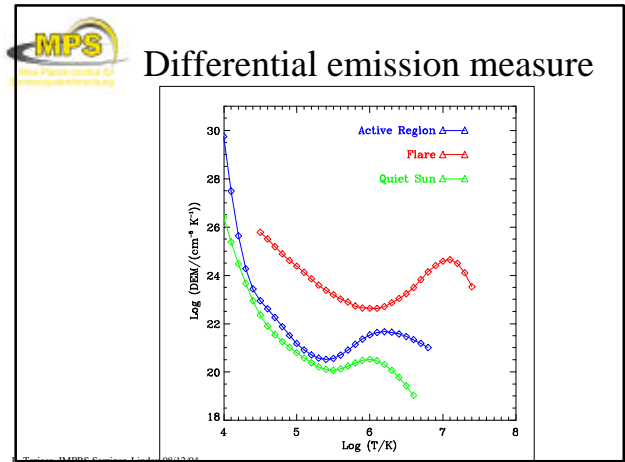
Line radiance

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

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

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

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



MPS
Max-Planck-Institut für Sonnensystemforschung

Atomic processes

Process	Rate ($\text{cm}^{-3} \text{s}^{-1}$)	Characteristic time (s)
Collisional excitation	$N_e N_e C_{ij}$	$2 \cdot 10^{-3}$
Collisional deexcitation	$N_j N_e C_{ji}$	$2 \cdot 10^{-3}$
Spontaneous radiative decay	$N_j A_{ji}$	$4 \cdot 10^{-3}$
Collisional ionization	$N_e N_{ion} q_{ion}$	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, $N_e=10^{10} \text{ cm}^{-3}$).

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

MPS
Max-Planck-Institut für Sonnensystemforschung

Thermal equilibrium

T_e (K)	N_e (cm^{-3})	
	5×10^8	10^{10}
10^5	$t_{ee} = 10^{-3}$	$t_{ee} = 5 \times 10^{-5}$
	$t_{pp} = 0.04$	$t_{pp} = 2 \times 10^{-3}$
10^6	$t_{ei} = 0.8$	$t_{ei} = 0.04$
	$t_{ee} = 0.03$	$t_{ee} = 0.02$
	$t_{pp} = 1.3$	$t_{pp} = 0.7$
	$t_{ei} = 26$	$t_{ei} = 1.3$

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

MPS
Max Planck Institute for Solar System Research

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

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

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

MPS
Max Planck Institute for Solar System Research

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

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

MPS
Max Planck Institute for Solar System Research

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

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

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

MPS
Max Planck Institute for Solar System Research

Collisional rate coefficients

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

$$\sigma_{ij}(E) = \frac{\pi a_0^2 I_{ij} \Omega_{ij}(E)}{\omega_j E}$$

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

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

$$C_{ij} = \frac{8.63 \times 10^{-6} \Omega_{ij}}{\omega_j T_e^{3/2}} \exp\left(-\frac{\Delta E_{ij}}{kT_e}\right)$$

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

MPS
Max Planck Institute for Solar System Research

Excitation (N_j/N_{ion})

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

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

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

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

MPS
Max Planck Institute for Solar System Research

Excitation (N_j/N_{ion})

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

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

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

MPS Max Planck Institut für Sonnensystemforschung

Abundance (N_{el}/N_H)

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

Element	Abundance	Ionization	Ionization Energy (eV)
H	12.00	1.00	13.60
He	10.95	1.00	24.46
C	8.43	1.00	11.42
N	8.43	1.00	14.53
O	8.69	1.00	13.81
Ne	8.11	1.00	21.51
Na	7.09	1.00	5.14
Mg	7.69	1.00	7.38
Si	7.51	1.00	8.45
S	7.13	1.00	10.36
Ar	6.63	1.00	15.76
K	5.64	1.00	4.19
Ca	6.44	1.00	9.00
Sc	5.45	1.00	6.56
Ti	6.25	1.00	7.92
V	5.26	1.00	6.50
Cr	6.06	1.00	7.86
Mn	5.87	1.00	7.43
Fe	8.11	1.00	7.90
Ni	7.92	1.00	7.53
Cu	5.98	1.00	7.73
Zn	6.78	1.00	9.39
Ga	5.79	1.00	7.46
Ge	5.80	1.00	7.62
As	5.81	1.00	9.78
Se	5.82	1.00	9.75
Br	5.83	1.00	10.44
Kr	5.84	1.00	13.99
Rb	5.85	1.00	4.18
Sr	5.86	1.00	5.49
Zr	5.87	1.00	9.14
Nb	5.88	1.00	9.13
Mo	5.89	1.00	7.39
Cd	5.90	1.00	8.98
Hg	5.91	1.00	10.44
Pb	5.92	1.00	8.41
Bi	5.93	1.00	8.98
Po	5.94	1.00	8.41
At	5.95	1.00	8.98
Tl	5.96	1.00	8.41
Pb	5.97	1.00	8.98
Bi	5.98	1.00	8.41
Po	5.99	1.00	8.98
At	6.00	1.00	8.41
Tl	6.01	1.00	8.98
Pb	6.02	1.00	8.41
Bi	6.03	1.00	8.98
Po	6.04	1.00	8.41
At	6.05	1.00	8.98
Tl	6.06	1.00	8.41
Pb	6.07	1.00	8.98
Bi	6.08	1.00	8.41
Po	6.09	1.00	8.98
At	6.10	1.00	8.41
Tl	6.11	1.00	8.98
Pb	6.12	1.00	8.41
Bi	6.13	1.00	8.98
Po	6.14	1.00	8.41
At	6.15	1.00	8.98
Tl	6.16	1.00	8.41
Pb	6.17	1.00	8.98
Bi	6.18	1.00	8.41
Po	6.19	1.00	8.98
At	6.20	1.00	8.41
Tl	6.21	1.00	8.98
Pb	6.22	1.00	8.41
Bi	6.23	1.00	8.98
Po	6.24	1.00	8.41
At	6.25	1.00	8.98
Tl	6.26	1.00	8.41
Pb	6.27	1.00	8.98
Bi	6.28	1.00	8.41
Po	6.29	1.00	8.98
At	6.30	1.00	8.41
Tl	6.31	1.00	8.98
Pb	6.32	1.00	8.41
Bi	6.33	1.00	8.98
Po	6.34	1.00	8.41
At	6.35	1.00	8.98
Tl	6.36	1.00	8.41
Pb	6.37	1.00	8.98
Bi	6.38	1.00	8.41
Po	6.39	1.00	8.98
At	6.40	1.00	8.41
Tl	6.41	1.00	8.98
Pb	6.42	1.00	8.41
Bi	6.43	1.00	8.98
Po	6.44	1.00	8.41
At	6.45	1.00	8.98
Tl	6.46	1.00	8.41
Pb	6.47	1.00	8.98
Bi	6.48	1.00	8.41
Po	6.49	1.00	8.98
At	6.50	1.00	8.41

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

MPS Max Planck Institut für Sonnensystemforschung

Two – level atom

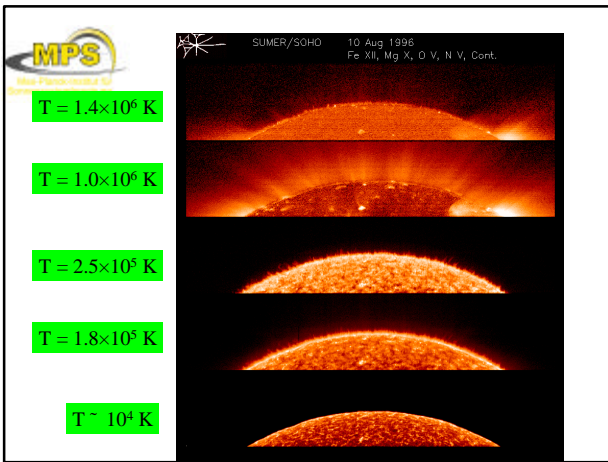
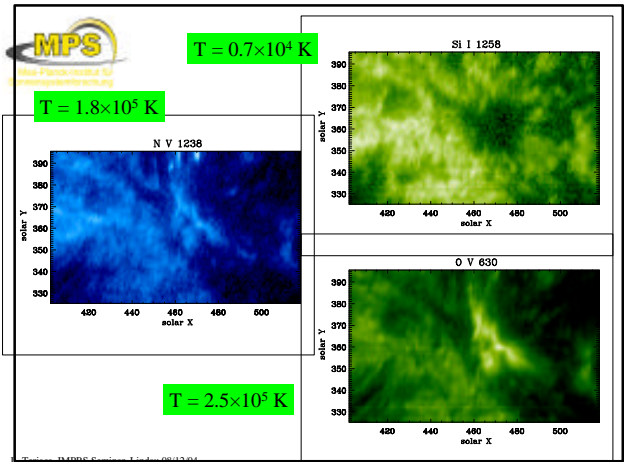
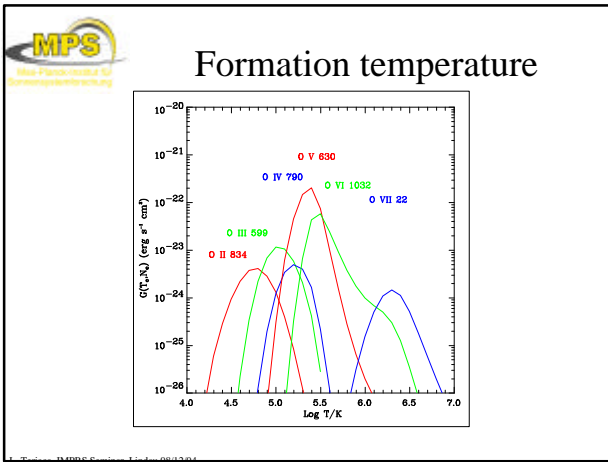
$N_e N_g C_{gu} = N_0 A_{0g}$

$G(T_e)_{gu} = \frac{hc N_{ion} N_{el} N_H N_e}{\lambda_{0g} N_{el} N_H N_e} C_{gu}$

$G(T_e)_{gu} = \frac{hc N_{ion} N_{el} N_H}{\lambda_{0g} N_{el} N_H N_e} \frac{8.63 \times 10^{-6} \Omega_{H\beta}}{\omega_l T_e^2} \exp\left(-\frac{\Delta E_{lj}}{kT_e}\right)$

$N_g = N_{ion}$

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



MPS Max Planck Institut für Sonnensystemforschung

Emission Measure

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

$\langle G(T_e)_{ji} \rangle = \frac{1}{T_{max}} \frac{\int_h G(T_e)_{ji} dh}{10^{(T_{max}+0.15)} - 10^{(T_{max}-0.15)}}$ (erg s⁻¹ cm³)

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

$EM_c = \int_h N_e^2 dh$ (cm⁻⁵)

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

MPS
Max Planck Institut für Sonnensystemforschung

Electron density

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

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

Density sensitive line radiance ratio

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

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

MPS
Max Planck Institut für Sonnensystemforschung

Coronal densities

Banerjee, Teriaca, Doyle, Wilhelm, 1998, A&A 339, 208

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

MPS
Max Planck Institut für Sonnensystemforschung

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:

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

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

MPS
Max Planck Institut für Sonnensystemforschung

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:

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

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

MPS
Max Planck Institut für Sonnensystemforschung

Line profile

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

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

However, we observe:

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

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

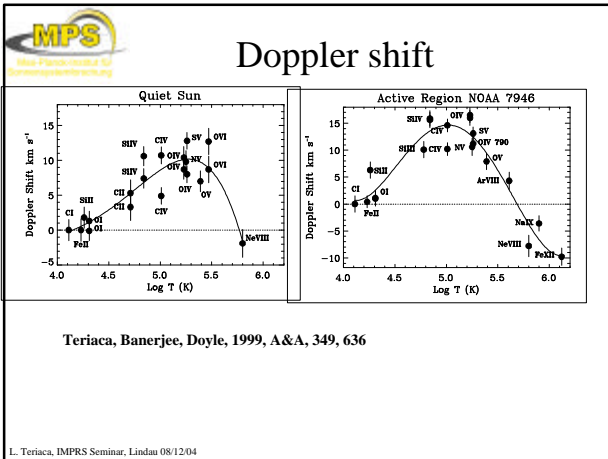
L. Teriaca, IMPRS Seminar, Lindau 08/12/04

MPS
Max Planck Institut für Sonnensystemforschung

Non-thermal velocity

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

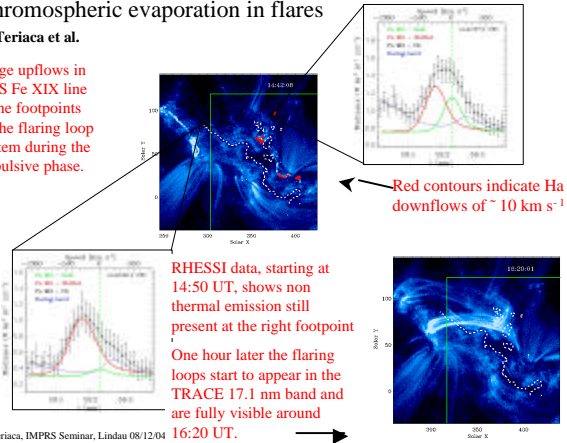
L. Teriaca, IMPRS Seminar, Lindau 08/12/04



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.



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.

