Radiation Diagnostics of the Solar Corona

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Analysis Techniques for Turbulent Plasmas
Calabria, Sept. 2004

What is RAL?

- Houses large facilities (ISIS, CLF) and departments including *Space Science & Technology*
- Solar Physics group has played a hardware role in most solar space missions since the 70's
- PI institute for CDS on SOHO satellite

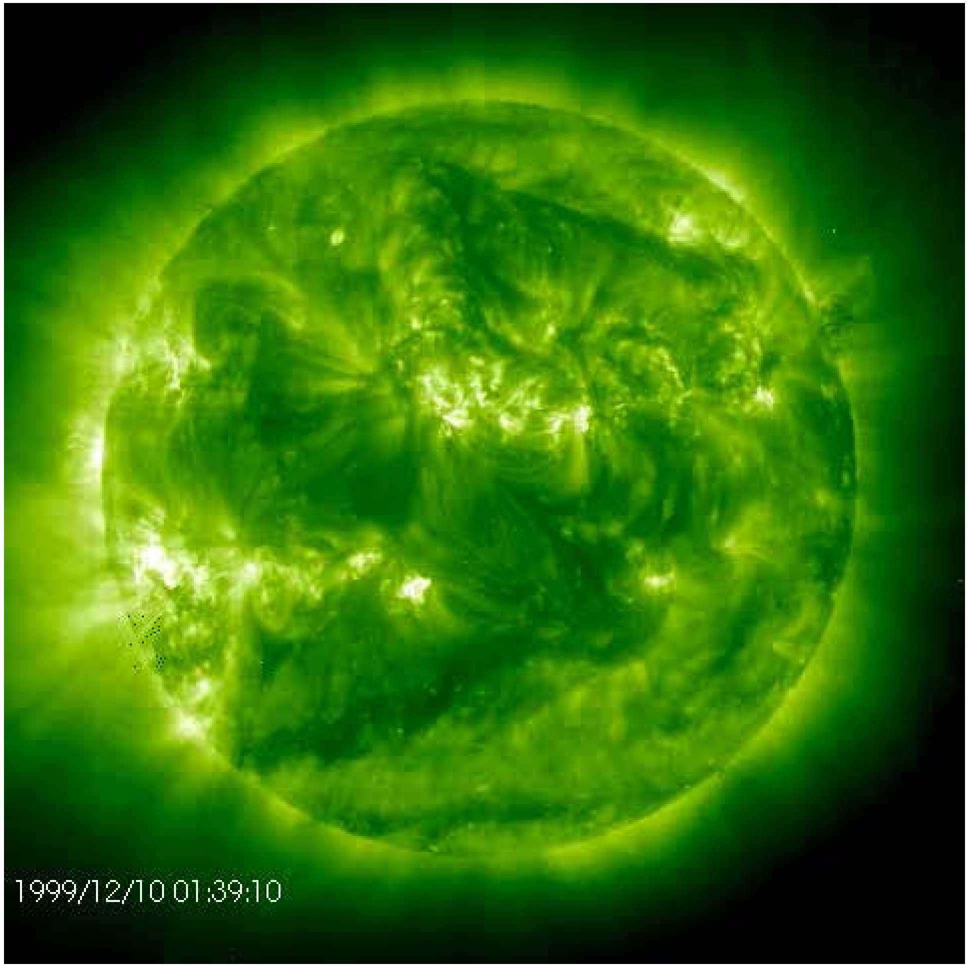
Overview

- Introduction to Sun
- Ultraviolet radiation
- Types of solar data
- Diagnostics: imaging instruments
- Diagnostics: spectroscopic instruments
- Future satellites

The Solar Corona

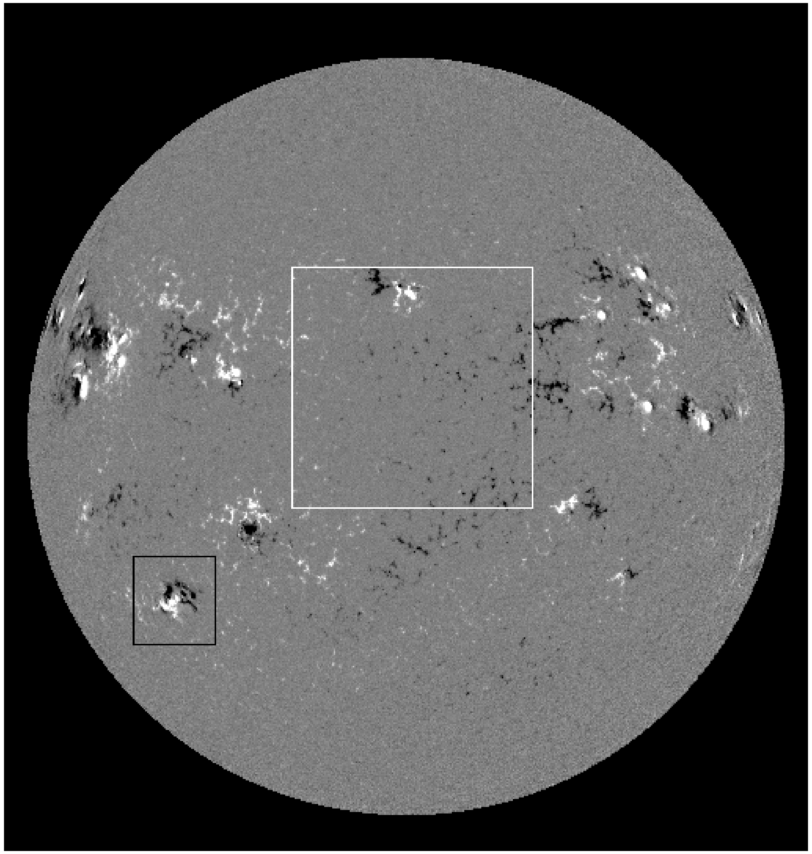
- Recent satellites have revolutionized our view of Sun's corona
  - Yohkoh, 1991-2001
  - SOHO, 1995-
  - TRACE, 1998-
  - RHESSI, 2002-

The Dynamic Corona

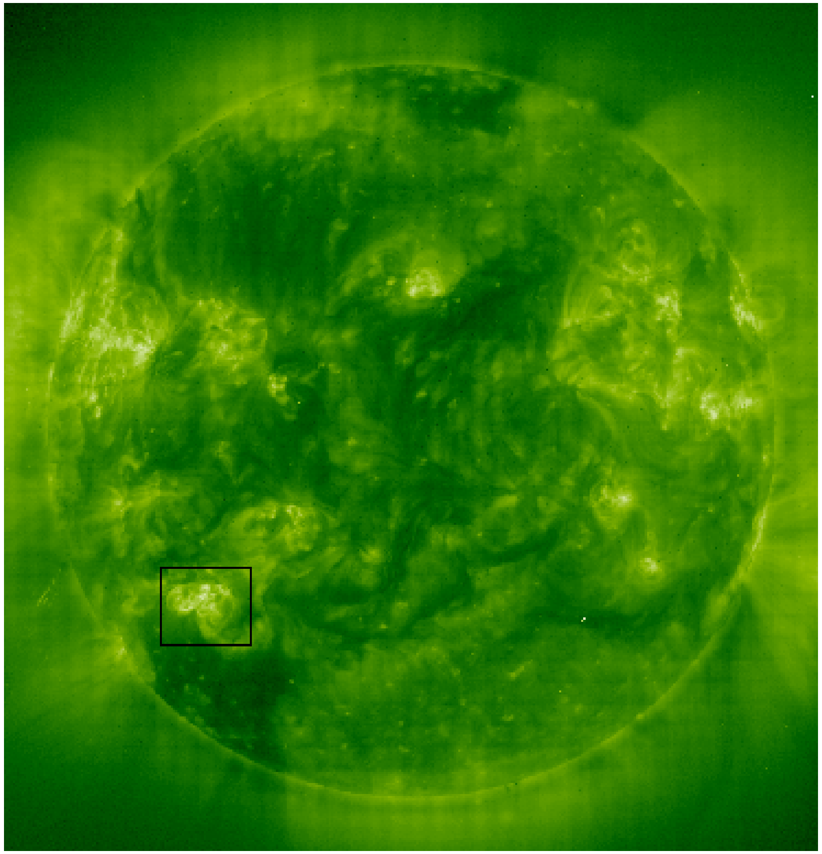


SOHO/EIT
195 filter
1.5 million K

Corona & Magnetic Fields

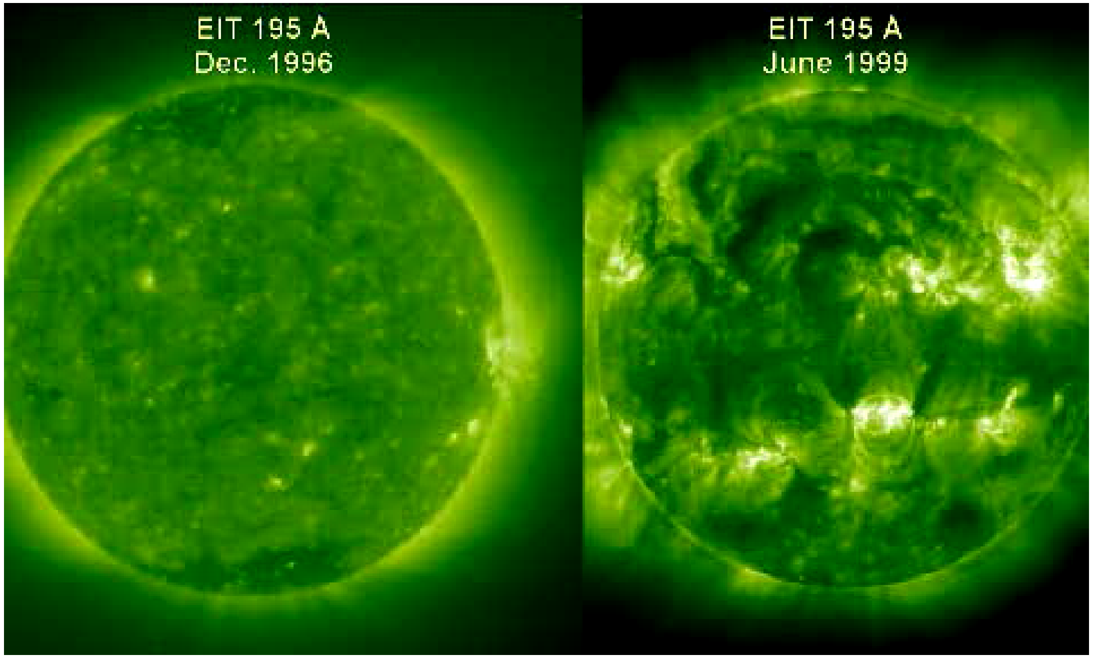


SOHO/MDI



SOHO/EIT

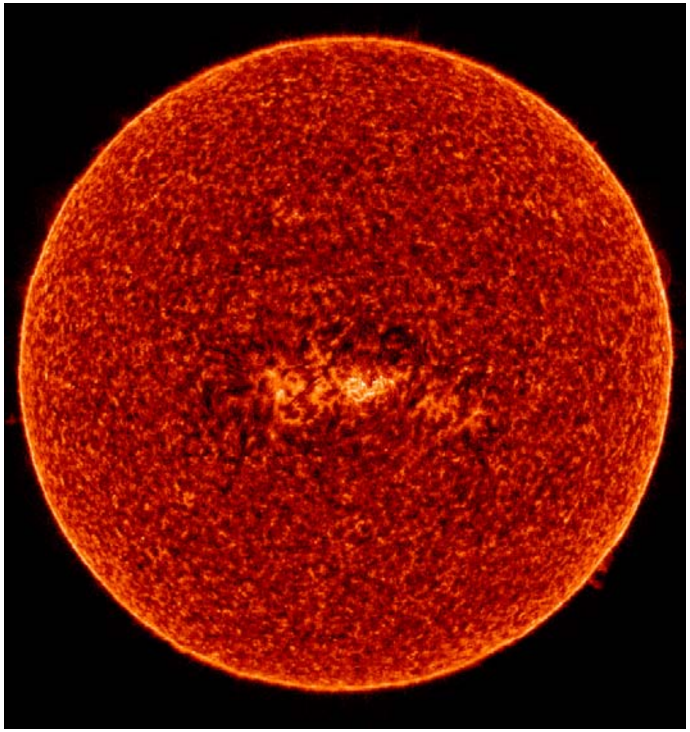
Solar Cycle



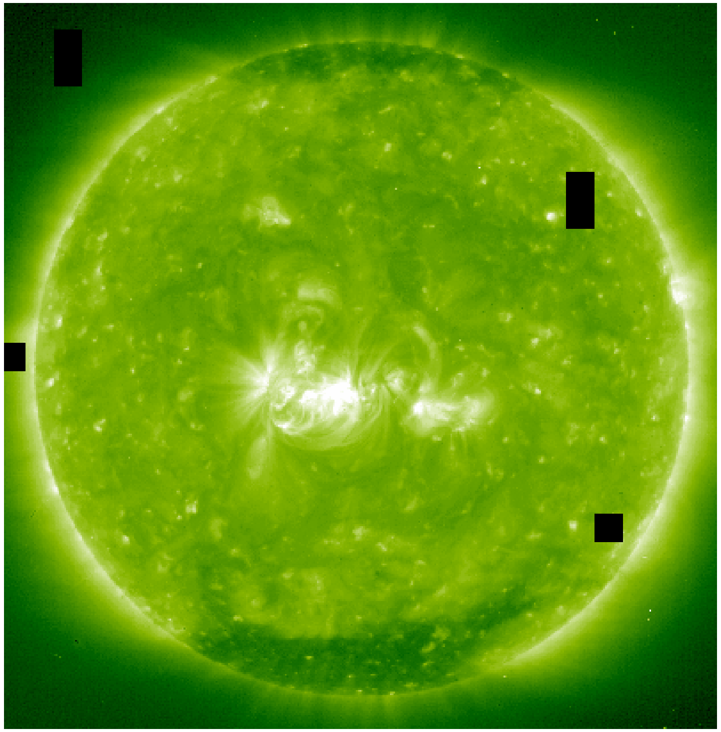
The Transition Region

- Small layer between chromosphere and corona (20,000 – 1 million K)

Transition region (SOHO/SUMER)



Corona (SOHO/EIT)

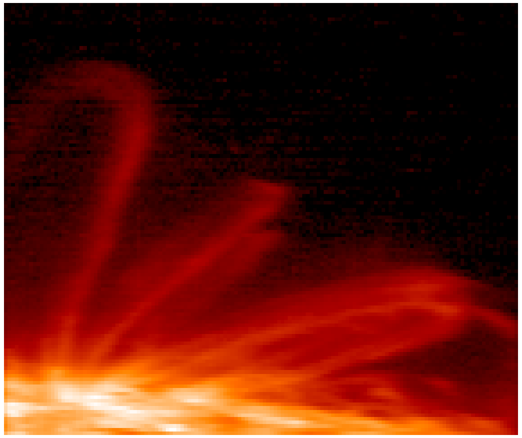


CCLRC Rutherford Appleton Laboratory

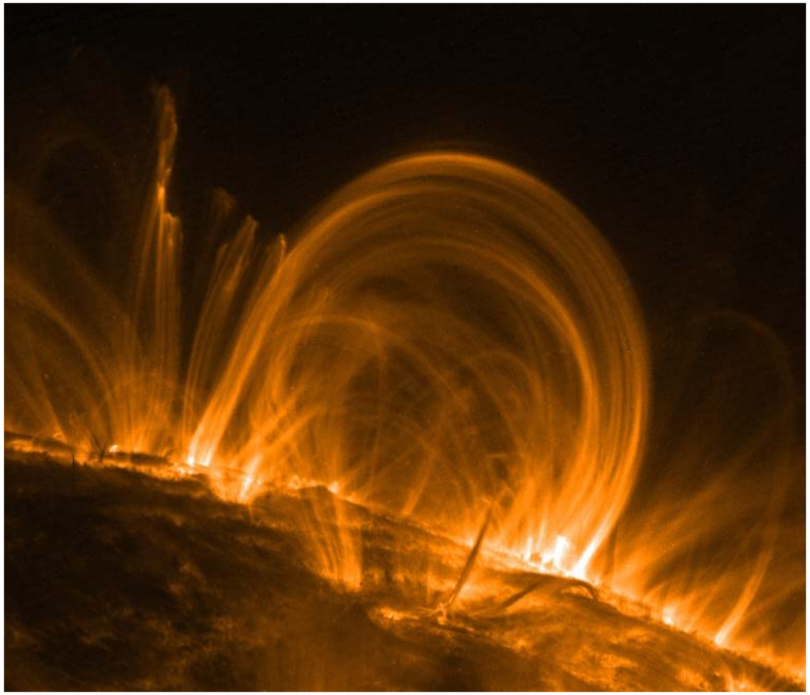
Coronal Loops

- The basic "building block" of the solar atmosphere

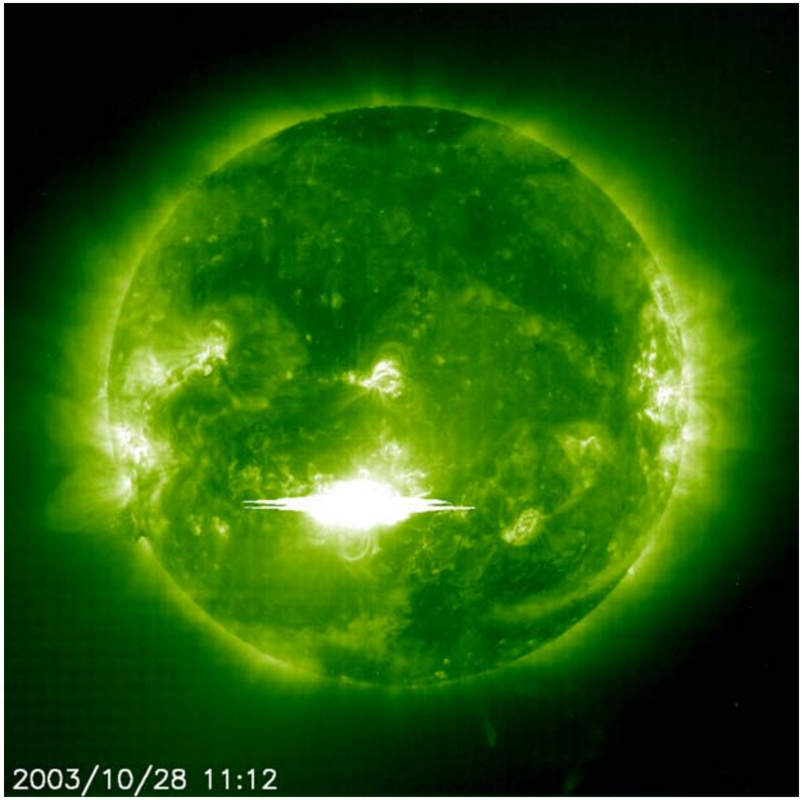
Transition region loops, 300,000 K (SOHO/CDS)

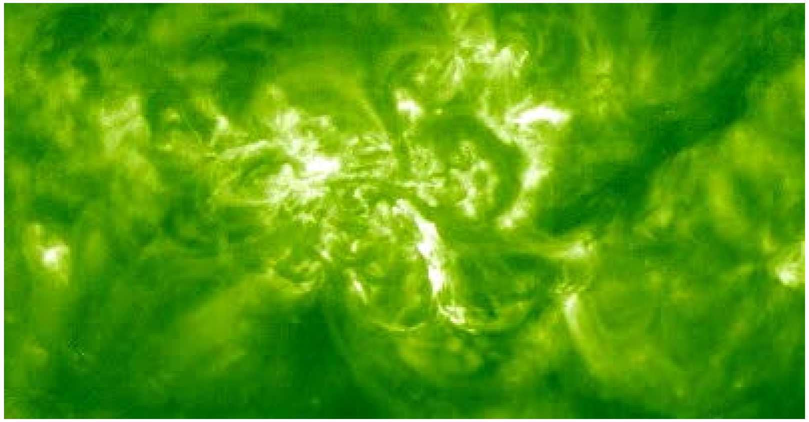


Coronal loops, 1 million K (TRACE)



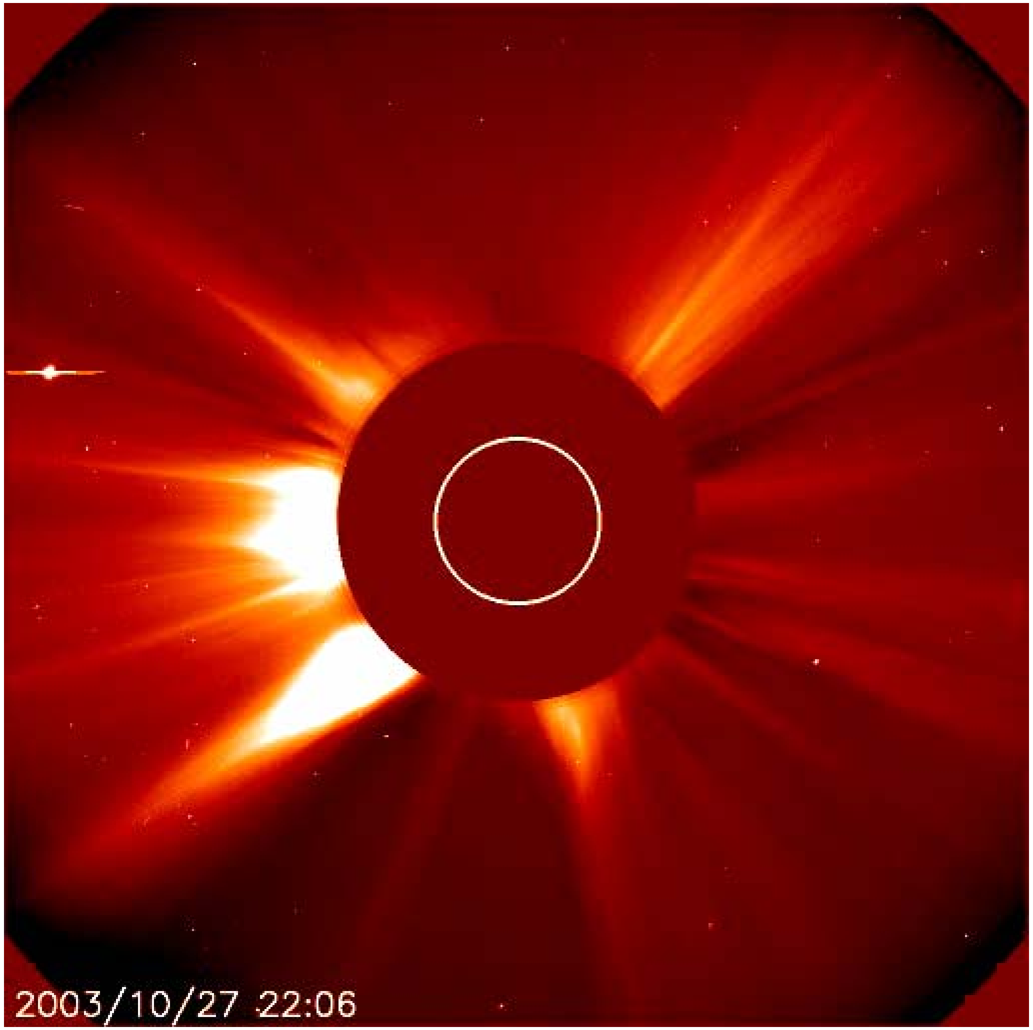
Flares





Large X17 flare, 28 Oct 2003
SOHO/EIT, 195 filter

Coronal Mass Ejection

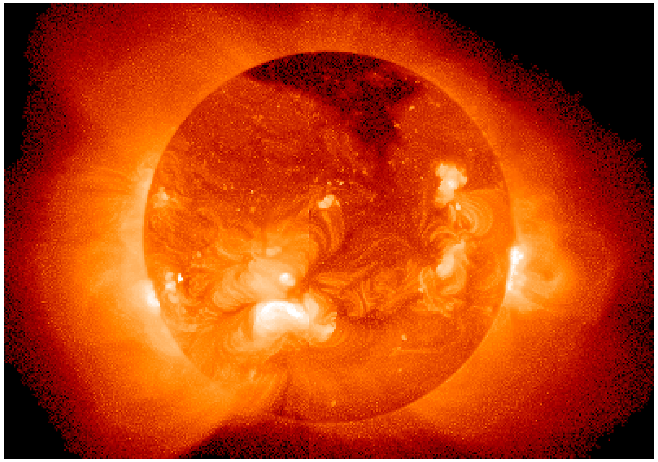


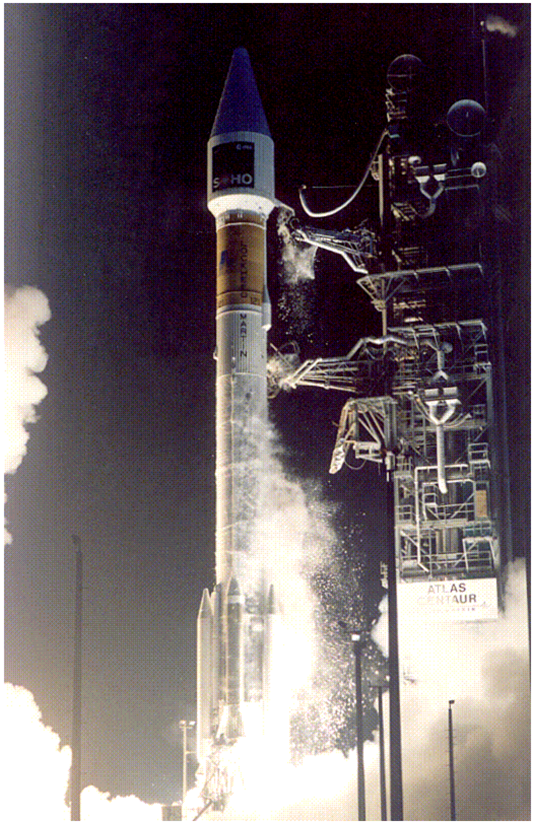
SOHO/LASCO
C2 coronagraph

Why go into Space?

- Perfect ‘seeing’ conditions
- Access to new wavelength regions
- Observe Sun continuously for long periods

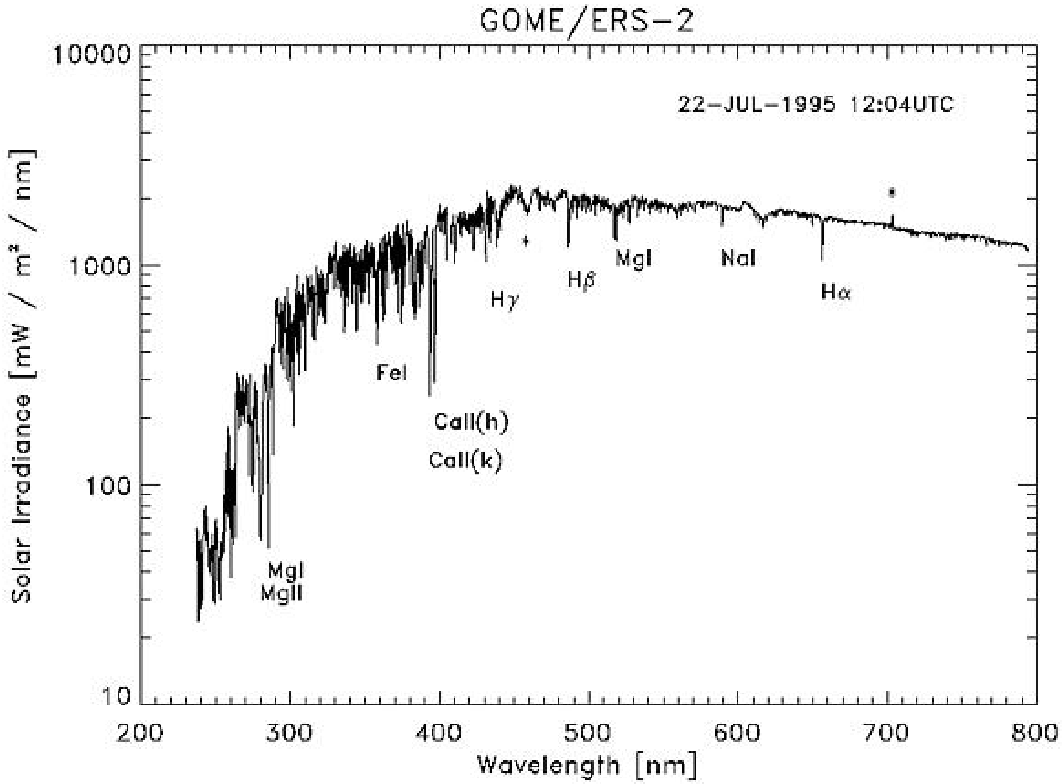
- See Sun from different angles
- Get closer to the Sun





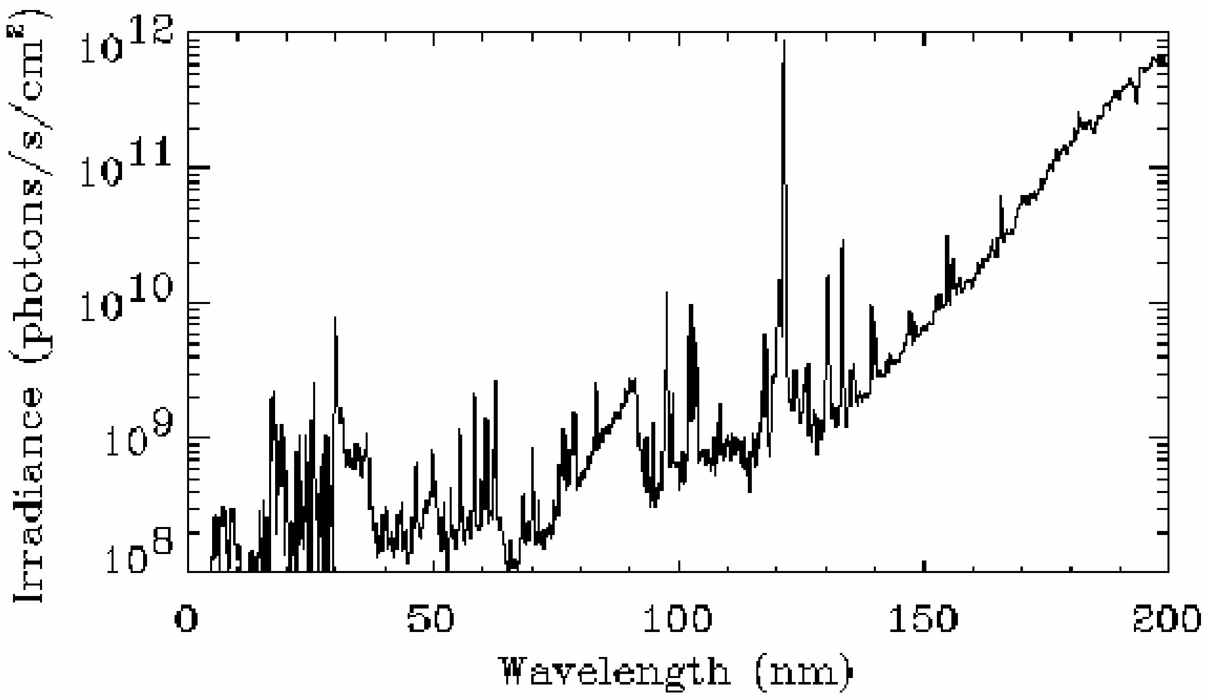
Solar Visible Spectrum

- Shows *continuum* (≈ blackbody 5800 K) and *absorption* lines



Solar Ultraviolet Spectrum

- In the UV, continuum emission disappears and spectrum dominated by *emission lines*
- The ‘quiet’ solar atmosphere emits most radiation at UV wavelengths



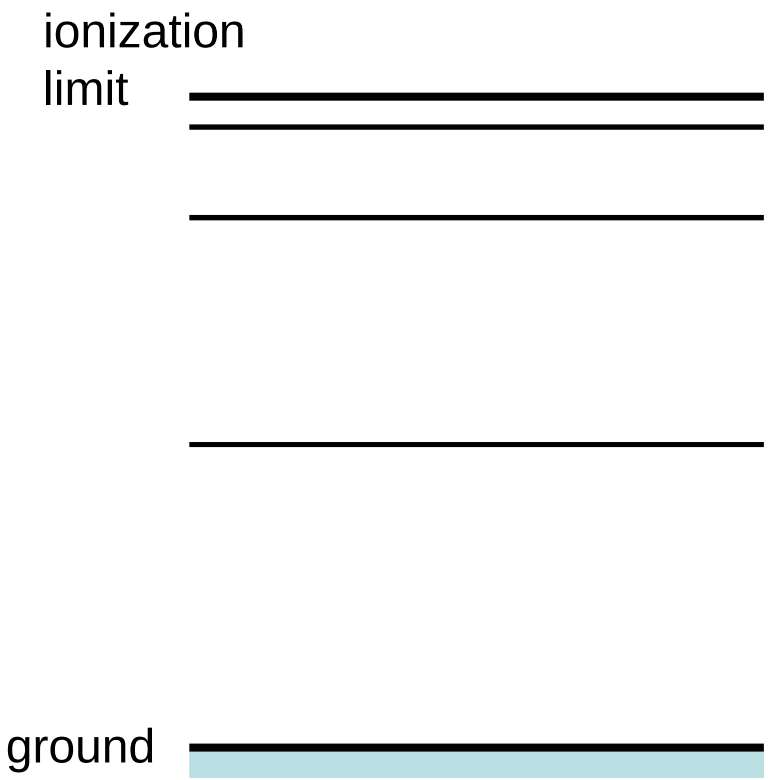
Ultraviolet Radiation

- Extends from 10 to 380 nm
- 99 % of UV that reaches Earth's surface is > 315 nm (UV-A)
- UV-B radiation (200-315 nm) is absorbed by oxygen molecules to produce ozone
- Variation of extreme UV radiation modifies size of the Earth's ionosphere

- UV radiation below 200 nm provides excellent diagnostic possibilities for the Sun's transition region and corona ($T > 20{,}000$ K)
  - requires satellite-based instrumentation

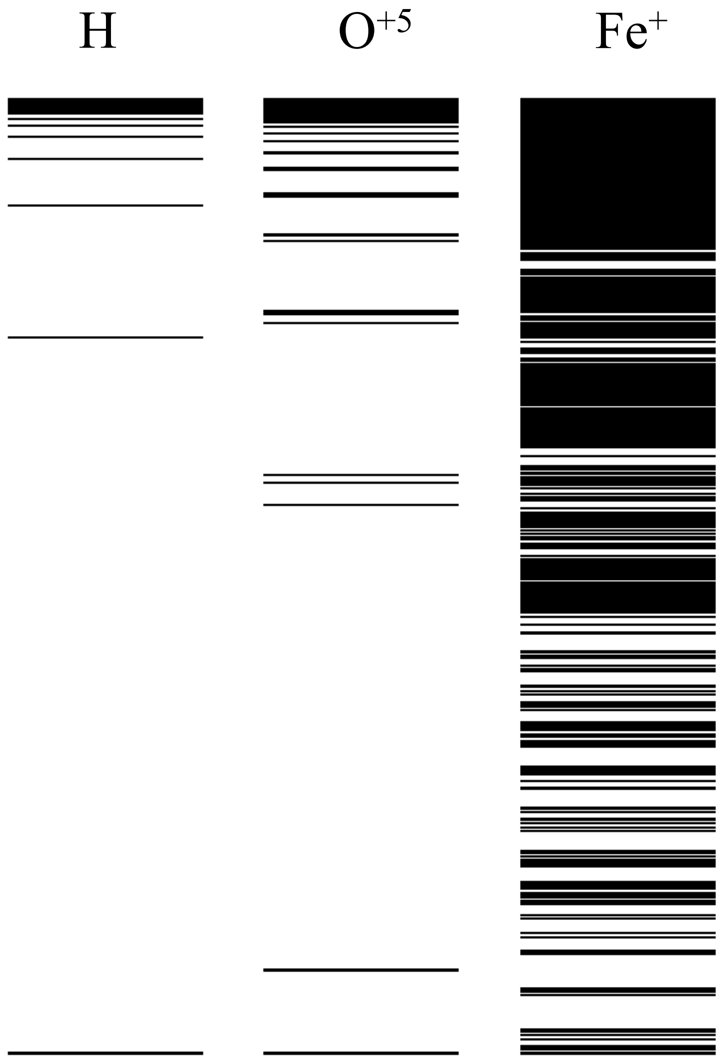
Atomic Structure Basics

- Quantum physics leads to electrons orbiting the nucleus lying in discrete orbitals
- Energy levels can be labelled by integers, E_i
- Lowest level is *ground level*
- Higher levels become squashed together, merging into ionization limit



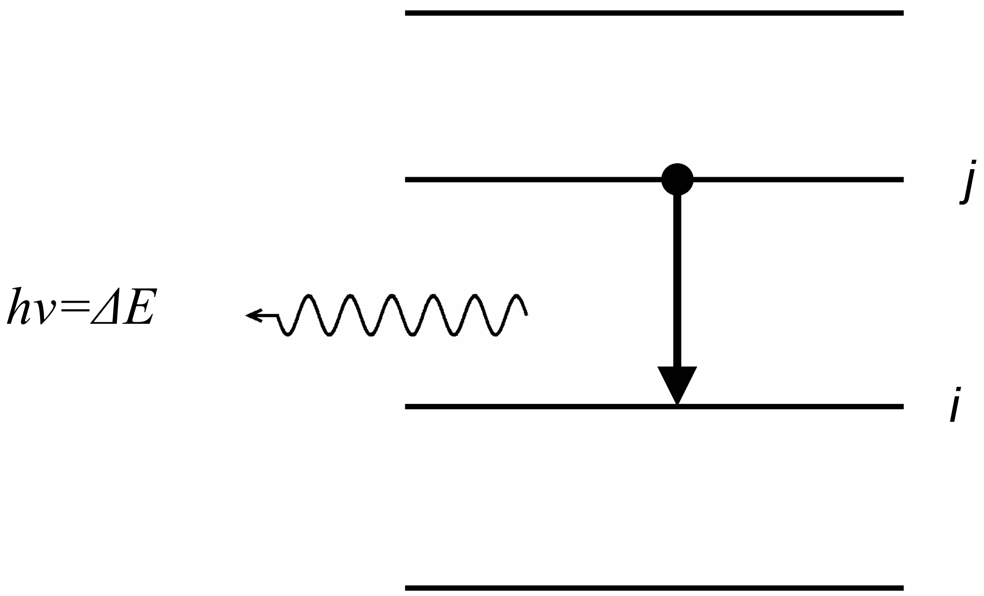
Level structure

- Hydrogen has simple structure (Rydberg level series)
- Li-like O^{+5} has 3 electrons, yet series remains simple
- Large ions such as Fe^{+} have very complex level structure

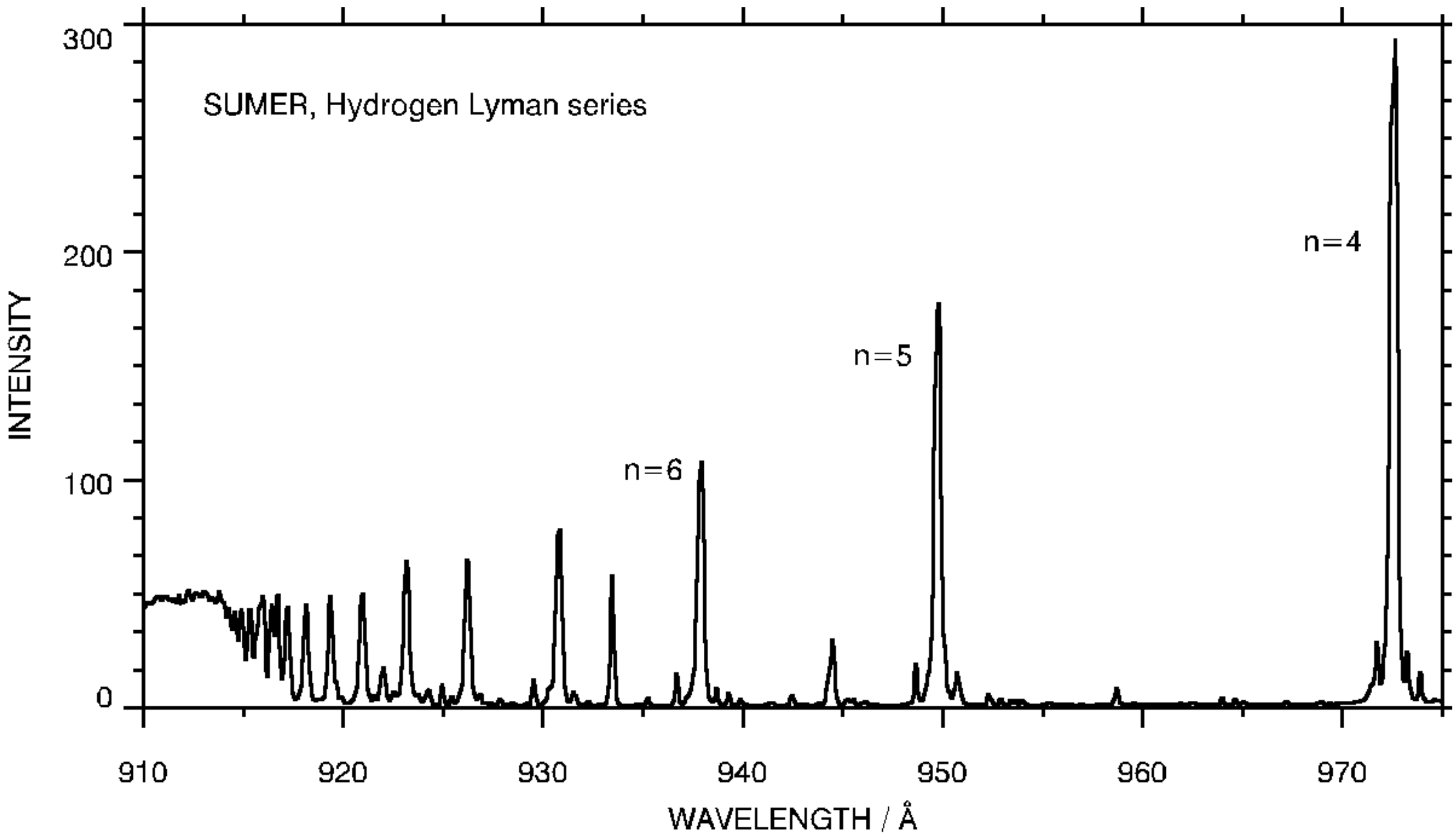


Atomic Transitions

- Emission lines arise from transitions between ion levels
- Photon energy = $E_j - E_i$



Hydrogen Spectrum



UV history

- UV instrumentation has been flown on many solar satellites
  - *Orbiting Solar Observatories* (OSO), 1962-78
  - *Skylab*, 1973-74
  - *Solar Maximum Mission* (*SMM*), 1980-89
  - *SOHO*, 1995-
  - *TRACE*, 1998-

UV History

- Also a key observation range for astronomy satellites
  - *Copernicus*, 1972-1981
  - *IUE*, 1978-1996
  - *Hubble Space Telescope*, 1991-
  - *Extreme Ultraviolet Explorer* (*EUVE*), 1992-2001
  - *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), 1999-

Remote Sensing of the Sun

- Information only derived from solar radiation
- 4 ‘dimensions’: t, x, y, λ
- Detectors are 2-dimensional, time obtained by repeated exposures
- Something has to go!
  - x, y or λ

Remote sensing of the Sun

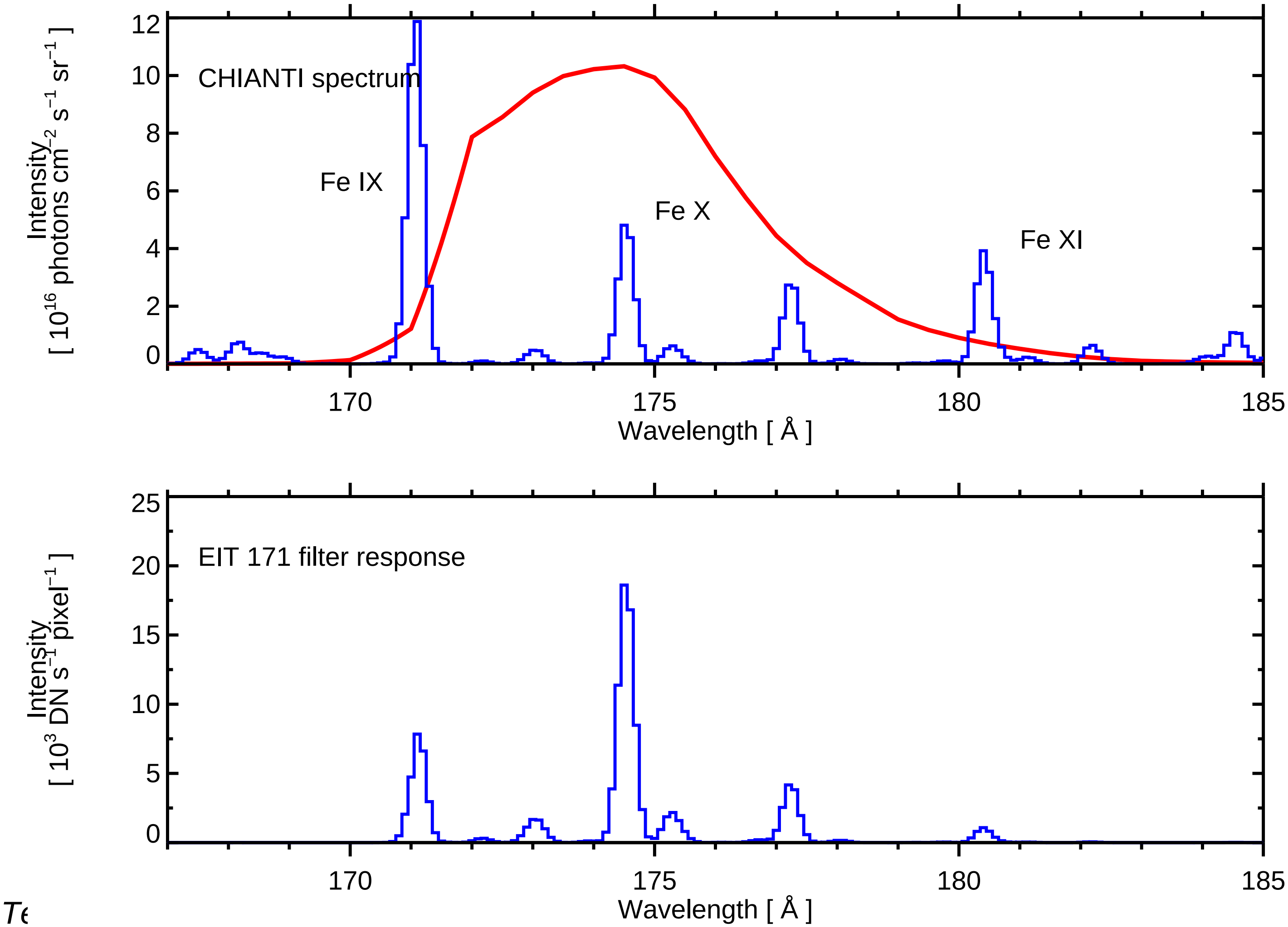
- Two approaches

- *Filtergrams*
  - Filter out a small portion of the spectrum, and take X-Y images

- *Spectroscopy*
  - Throw out one of the spatial dimensions to obtain wavelength resolution

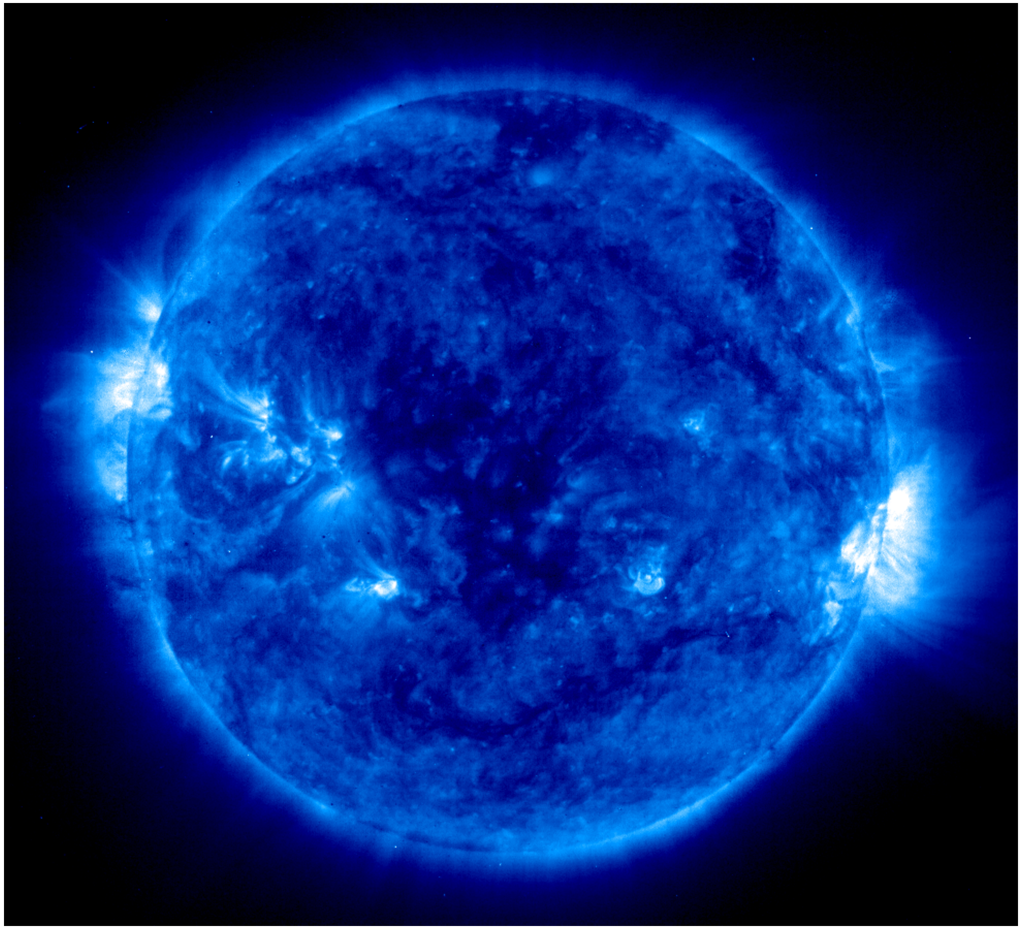
Filtergram Example: SOHO/EIT

- EIT Fe IX/X 173 filter lets through only radiation around 173 Å



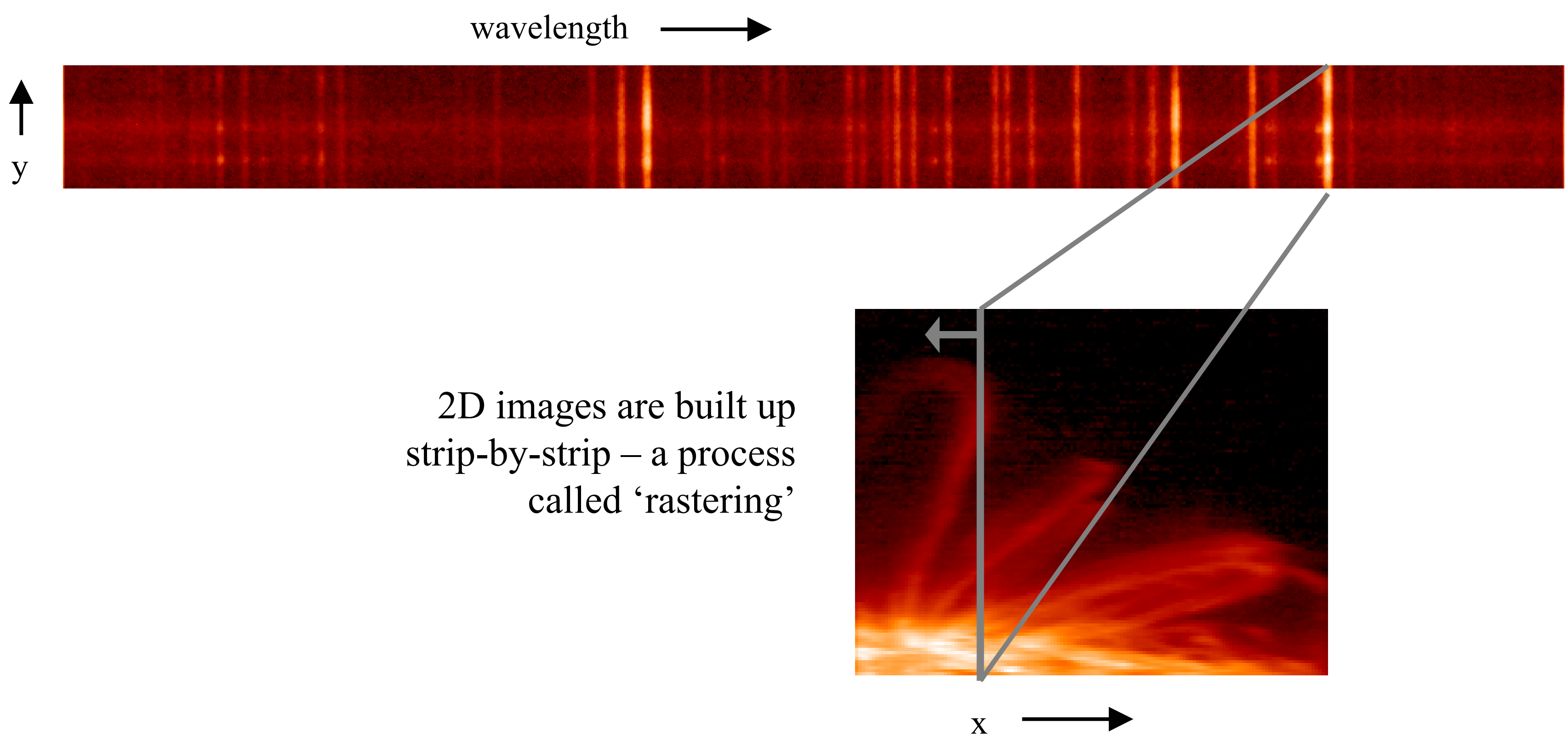
Filtergram Example: SOHO/EIT

- Radiation corresponds to ≈ 1 million K (EIT Fe IX/X 173 filter)



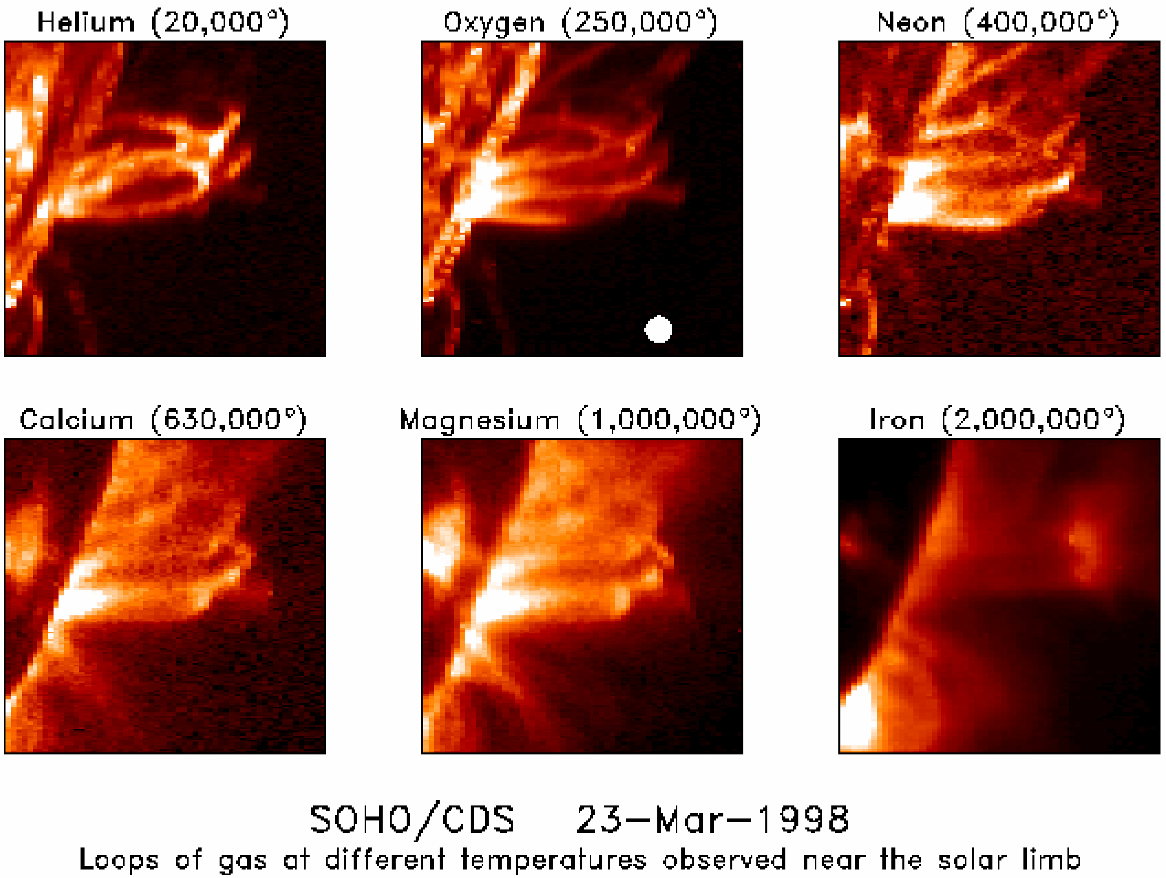
Spectroscopy Example: CDS

- 2D images are built up by repeated exposures at neighbouring positions



2D images are built up strip-by-strip – a process called ‘rastering’

CDS Images


Helium (20,000°)
Oxygen (250,000°)
Neon (400,000°)
Calcium (630,000°)
Magnesium (1,000,000°)
Iron (2,000,000°)
SOHO/CDS 23–Mar–1998
Loops of gas at different temperatures observed near the solar limb

Imaging vs. Spectroscopy

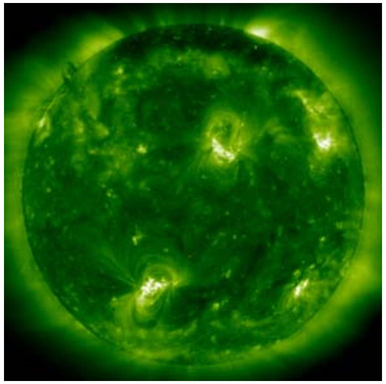
	Advantages	**Disadvantages**
Filtergrams (Imaging)	High time cadence; easy to analyse	Ambiguous interpretations
Spectroscopy	Detailed plasma information: temperature, density, emission measure, abundances, velocities	Rasters can be slow; difficult to analyse; useful lines often weak

Satellite Restrictions

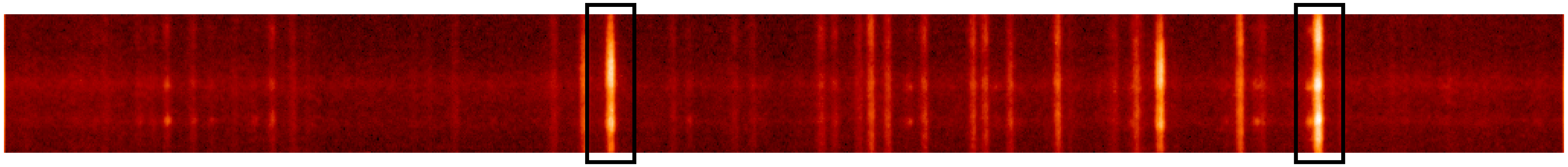
- Two basic features of satellites can lead to restrictions on data quality
- *Telemetry*
  - the rate at which data can be sent to Earth
- *Satellite orbit*

Telemetry

- E.g., SOHO has a standard telemetry rate of 40 kilobits/s divided amongst 12 scientific instruments
- For EIT this means typically 4 images/hour



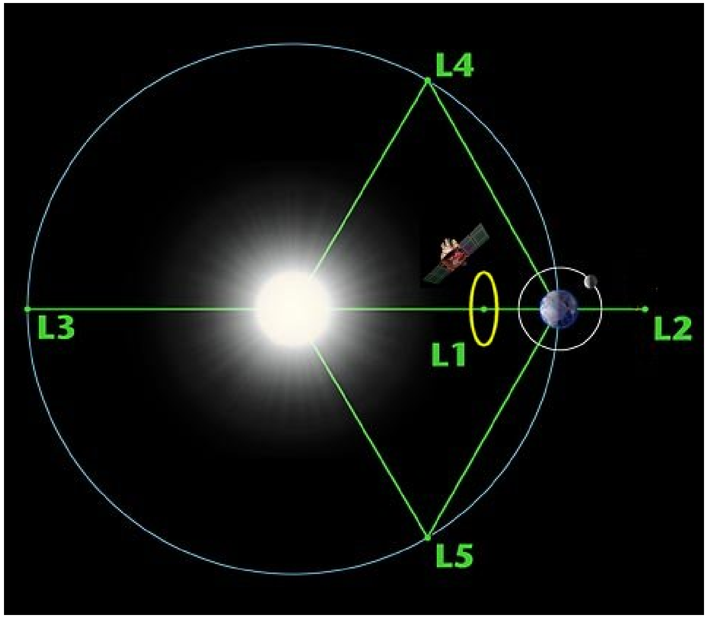
- A single CDS spectra takes 10 mins. A full raster takes 12 hours!
  - necessary to select spectral windows



Satellite Orbits

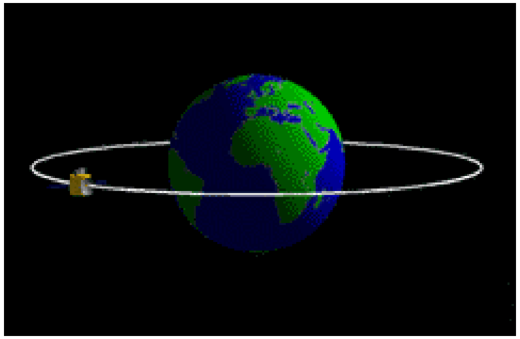
- A standard low Earth orbit means the Earth blocks view of the Sun
  - continuous tracking of features not possible
  - singular events such as flares can be missed

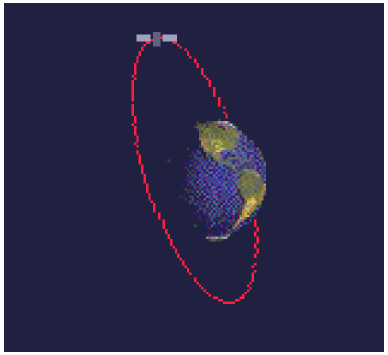
- Solution for SOHO was to fly to L1 Lagrange point
- Uninterrupted view of the Sun



Satellite Orbits

- Two useful Earth orbits for observing the Sun
- Geosynchronous
  - 5.5 Earth radii above surface; good visibility of Sun
  - Allows dedicated ground station
- Sun-synchronous
  - Polar orbit, allows 24 hour coverage of Sun
  - Passes over same point on surface each day





Diagnostics of the Corona

- Examples will be presented from imaging and spectroscopic instruments

- *Imaging*
  - TRACE
  - SOHO/EIT

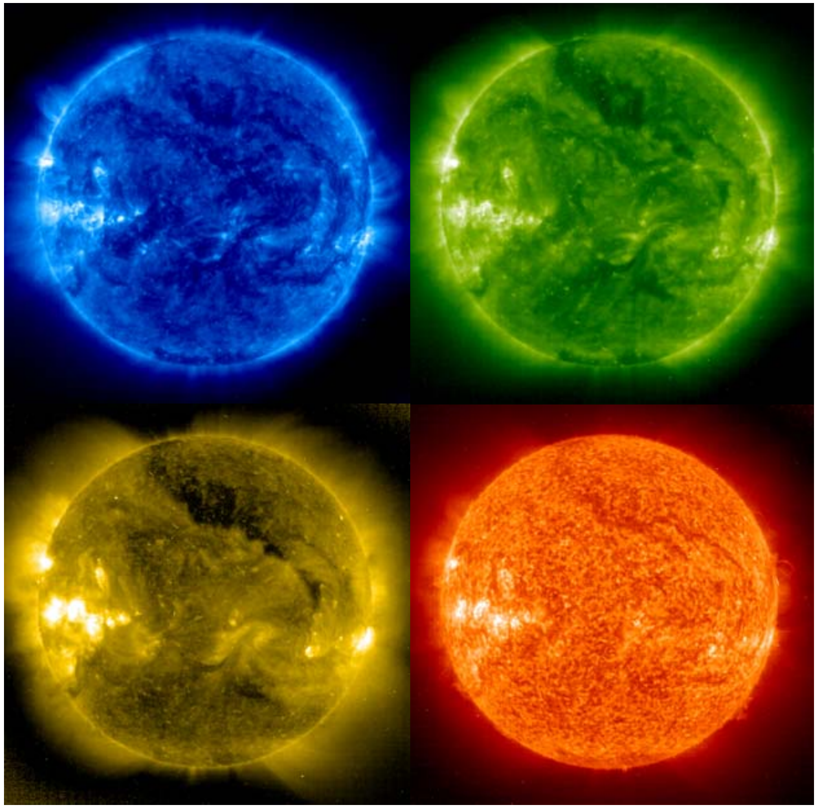
- *Spectroscopy*
  - CDS
  - SUMER
  - UVCS

Imaging Instruments

- Filters on EIT and TRACE provide a temperature slice through the solar atmosphere

Fe IX/X 171
1 million K

Fe XII 195
1.5 million K

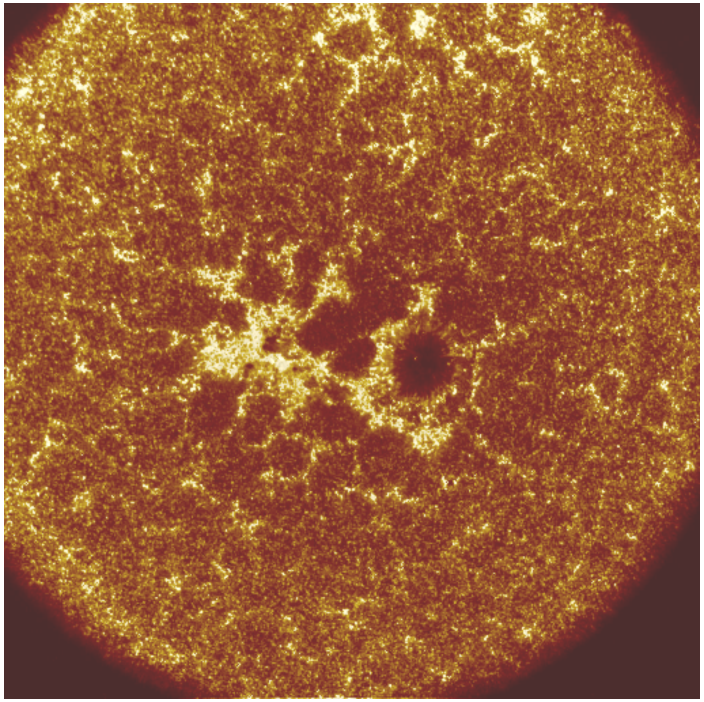


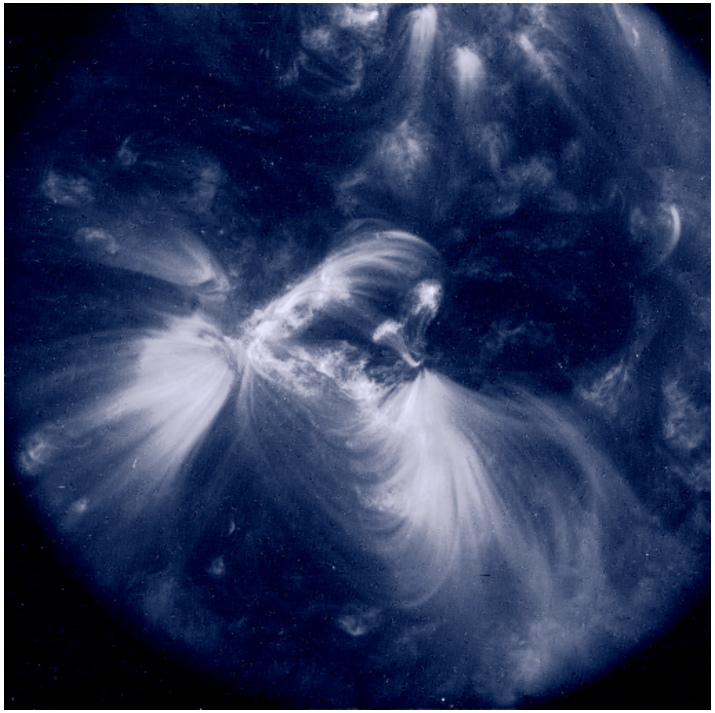
Fe XV 284
2 million K

He II 304
20,000 K

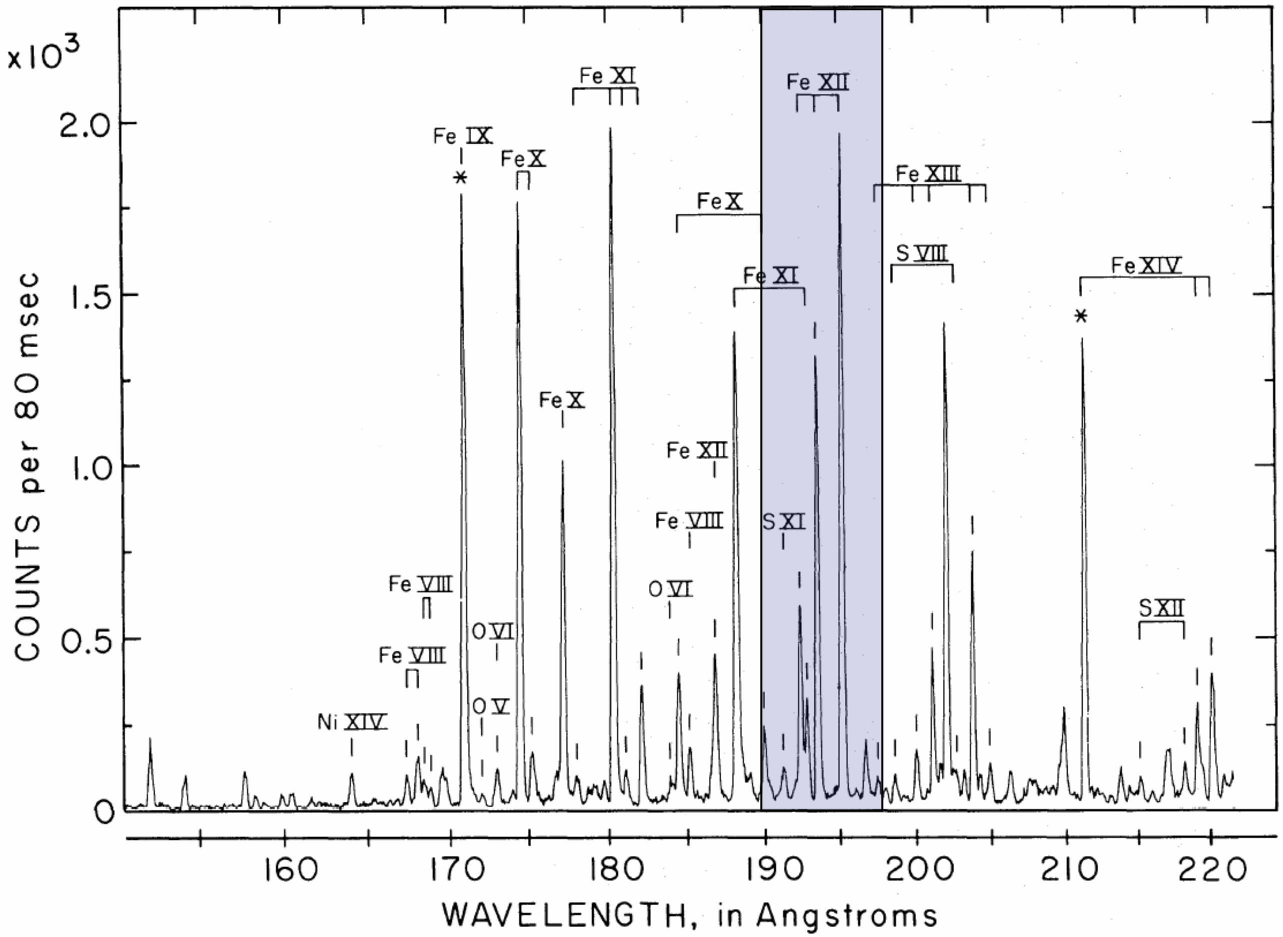
TRACE

- TRACE has 0.5 arcsec pixels compared to 2.5 arcsec for EIT
- Highest resolution images of corona
- Sees a sub-region of the Sun





UV spectrum

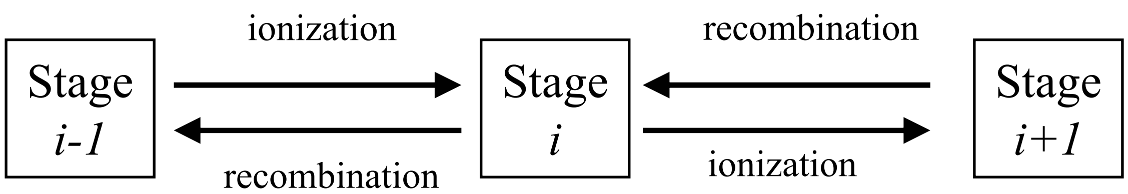


Malinovsky & Heroux (1973)

Ionization balance

- Collisions with electrons can remove or add electrons to an ion
- Remove electrons (*ionization*)
  - direct
  - excitation-autoionization
- Add electrons (*recombination*)
  - radiative
  - dielectronic
- In the corona only 1-electron recombination and ionization is relevant

Ionization Balance

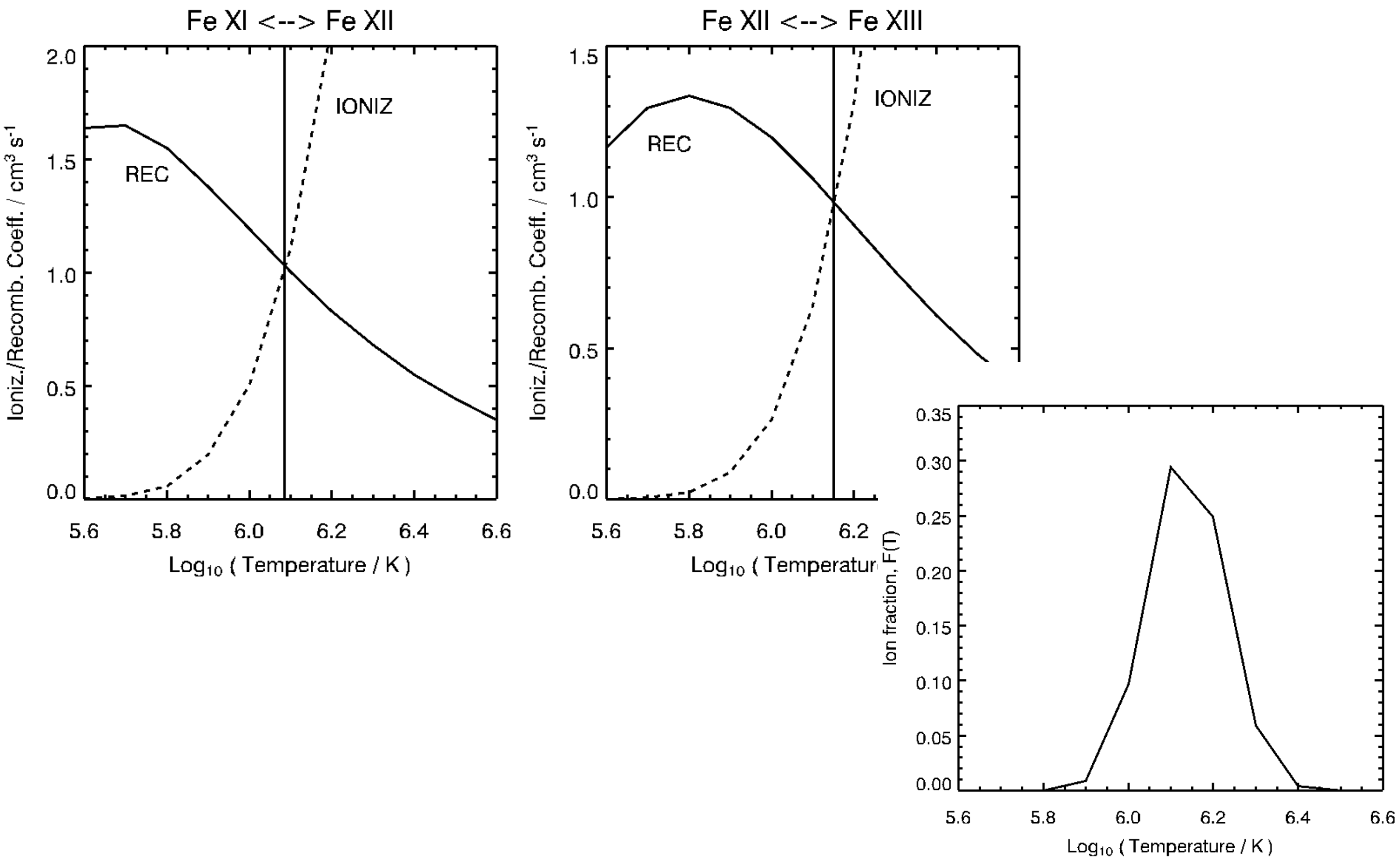


- Solving for all ionization stages, *i*, gives ionization fraction

$$F_i(T) = \frac{N^i}{\sum_j N^j}$$

- Tables of updated ionization fractions are published every few years
  - Mazzotta et al. (1998, A&A)
  - Arnaud & Raymond (1992, ApJS)
  - Arnaud & Rothenflug (1985, A&AS)

Fe XII Ion Fraction



Oscillating Coronal Loops

- Aschwanden et al. (2000) found, from TRACE data, a set of coronal loops that oscillated following a flare

- Coronal loop oscillation

Coronal Magnetic Field

- Very difficult to measure, yet key parameter in coronal heating models

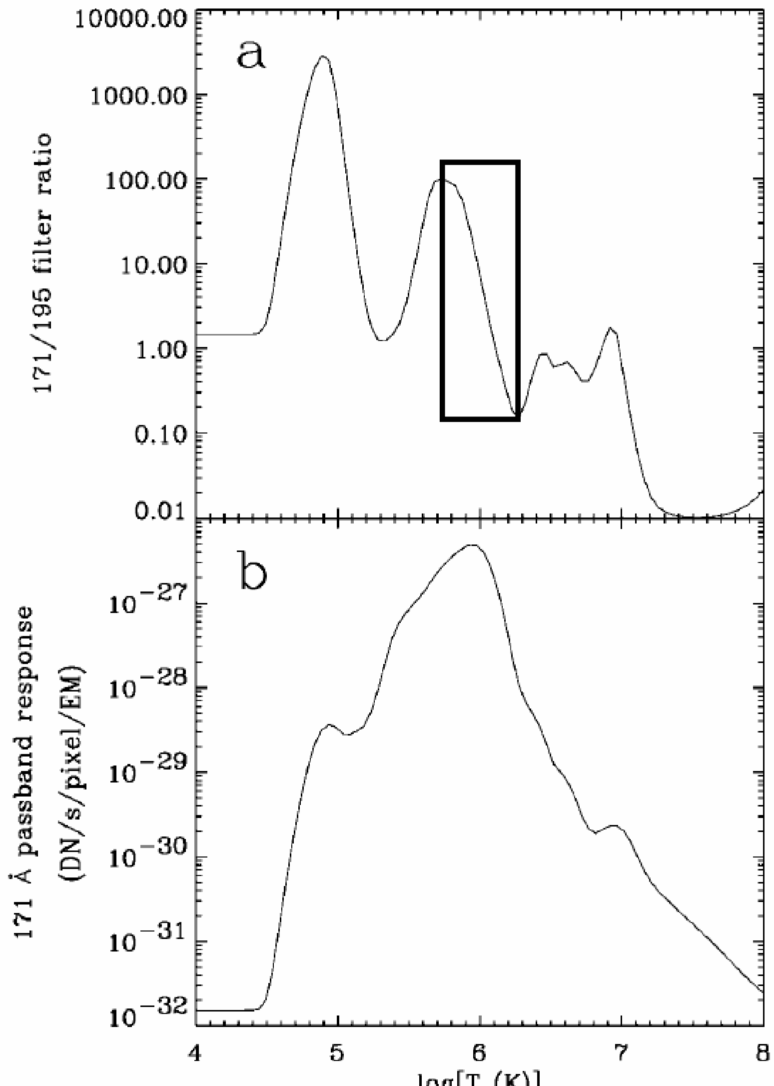
- Nakariakov & Ofman (2001, A&A) used oscillating loops to derive coronal magnetic field of 13 ± 9 Gauss
  – oscillation is a global standing kink wave
  – field strength related to oscillation period, loop length and loop density

$$B_0 = (4\pi\rho_0)^{1/2} C_{\mathrm{A}0} = \frac{\sqrt{2}\,\pi^{3/2} L}{P} \sqrt{\rho_0 (1 + \rho_{\mathrm{e}}/\rho_0)}.$$

Temperature Diagnostic

- Taking ratios of filter images leads to temperature estimates

- At coronal temperatures, TRACE 171/195 ratio directly related to temperature

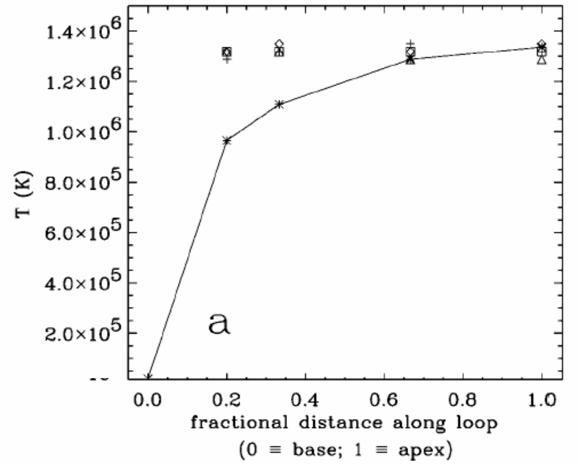


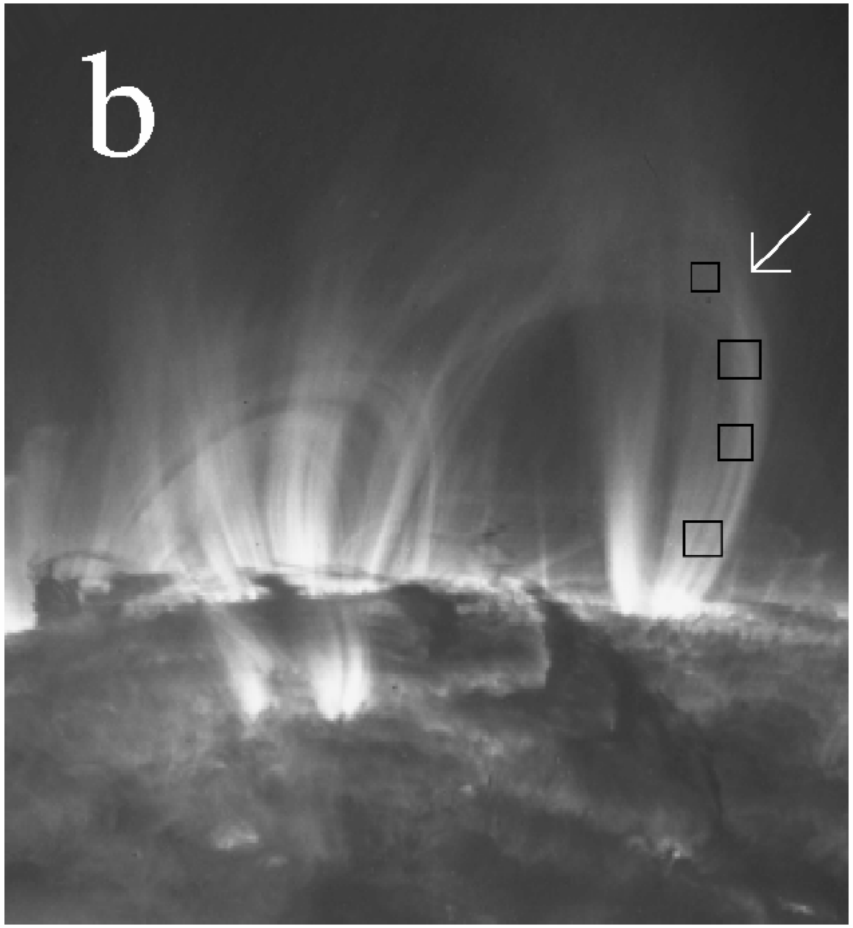
Lenz et al. (1999, ApJ)

Coronal Loop Heating

- Lenz et al. used the TRACE 195/171 ratio to show that coronal loops are close to isothermal
- Requires loop heating at footpoints in hydrostatic models (Aschwanden 2000, ApJ)

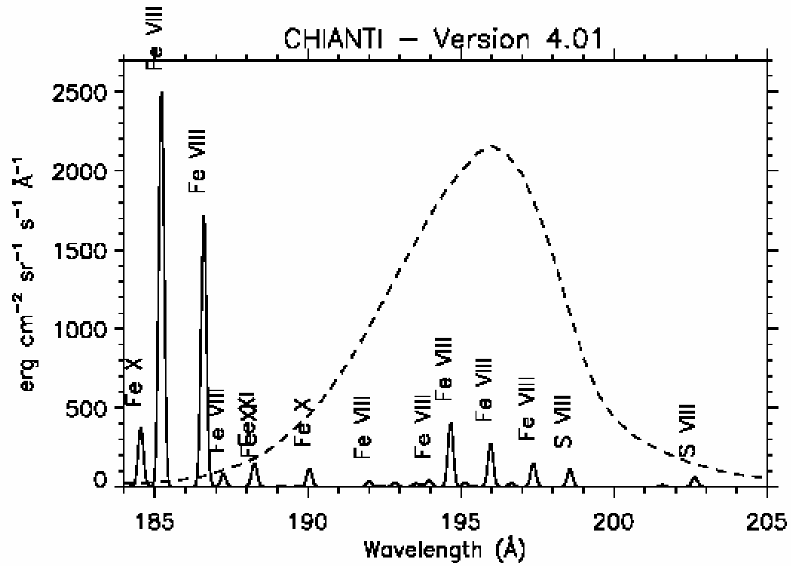
- Location of coronal heating determined!

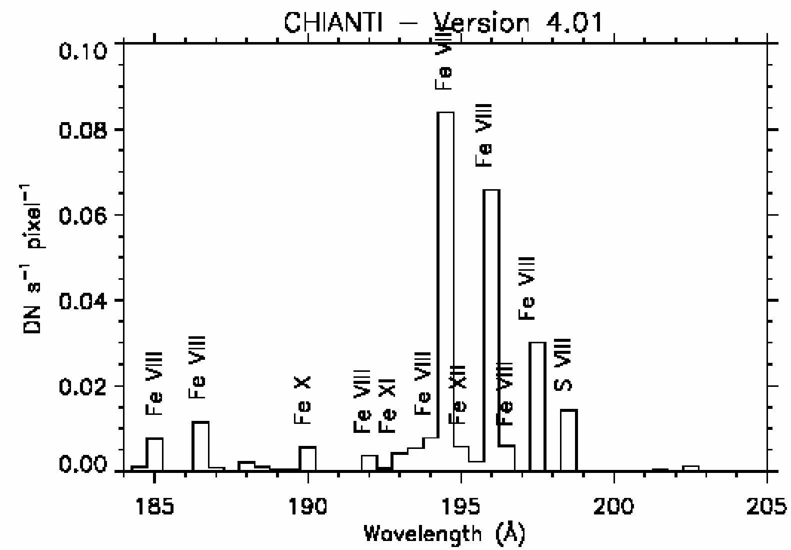




‘Purity’ of EIT & TRACE Bands

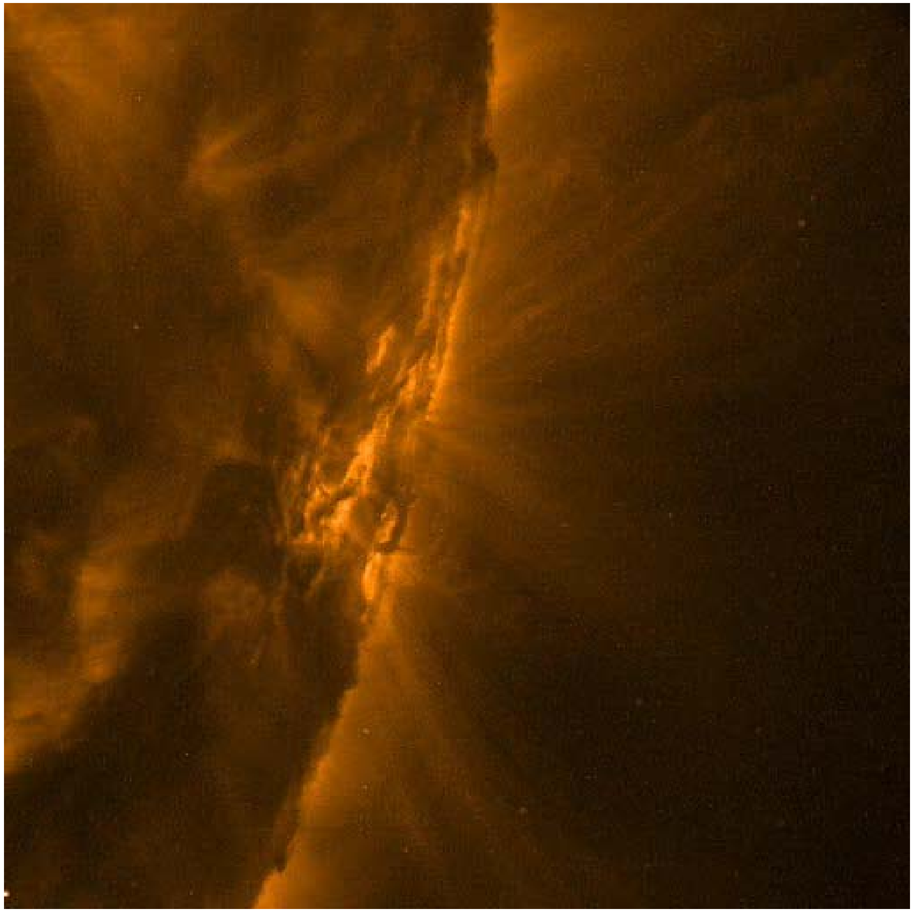
- In most cases the EIT and TRACE 195 band is dominated by Fe XII emission implying temperatures of ≈ 1.5 million K
- At temperatures < 1 million K, there is no Fe XII emission and Fe VIII dominates the 195 band (Del Zanna & Mason 2003)





TRACE: Fe XII & Fe XXIV

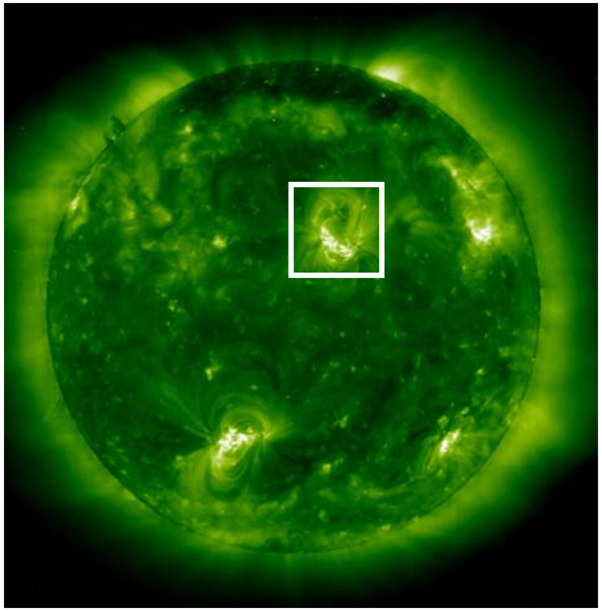
- At flare temperatures (~10 million K) a strong Fe XXIV appears in TRACE 195 band



SOHO Spectrometers

- Coronal Diagnostic Spectrometer (CDS)
- Solar Ultraviolet Measurements of Emitted Radiation (SUMER)
- Ultraviolet Coronagraph Spectrometer (UVCS)

- CDS and SUMER look on-disk and cover 150-1600 Å
- UVCS is an off-limb instrument covering



Spectroscopy

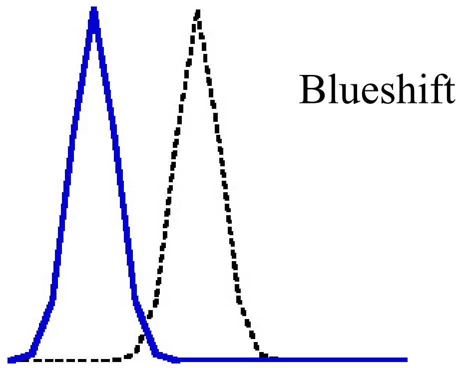
- Emission line diagnostics come in two types

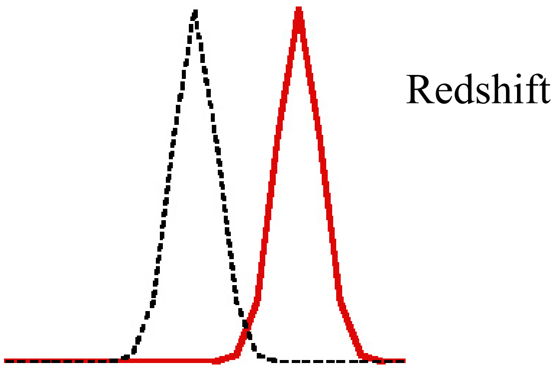
- *Study of shape and position of emission lines*
  - yields plasma velocity, broadening parameters

- *Study of emission line strengths*
  - yields temperatures, densities, abundances, emission measure
  - requires detailed atomic data

Doppler shifts

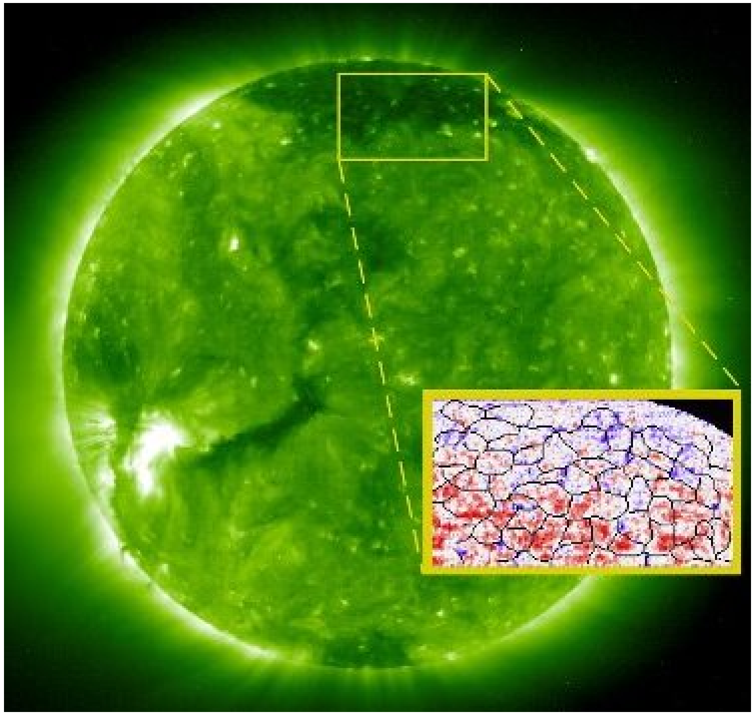
- Each emission line has a standard position (the *rest wavelength*)
- Shifts from this position imply motion of the plasma
  - *blueshifts*: towards the observer
  - *redshifts*: away from the observer





Acceleration of the Solar Wind

- Hassler et al. (1999, *Science*) measured velocity shifts in a coronal hole with SUMER
- Found small *blueshifts* implying upflow of plasma at velocities 5-20 km/s
- The source of the solar wind!



Line Width Diagnostics

- The width of emission lines can be written in velocity units as

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{c}$$

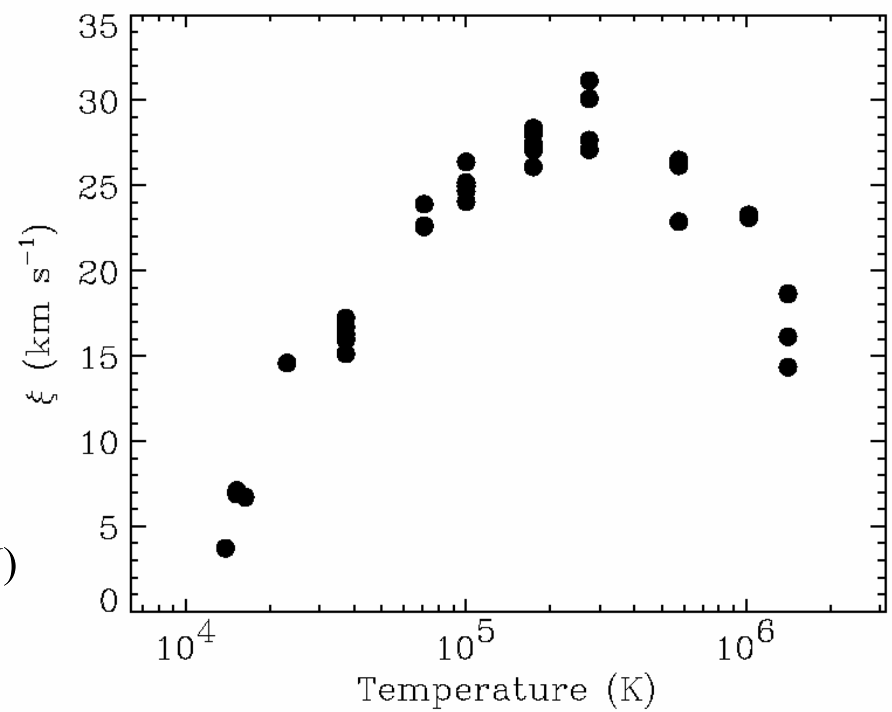
- The components of Δv are written as

$$\Delta v^2 = \Delta v_{\mathrm{I}}{}^2 + \frac{2kT}{M} + \xi^2$$

- where
  - Δv_{I} is the instrumental width
  - $2kT/M$ is the thermal width
  - ξ is the non-thermal velocity

Non-thermal Velocities

- Peak ξ^2 values are found at $\approx 3 \times 10^5$ K
- Several theories for excess broadening
  - supposition of flows in many different structures
  - Alfvén waves
  - turbulence
  - nanoflare heating



Chae et al. (1998, ApJ)

Explosive Events

- Emission line profiles are usually *Gaussian*
- Explosive events in the transition region (~ 10^5 K) show strongly non-Gaussian profiles

- Sudden release of energy related to magnetic field

Dere et al. 1989, Sol. Phys.

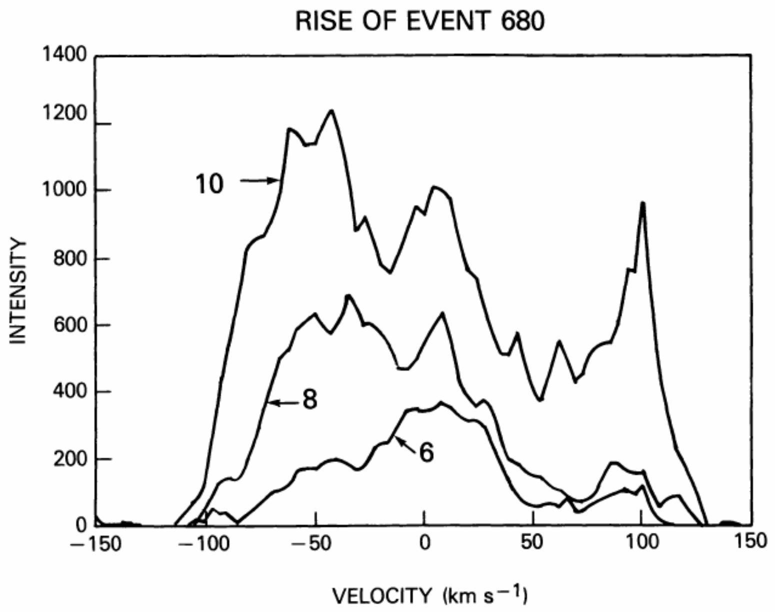
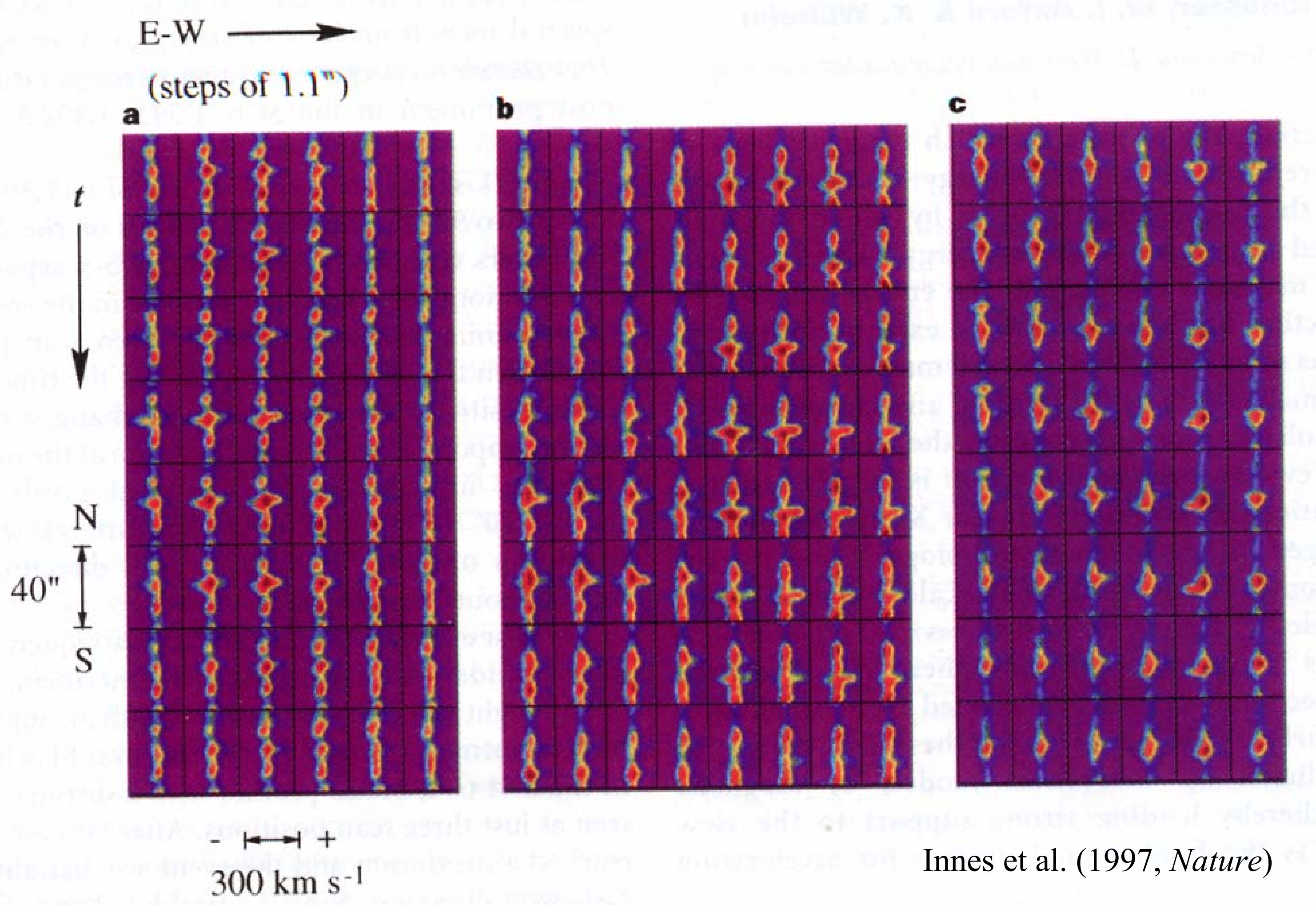


Fig. 2. C IV profiles during the rise phase of explosive event No. 1.

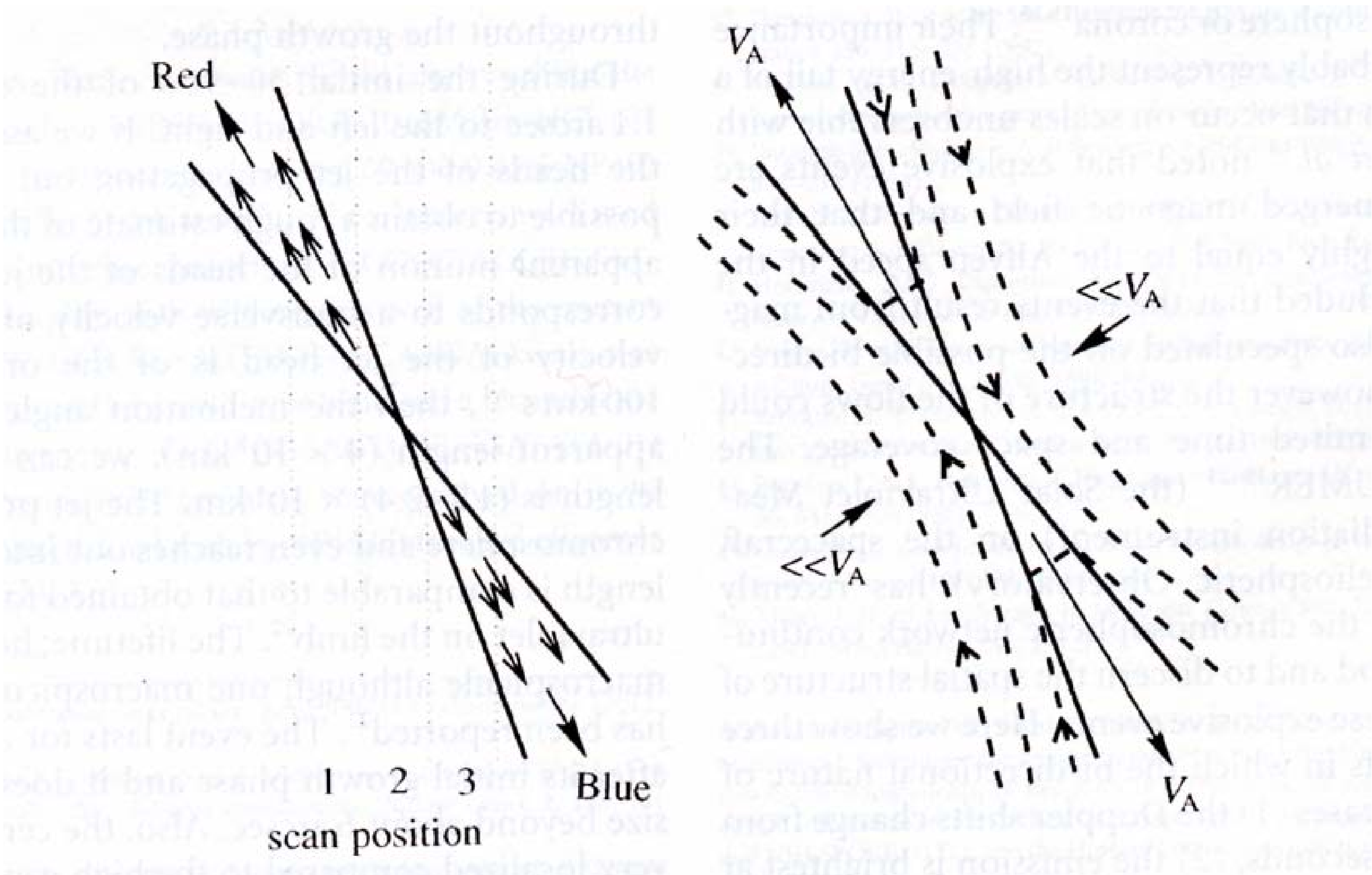
Bi-directional Jets



Innes et al. (1997, *Nature*)

Magnetic Reconnection

- Evidence of magnetic reconnection



Line Ratio Diagnostics

- To correctly model emission line strengths in corona and transition region requires detailed atomic data

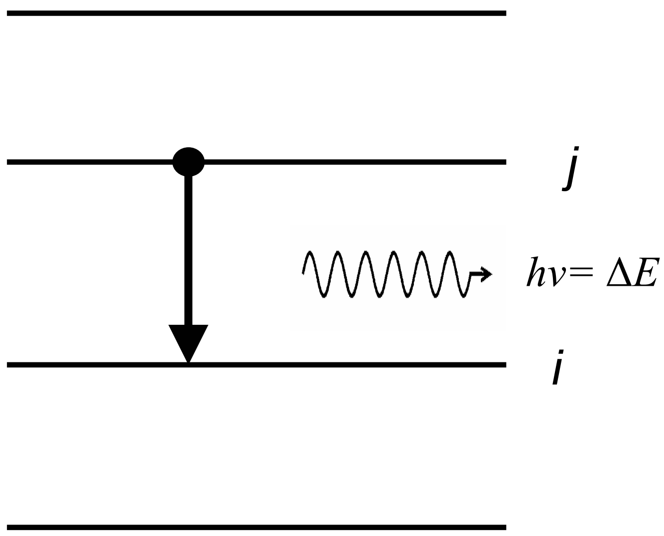
- Plasma is not in thermal equilibrium, so *level balance equations* have to be explicitly solved

Emissivities

- An emission line arises from the decay of some level j to a lower level i (often the ground level)
- Emitted photon has energy $\Delta E = E_j - E_i$

- Strength of emission line determined by *emissivity*

$$\varepsilon_{ij} = N_j A_{ji}$$



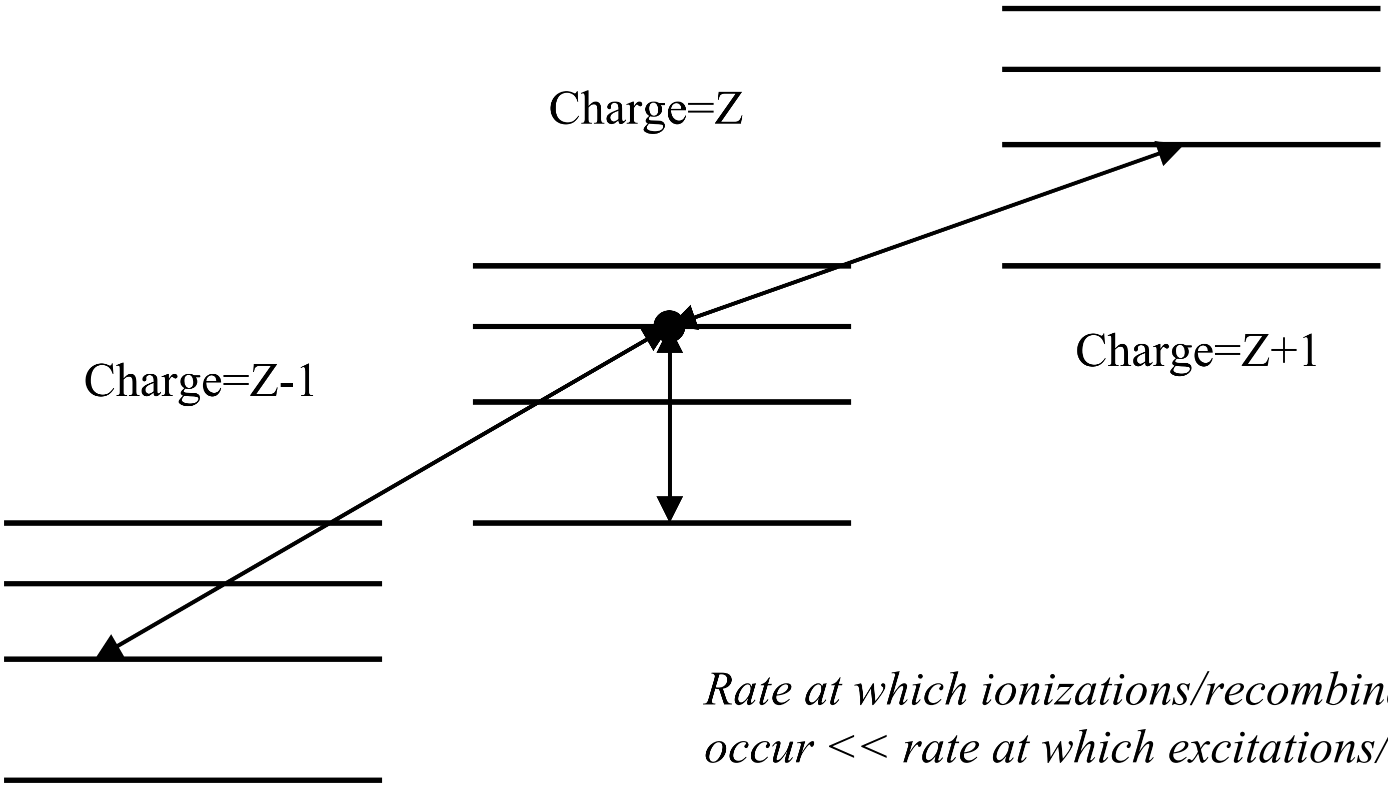
- N_j population of level j
- A_{ji} radiative decay rate
  - measure of strength of transition

Key Approximation 1

- Coronal plasma is *optically thin*
  - once emitted, photons are not re-absorbed
  - theoretical line *emissivity* directly related to observed line *intensity*

Key Approximation 2

- *Ionization* balance separate from *level* balance



Rate at which ionizations/recombinations occur << rate at which excitations/decays occur

Key Approximation 3

- Only relevant atomic processes for level balance are
  - electron excitation/de-excitation
  - spontaneous radiative decay

- Low coronal density (10^8-10^{10} cm^{-3}) means collisions are rare
- Typically it takes ~ 1 s to excite a level, but it decays in ~ 10^{-10} s
- Most ions have electrons in the lowest energy levels

Emissivity

- The emissivity of an emission line is given as

$$\varepsilon_{ij} = N_j A_{ji}$$

- this is re-written as (using Fe XII as example)

$$\varepsilon_{ij} = \frac{N_j}{N(\text{Fe XII})} \underbrace{\frac{N(\text{Fe XII})}{N(\text{Fe})}}_{F(T)} \underbrace{\frac{N(\text{Fe})}{N(\text{H})}}_{Ab(\text{Fe})} \underbrace{\frac{N(\text{H})}{N_e}}_{0.83} N_e A_{ji}$$

- $N_j/N(\text{Fe XII})$ is written as n_j, and $\sum n_j=1$

Level Balance Equations

$$n_i \sum_{j \neq i} \alpha_{ij} = \sum_{j \neq i} n_j \alpha_{ji}$$

(leaving level *i* = entering level *i*)

- α_{ij} is the rate at which transitions $i \rightarrow j$ occur
- solar corona: α contains (i) radiative decay rates, (ii) electron excitation/de-excitation rates

$$\alpha_{ij} = \begin{cases} N_e q_{ij} & (i < j) \\ A_{ij} + N_e q_{ij} & (i > j) \end{cases}$$

Level Balance Equations

- To solve the level balance equations requires atomic data

- *Radiative decay rates* (A-values)
- *Electron excitation rates* (q_{ij})

- Typical atomic models have 20-100 levels

- There are > 100 different ions relevant to corona, so a lot of atomic data required!

The CHIANTI database

- The first database to make atomic physics generally available to solar physicists
- Collaboration between UK, US and Italy
  - K. Dere, E. Landi, H. Mason, G. Del Zanna, M. Landini, P. Young
- First released in 1996, regularly updated
  - currently on version 4.2
- Provides all atomic data necessary for modelling coronal spectra
- Freely available

www.chianti.rl.ac.uk

CHIANTI data files

- CHIANTI is found within *Solarsoft*
  - $SSW/packages/chianti
- For each ion there is a directory, e.g., dbase/fe/fe_12
- 3 main files for each ion, e.g.,

fe_12.elvlc	Energy levels
fe_12.wgfa	Radiative decay rates
fe_12.splups	Upsilons

- Each is a text file, containing the atomic data for deriving level populations

CHIANTI energy file

- Example: Fe XII (filename: fe_12.elvlc)

1	1 3s2.3p3	4	0	S	1.5	4	0.0	0.000000
2	1 3s2.3p3	2	2	D	1.5	4	41555.0	0.378680
3	1 3s2.3p3	2	2	D	2.5	6	46088.0	0.419990
4	1 3s2.3p3	2	1	P	0.5	2	74108.0	0.675320
5	1 3s2.3p3	2	1	P	1.5	4	80515.0	0.733709
6	2 3s.3p4	4	1	P	2.5	6	274373.0	2.500278
7	2 3s.3p4	4	1	P	1.5	4	284005.0	2.588051
8	2 3s.3p4	4	1	P	0.5	2	288307.0	2.627254
9	2 3s.3p4	2	2	D	1.5	4	339761.0	3.096140
10	2 3s.3p4	2	2	D	2.5	6	341703.0	3.113836
11	2 3s.3p4	2	1	P	1.5	4	389668.0	3.550930
12	2 3s.3p4	2	1	P	0.5	2	394352.0	3.593610
13	2 3s.3p4	2	0	S	0.5	2	410401.0	3.739860

Index Configuration Level ID $\underbrace{\text{cm}^{-1} \quad \text{Ryd}}_{\text{Energy}}$

Level 1 (ground level): $3s^2\ 3p^3\ {}^4S_{3/2}$

CCLRC Rutherford Appleton Laboratory

CHIANTI A-value file

- Radiative decay rates (*A*-values) are stored in ".wgfa" file:

gf-value

1	2	2406.454	0.000e+00	4.419e+01
1	3	2169.766	0.000e+00	1.826e+00
2	3	22060.486	0.000e+00	8.945e-01
1	4	1349.384	0.000e+00	1.665e+02
2	4	3071.919	0.000e+00	6.427e+01
3	4	3568.886	0.000e+00	2.971e-01
1	5	1242.007	0.000e+00	3.214e+02
2	5	2566.740	0.000e+00	1.799e+02
3	5	2904.702	0.000e+00	7.277e+01
4	5	15607.958	0.000e+00	2.069e+00
1	6	364.468	1.898e-01	1.589e+09
2	6	429.521	1.919e-03	1.156e+07
3	6	438.050	3.681e-03	2.132e+07
4	6	499.339	0.000e+00	2.081e-01

Wavelength

A-value

Transition (i-j)

CHIANTI collision file

- CHIANTI contains spline fits to the Upsilons (Maxwellian-averaged collision strengths) in the “.splups” files:

Transition type

```
 26 12  1  2  2 0.000E+00 3.788E-01 2.500E+01 4.581E-01 2.861E-01 1.696E-01 8.726E-02 7.547E-02
 26 12  1  3  2 0.000E+00 4.199E-01 2.000E+01 4.995E-01 4.026E-01 2.521E-01 1.802E-01 1.390E-01
 26 12  1  4  2 0.000E+00 6.753E-01 2.000E+01 2.895E-01 1.788E-01 8.463E-02 4.564E-02 3.432E-02
 26 12  1  5  2 0.000E+00 7.337E-01 1.500E+01 6.869E-01 4.070E-01 2.078E-01 1.104E-01 9.906E-02
 26 12  2  3  2 0.000E+00 4.109E-02 1.800E+02 2.049E+00 1.683E+00 9.966E-01 4.835E-01 2.388E-01
 26 12  2  4  2 0.000E+00 2.966E-01 2.500E+01 8.656E-01 7.118E-01 7.264E-01 1.219E+00 1.795E+00
 26 12  2  5  2 0.000E+00 3.549E-01 2.000E+01 1.139E+00 1.000E+00 8.070E-01 9.929E-01 1.387E+00
 26 12  3  4  2 0.000E+00 3.138E-01 2.000E+01 9.235E-01 6.934E-01 5.849E-01 9.269E-01 1.493E+00
 26 12  3  5  2 0.000E+00 3.138E-01 2.500E+01 2.052E+00 1.844E+00 1.910E+00 3.308E+00 4.251E+00
 26 12  4  5  2 0.000E+00 5.838E-02 1.400E+02 1.020E+00 7.543E-01 4.328E-01 2.029E-01 9.571E-02
 26 12  1  6  1 2.353e-01 2.415e+00 2.900e+00 8.995e-01 7.588e-01 6.091e-01 4.760e-01 3.897e-01
 26 12  1  7  1 1.586e-01 2.495e+00 2.700e+00 6.414e-01 5.386e-01 4.282e-01 3.238e-01 2.542e-01
 26 12  1  8  1 8.147e-02 2.532e+00 2.700e+00 3.312e-01 2.775e-01 2.200e-01 1.655e-01 1.286e-01
 26 12  1  9  1 1.216e-04 3.071e+00 3.100e+00 2.794e-03 2.106e-03 1.438e-03 7.998e-04 1.579e-04
 26 12  1 10  1 1.259e-03 3.085e+00 2.300e+00 4.706e-03 3.940e-03 3.117e-03 2.229e-03 1.629e-03
```

Ion

gf

Energy

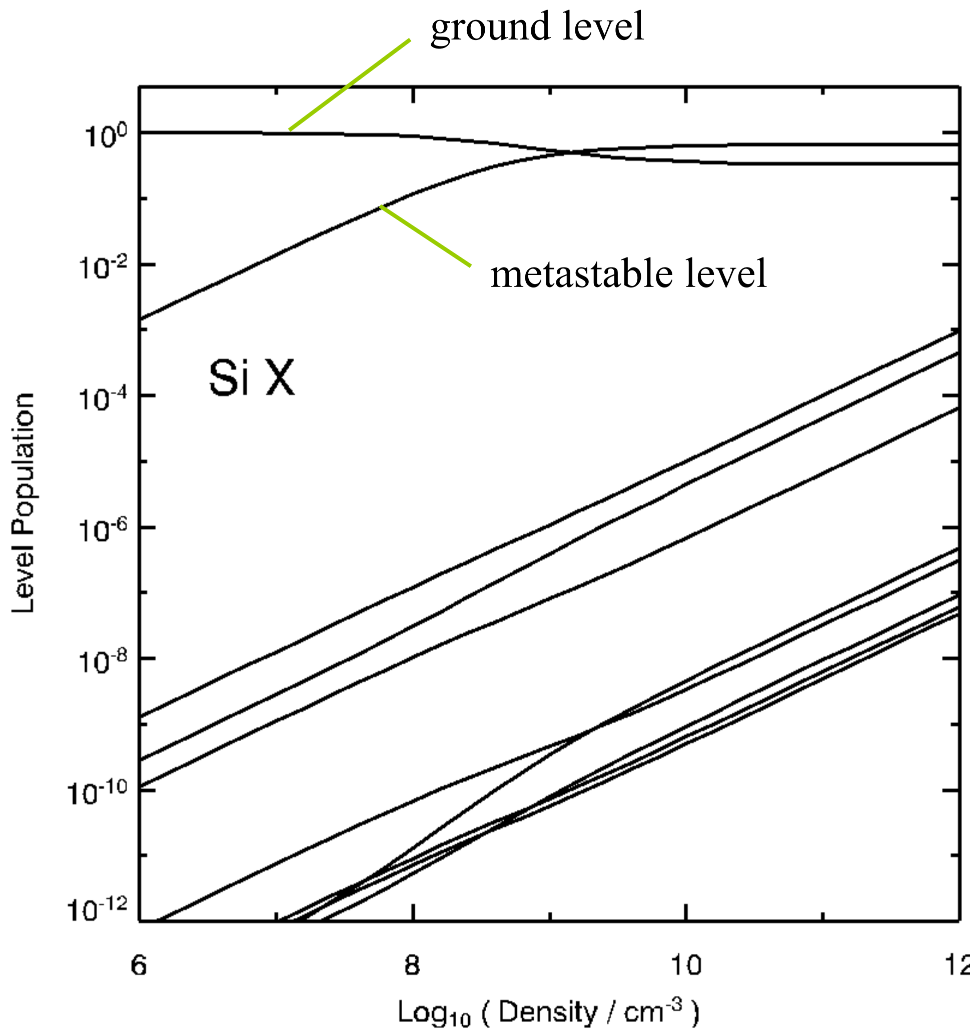
Scaling parameter

Spline values

Transition (*i-j*)

Level Populations: Si X

- Level populations (n_j) change with density
- Shows increasing importance of *electron collisions*



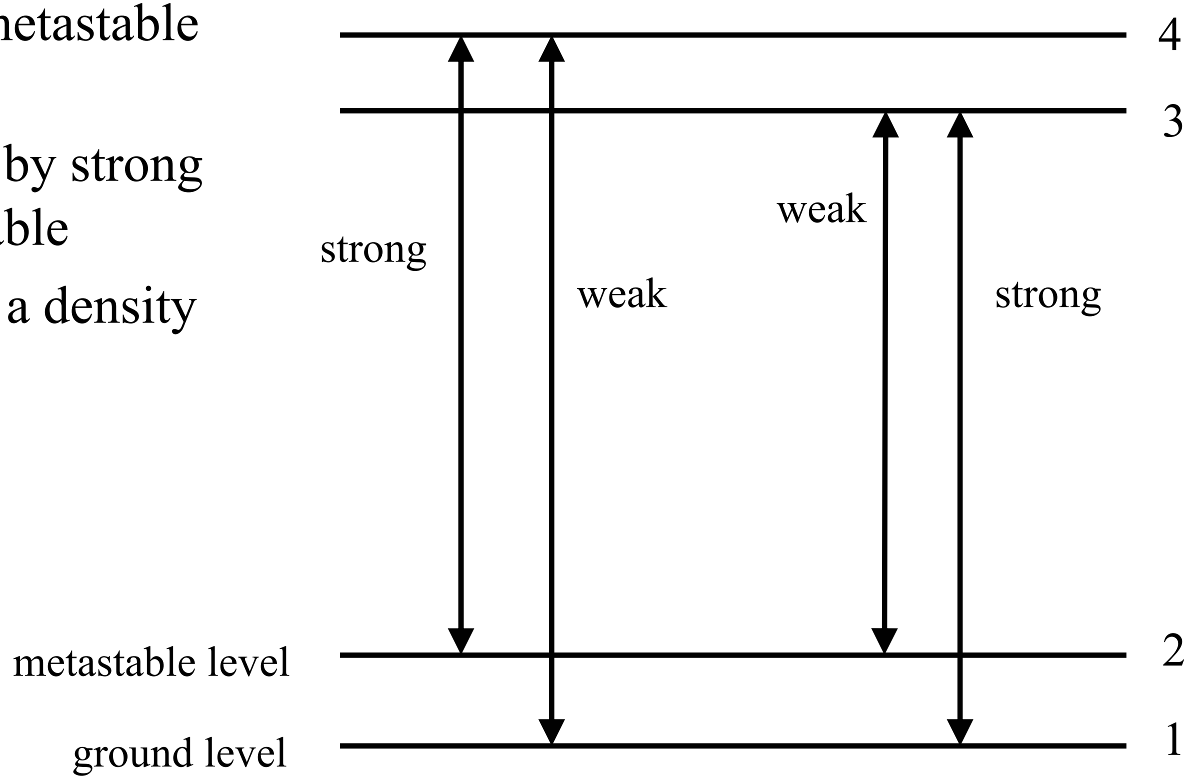
Metastable levels

- Most levels take $10^{-6} – 10^{-10}$ seconds to decay spontaneously
- *Metastable* levels typically take 0.01 – 100 seconds to decay
  - determined by atomic properties of level
- Metastables can end up with significant population, affecting the population of all levels
  - at low densities all levels are excited from the ground
  - at high densities, levels can be excited from ground *and* metastables

- Metastables are crucial for *density diagnostics*

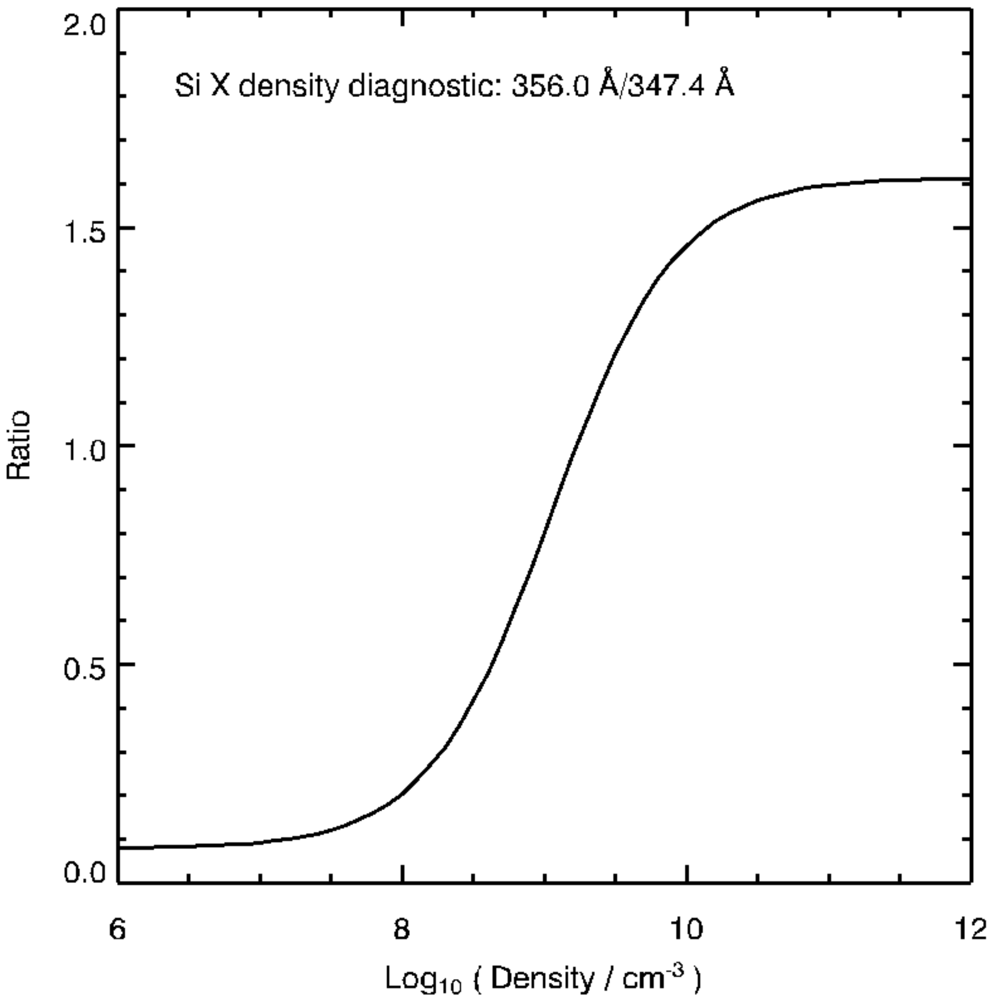
Density Diagnostics

- Level 4 populated by weak transition from ground
- As density increases, metastable gains population
- Level 4 can be excited by strong transition from metastable
- The ratio 4→2/3→1 is a density diagnostic

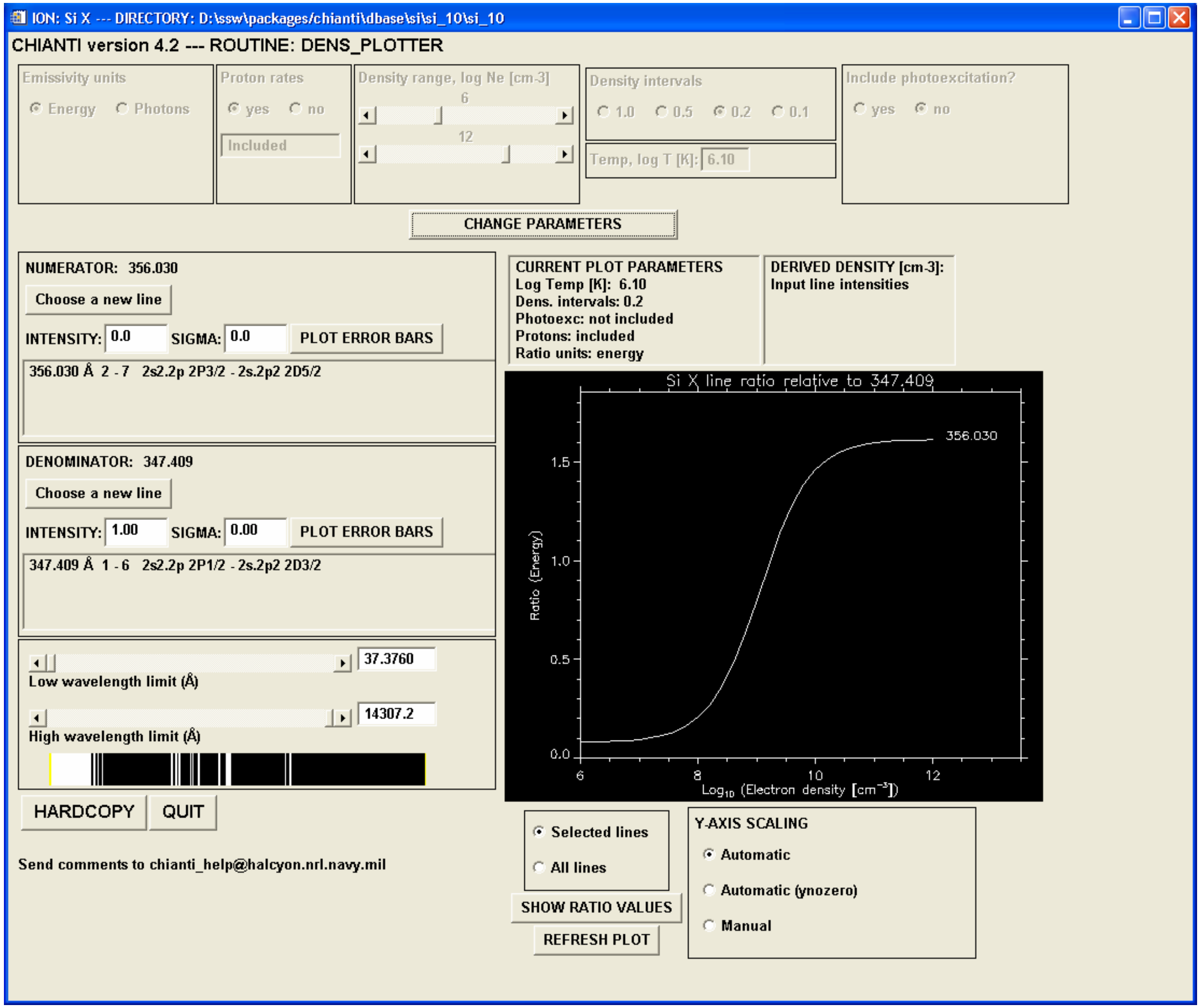


Si X Density Diagnostic

- Si X 356.0/347.4 ratio commonly used in analysis of CDS spectra



CHIANTI Software

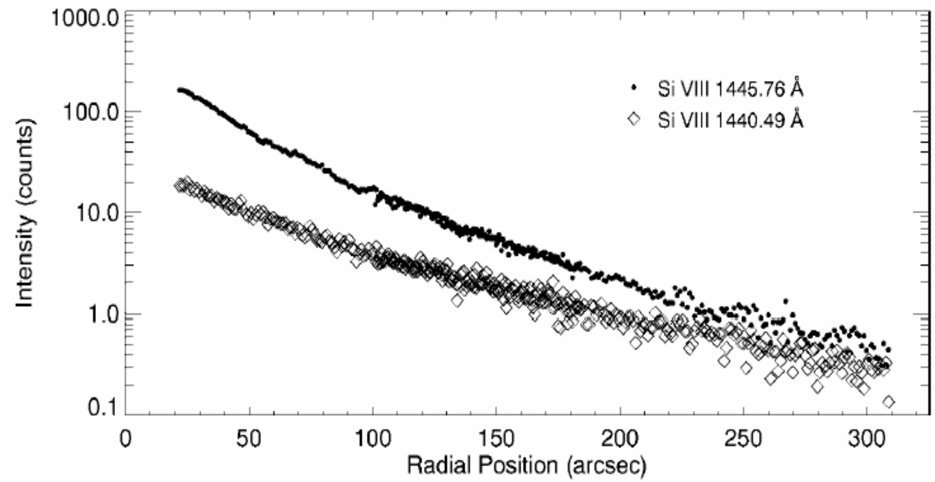


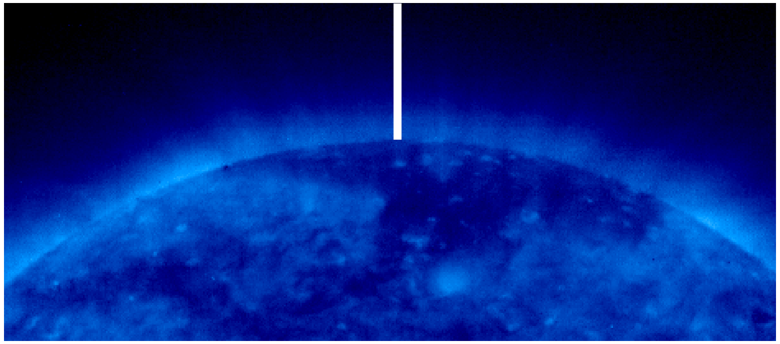
DENS_PLOTTER
CHIANTI IDL tool for studying density diagnostics

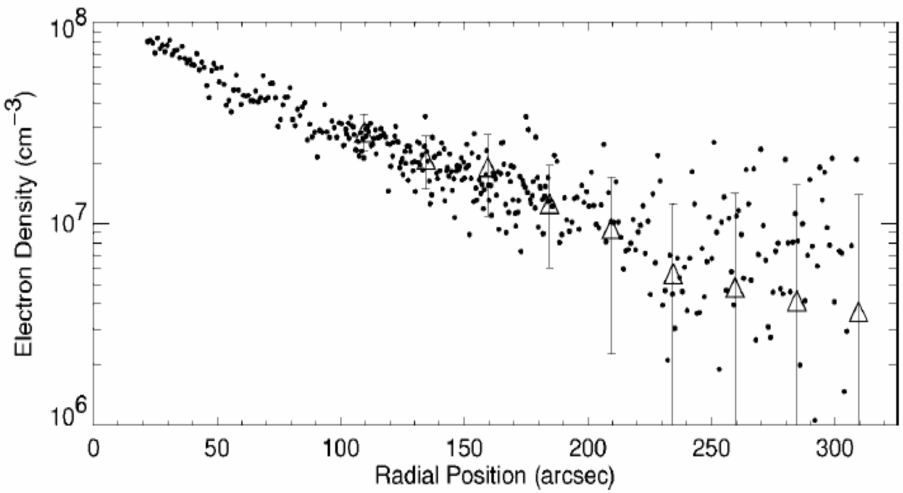
IDL> dens_plotter,’si_10’

Coronal Hole Density

- Si VIII 1446 Å/1440 Å ratio gives electron density above solar limb
- Doschek et al. (1997, ApJL) find exponential decrease with height in coronal hole from SUMER data

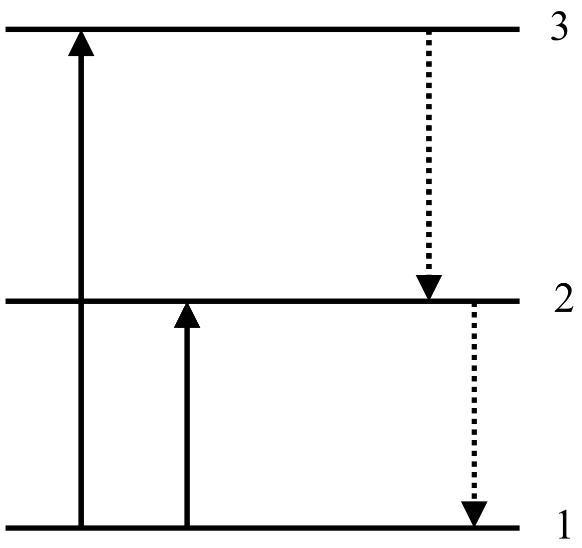






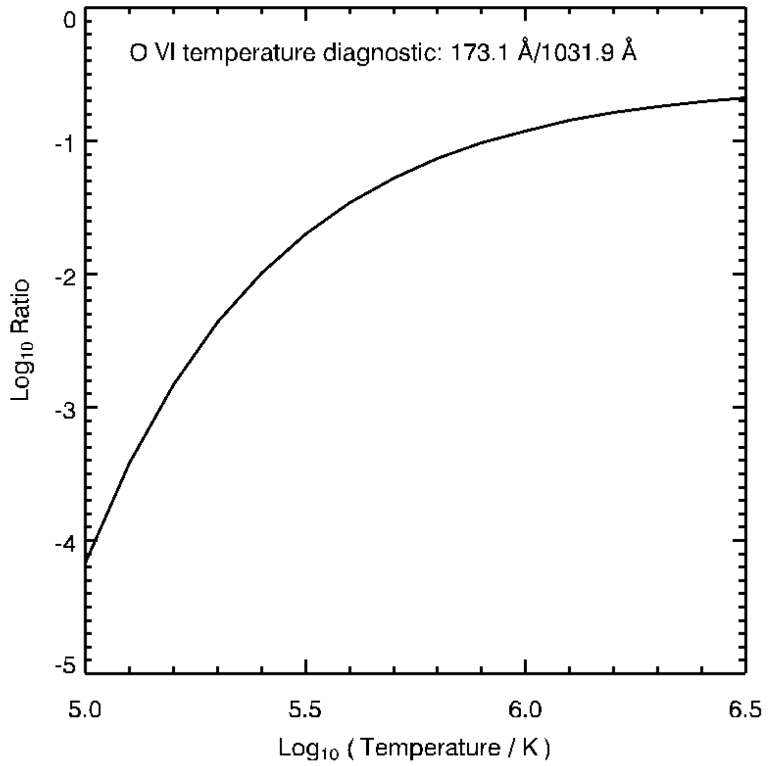
Temperature Diagnostics

- Single ions can be used to determine the electron temperature
  - less assumptions that with other methods, e.g., TRACE filter ratios
- At low temperatures, colliding electrons have low energy and so level 3 can not be excited easily
- At high temperatures electrons have greater energy and so level 3 can be excited
- Emission line ratio 3→2/2→1 increases with temperature

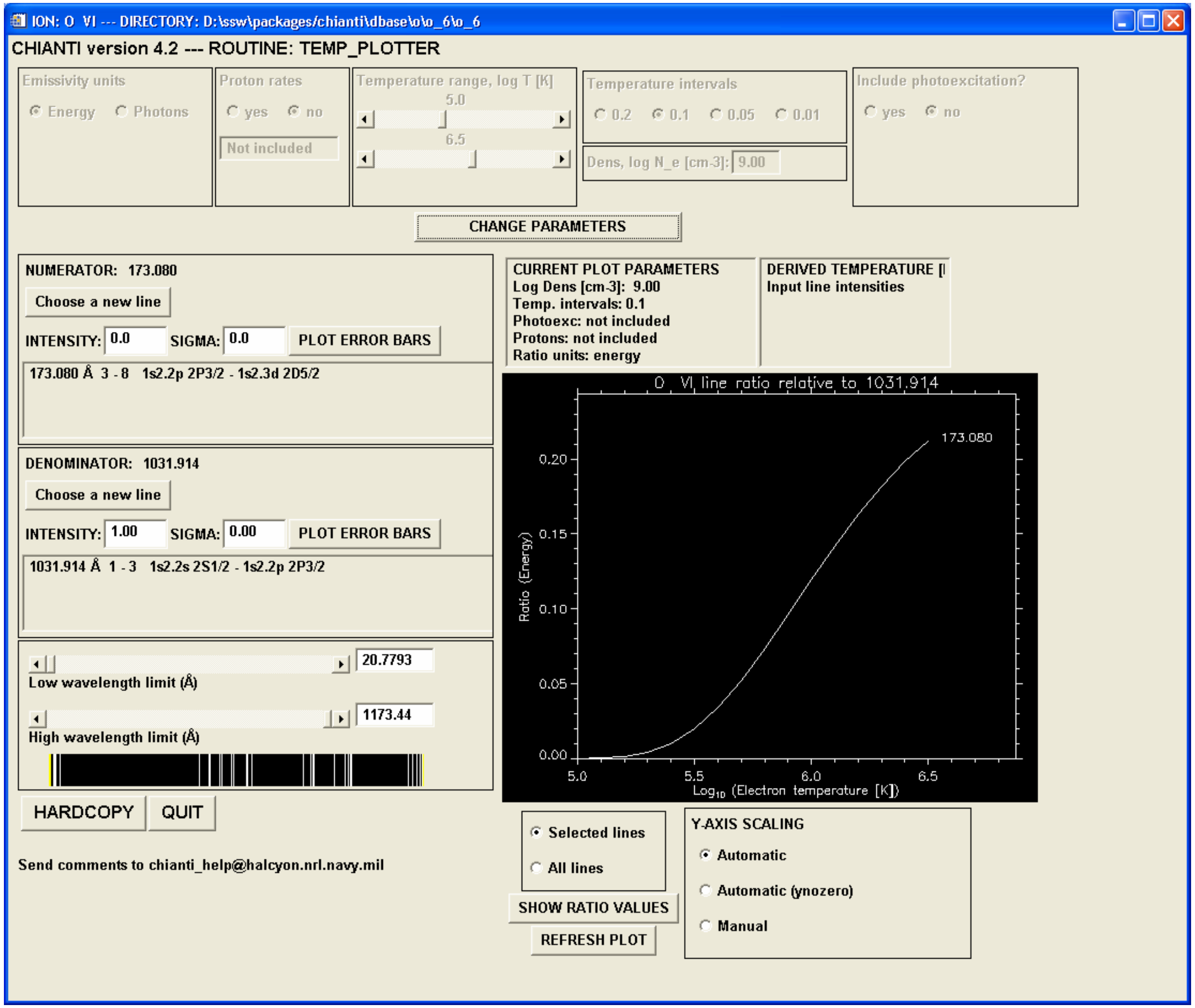


Example: O VI

- Transition 3→2 is at 173 Å (observed by CDS)
- Transition 2→1 is at 1032 Å (observed by SUMER)



CHIANTI Software

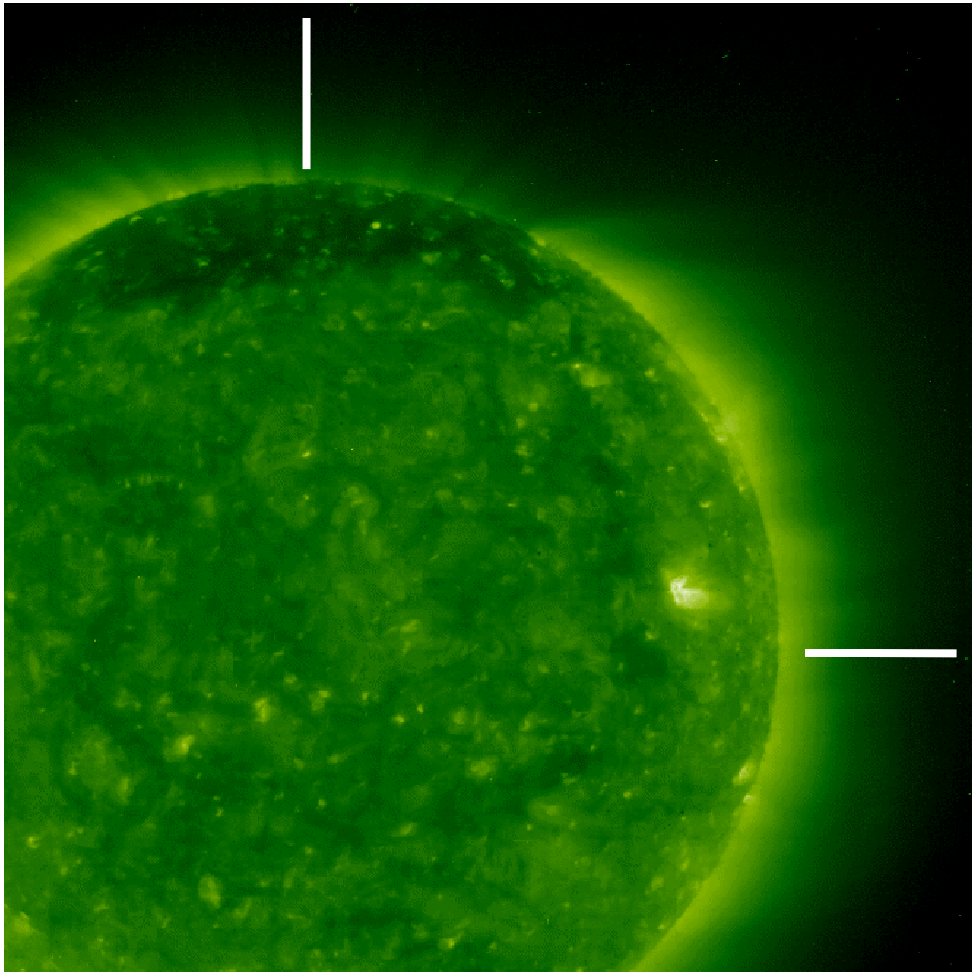


TEMP_PLOTTER
CHIANTI IDL tool for studying temperature diagnostics

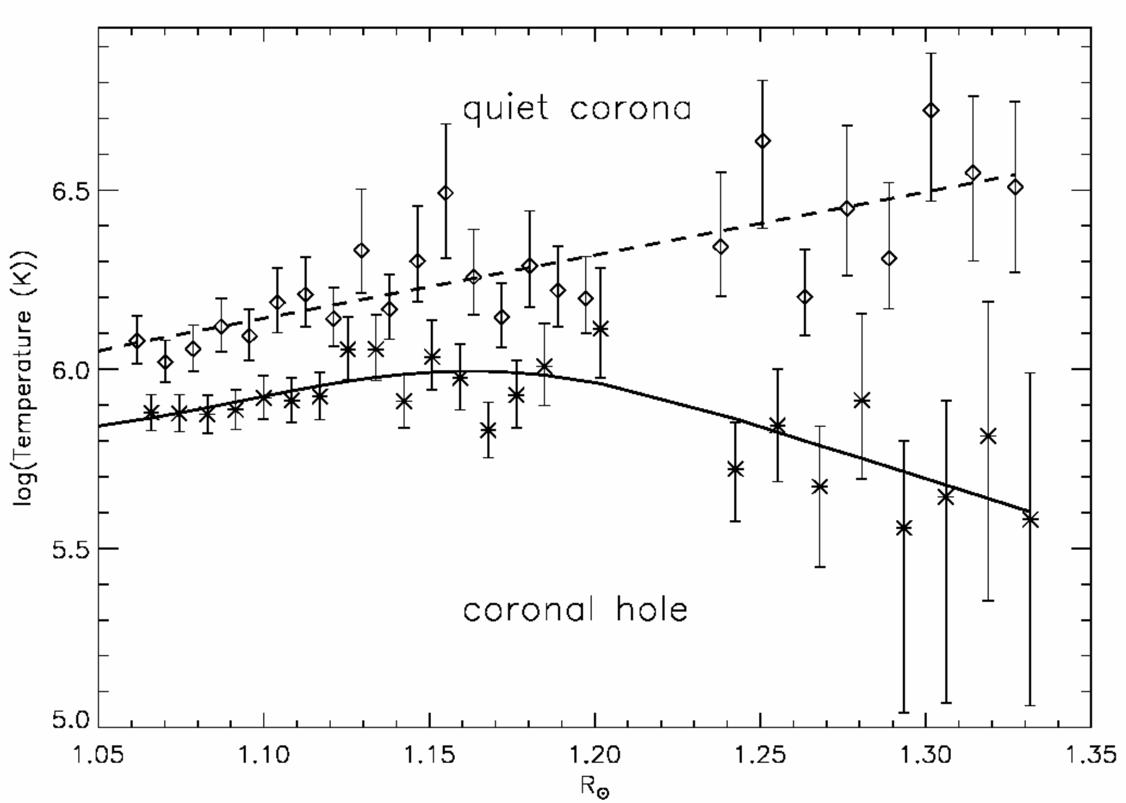
IDL> temp_plotter,’o_6’

Coronal Hole Temperature

- David et al. (1997) used O VI ratio to measure temperature in quiet Sun and coronal hole regions
- Required a special roll of the SOHO spacecraft



Coronal Hole Temperature

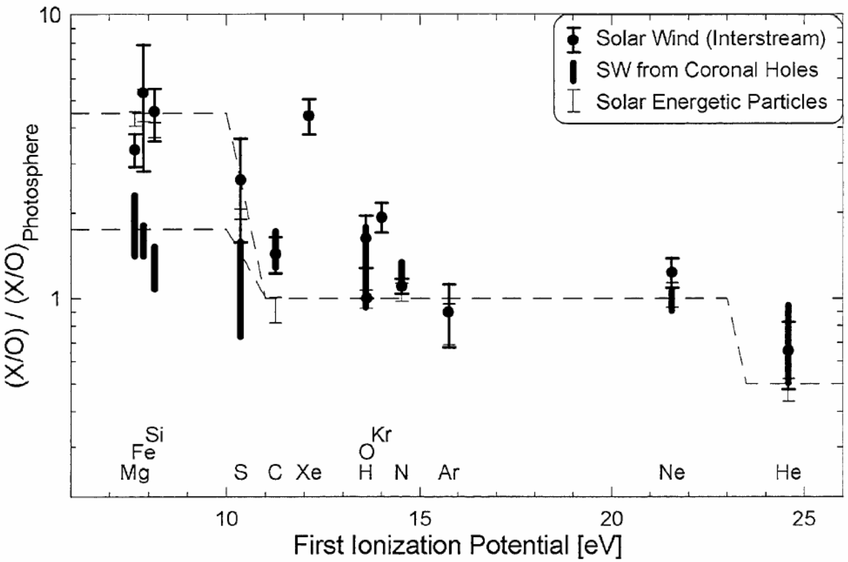


David et al. (1997, A&A)

- Fall-off of temperature in coronal hole suggests departure from equilibrium conditions in the low density coronal hole

Element Abundances

- Emission lines from two different elements allow the relative element abundance to be derived
- Both remote sensing spectroscopy and in situ solar wind measurements have revealed *abundance anomalies* in the corona
- Ions with a low *first ionization potential* (FIP) are enhanced over high FIP elements compared to the photosphere

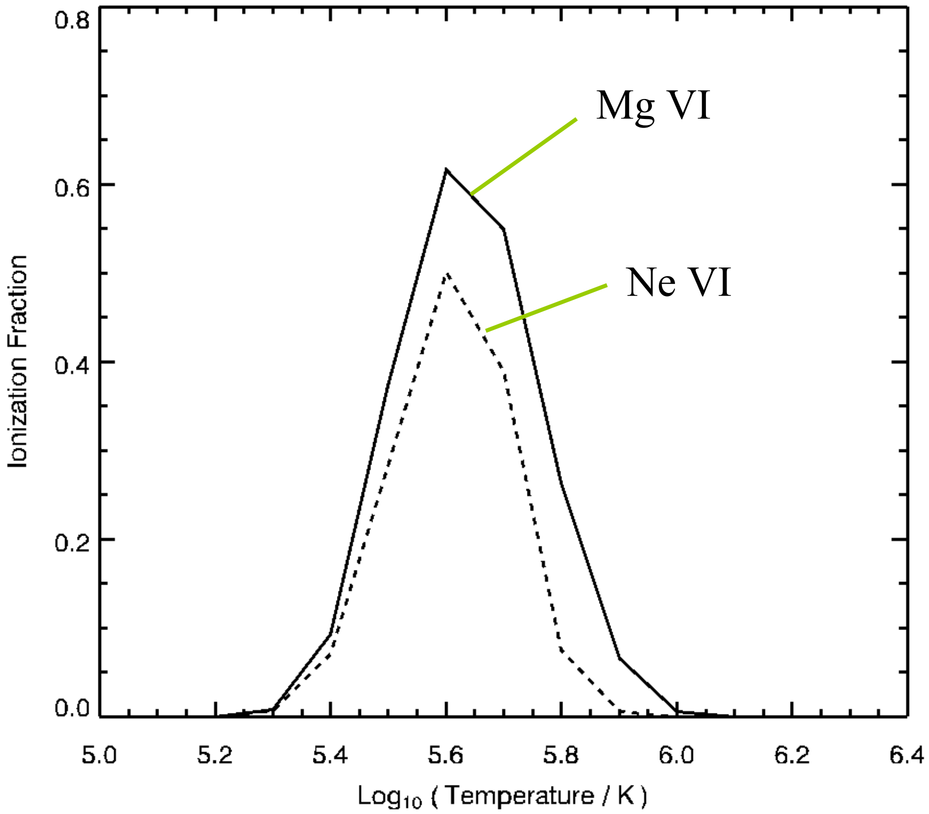


Von Steiger et al. (1997)

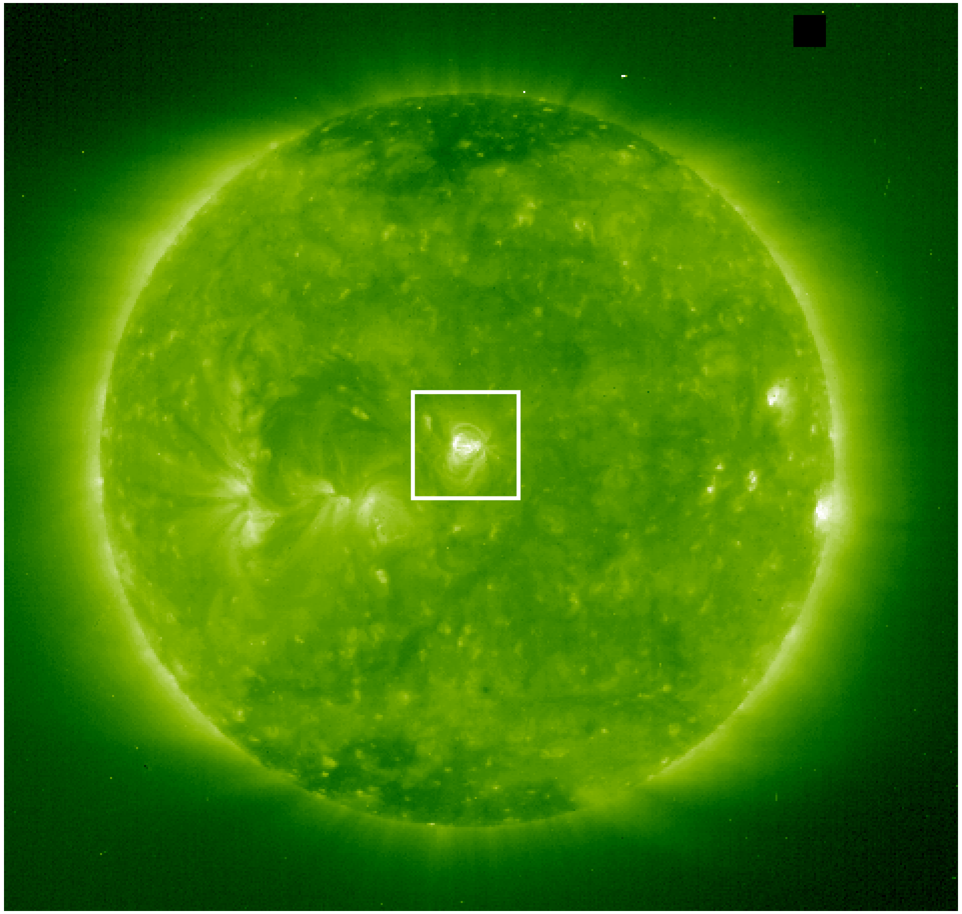
Remote Sensing Abundances

- If two ions are formed over the same temperature range, then ratio can reveal abundance anomalies
- Example: Mg VI & Ne VI

$$R_{\mathrm{obs}} \approx Q \frac{\varepsilon_{\mathrm{Mg\,VI}}}{\varepsilon_{\mathrm{Ne\,VI}}} \frac{Ab(\mathrm{Mg})}{Ab(\mathrm{Ne})}$$



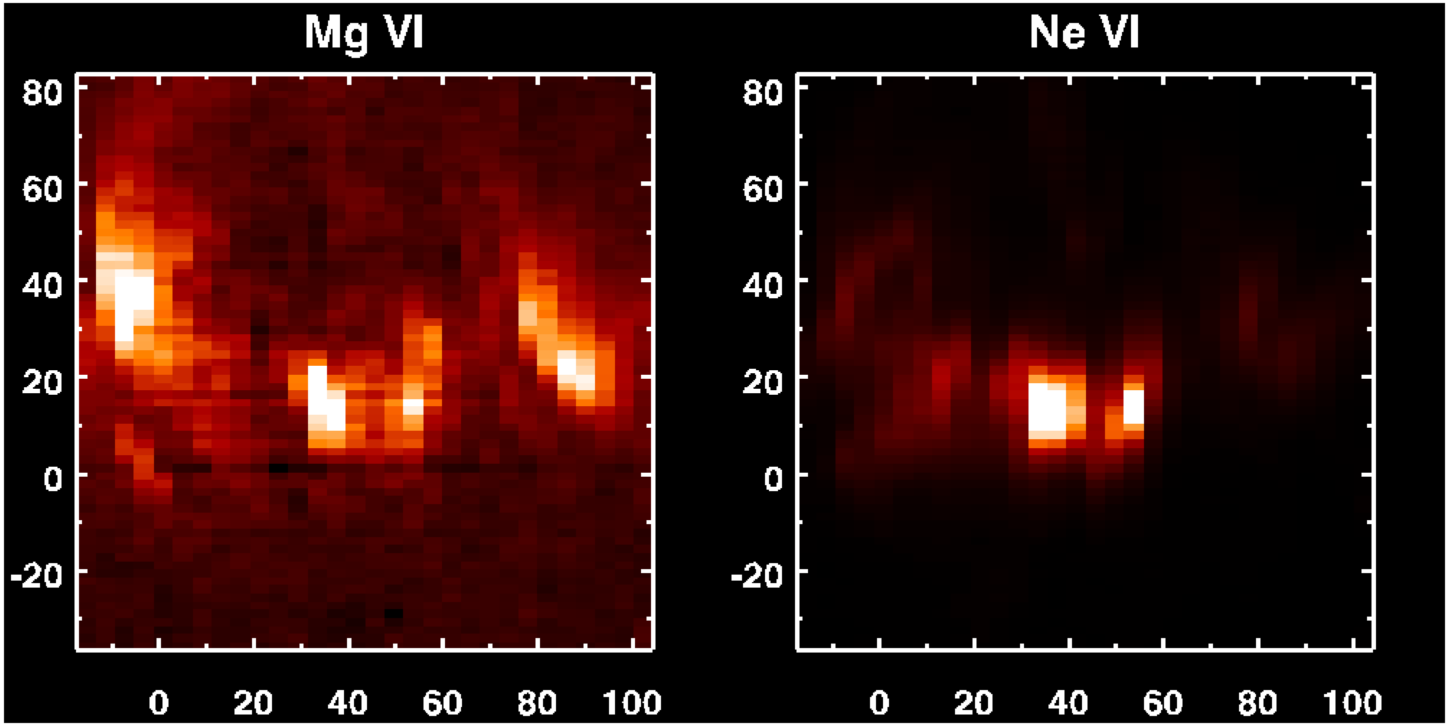
Mg/Ne Abundance Ratio



June 6, 1996

Mg/Ne Abundance

- Mg VI and Ne VI formed at ≈ 300,000 K (transition region)



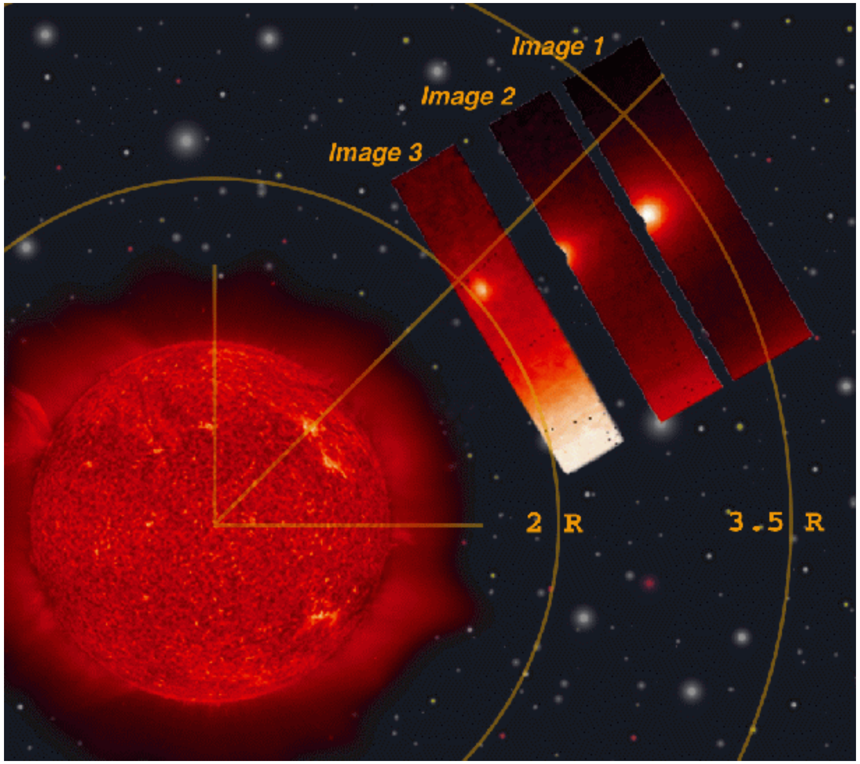
Young & Mason (1997, Sol. Phys.)

Mg/Ne Abundance

- Brightenings in AR centre show a photospheric Mg/Ne abundance
  - associated with emerging magnetic flux
- Brightenings at edge of AR show Mg/Ne enhanced by factor 10
  - bases of large, stable active region loops

UVCS Diagnostics

- UVCS observes extended corona ($1.25 - 10\ R_\odot$)

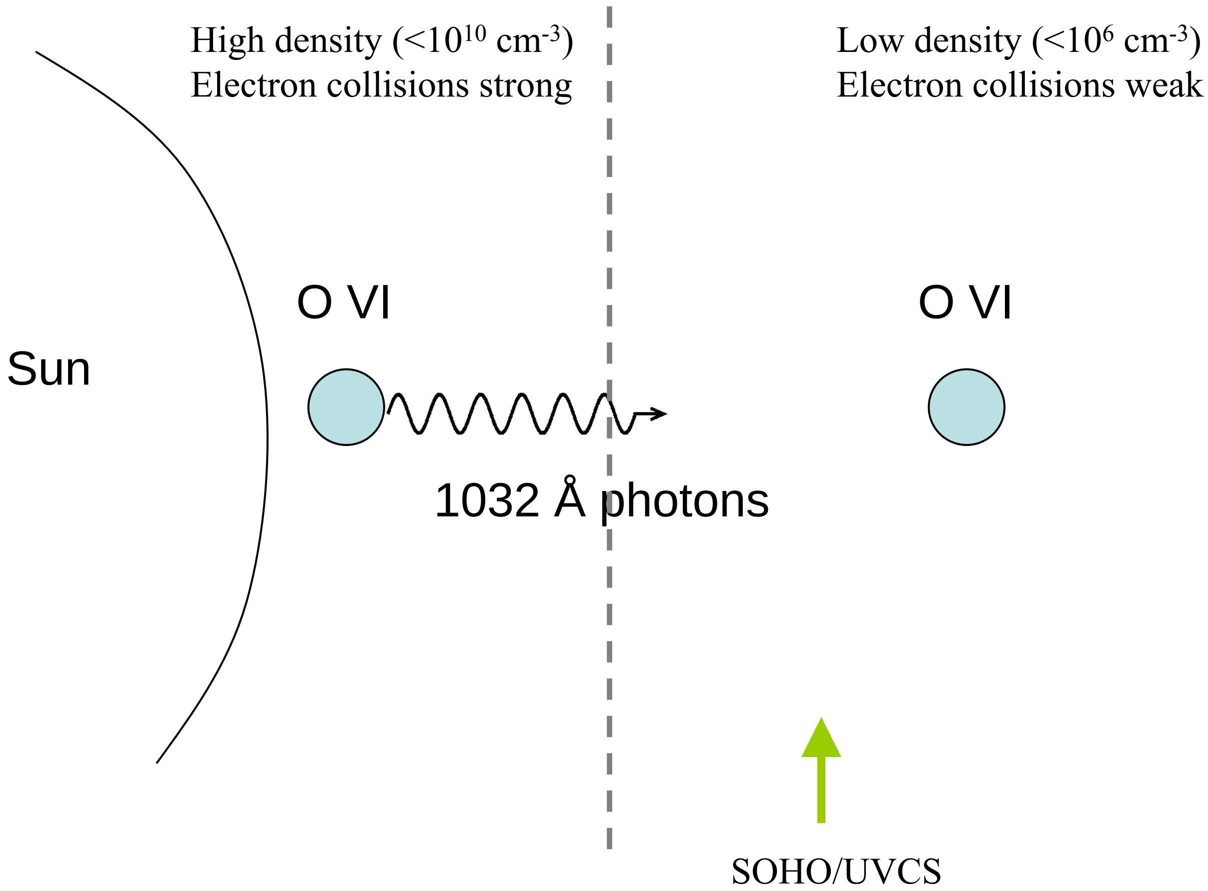


Photon Excitation

- At large heights above the Sun's surface electron density is low ($<10^6$ cm^{-3})
- Electron collisions are rare, and photon excitations can compete with electron excitation
  - photons come from the inner atmosphere
- Ion level populations (and emission line intensities) modified by radiation field

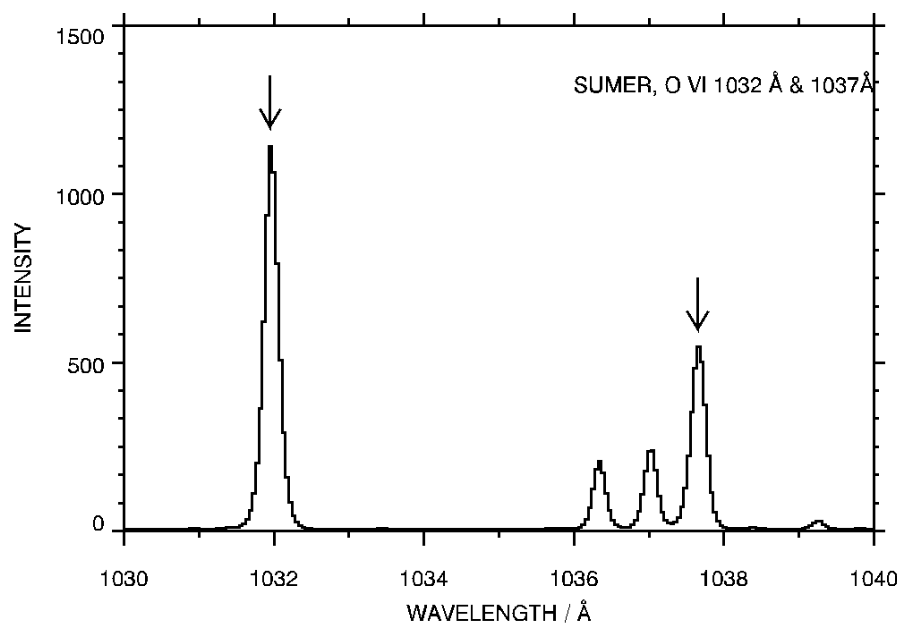
Example: O VI

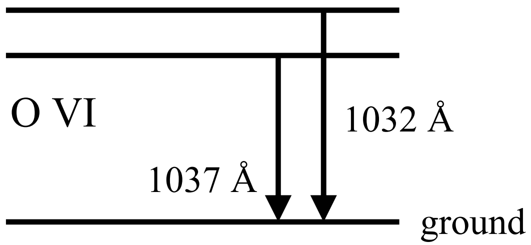
- A stationary O VI ion in the extended corona ‘sees’ radiation from O VI ions from the inner corona



Example: O VI

- O VI has two emission lines at 1032 Å and 1037 Å that have a ratio 2:1 in the inner corona
- In the low density outer corona, the inner corona radiation can excite transitions in the O VI ion





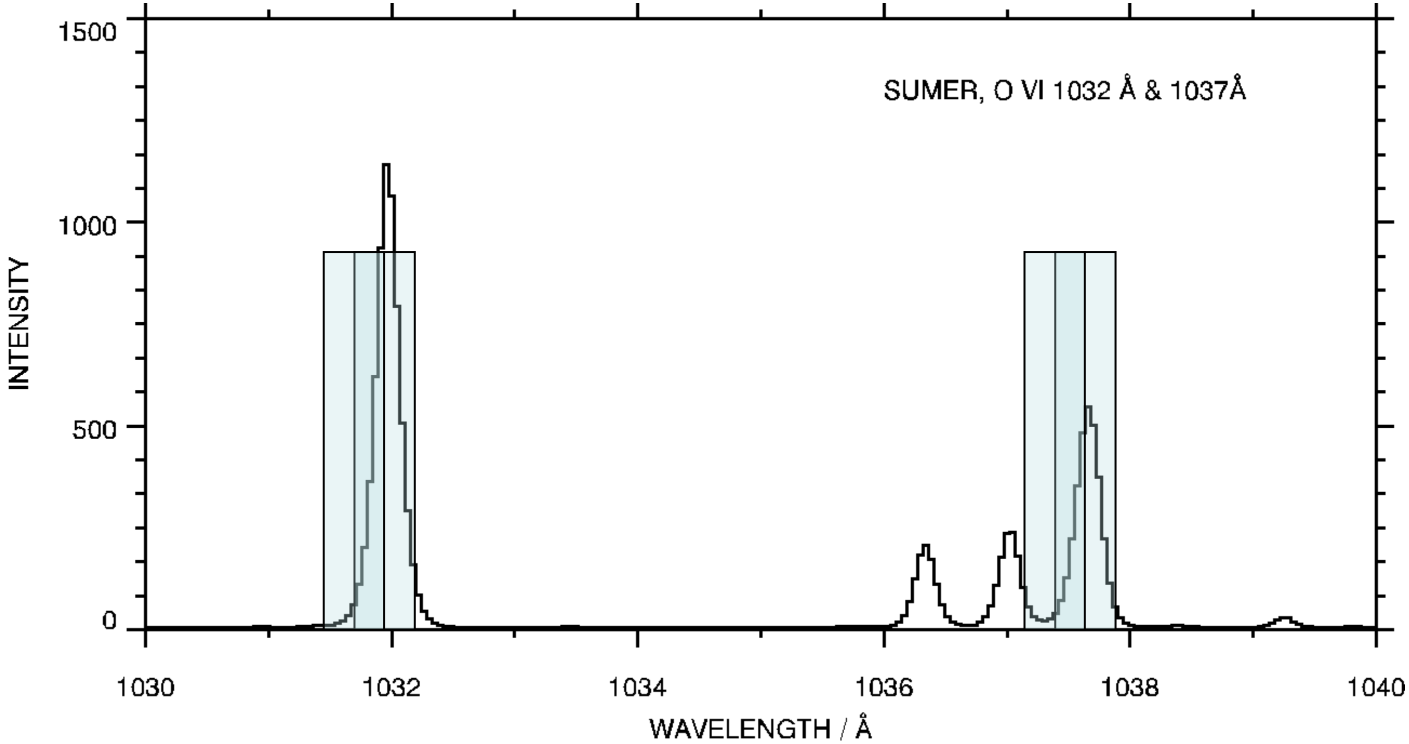
Example: O VI

- In the inner corona, O VI lines are collisionally-excited and have ratio 2:1

- If O VI lines are excited by photons they have ratio 4:1
  - twice as many photons excite 1032 line
  - 1032 line twice as likely to absorb photons
  - gives factor 4

Example: O VI

- However, if the extended corona is moving outwards at speeds ≥ 100 km/s it sees a *redshifted* spectrum from the inner corona
- The O VI lines are no longer excited by photons → return to collisional excitation and ratio of 2:1

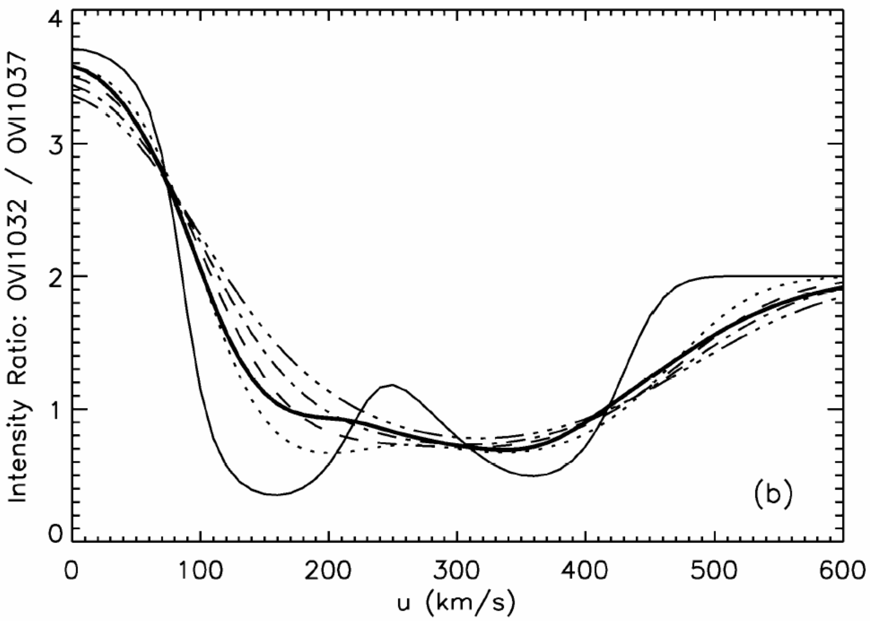


Example: O VI

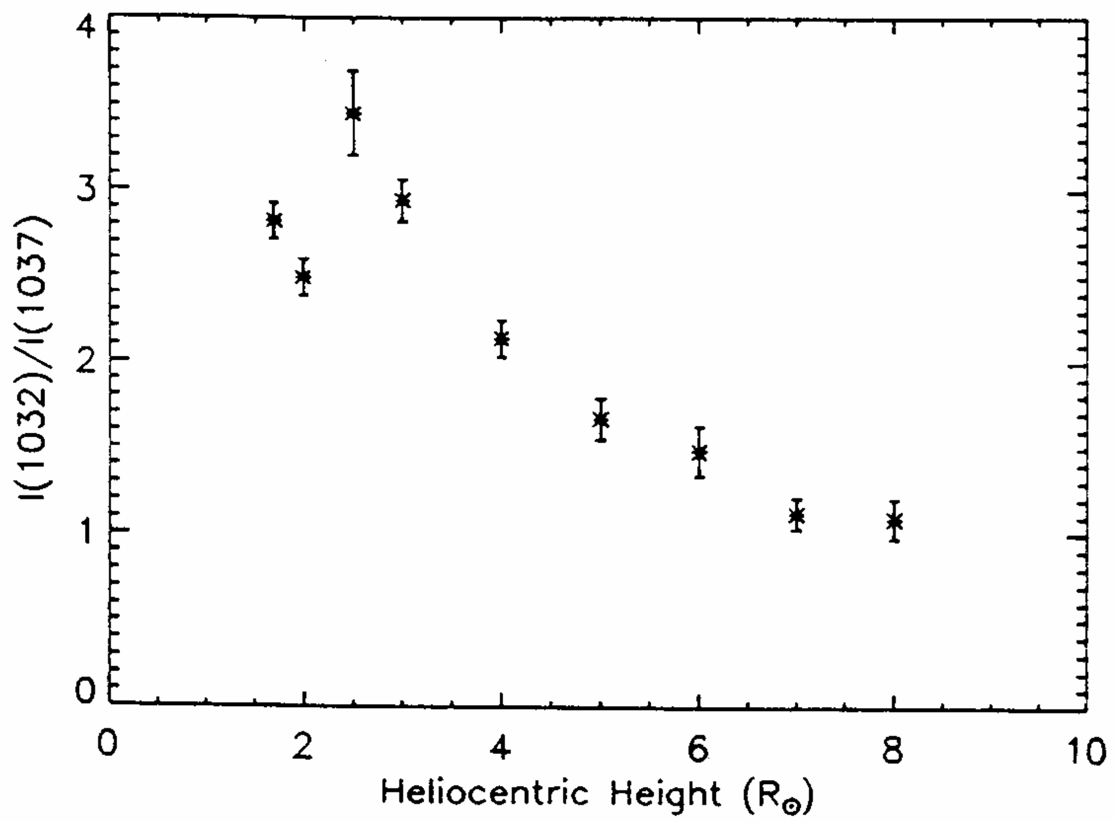
- Two C II lines at 1036.3 and 1037.0 Å (chromospheric)
- At velocities ≈ 150 km/s and ≈ 380 km/s these emission lines can photo-excite the O VI 1037.6 Å in the extended corona

- Causes O VI 1032/1037 ratio to become < 2

Li et al. (1998, ApJ)



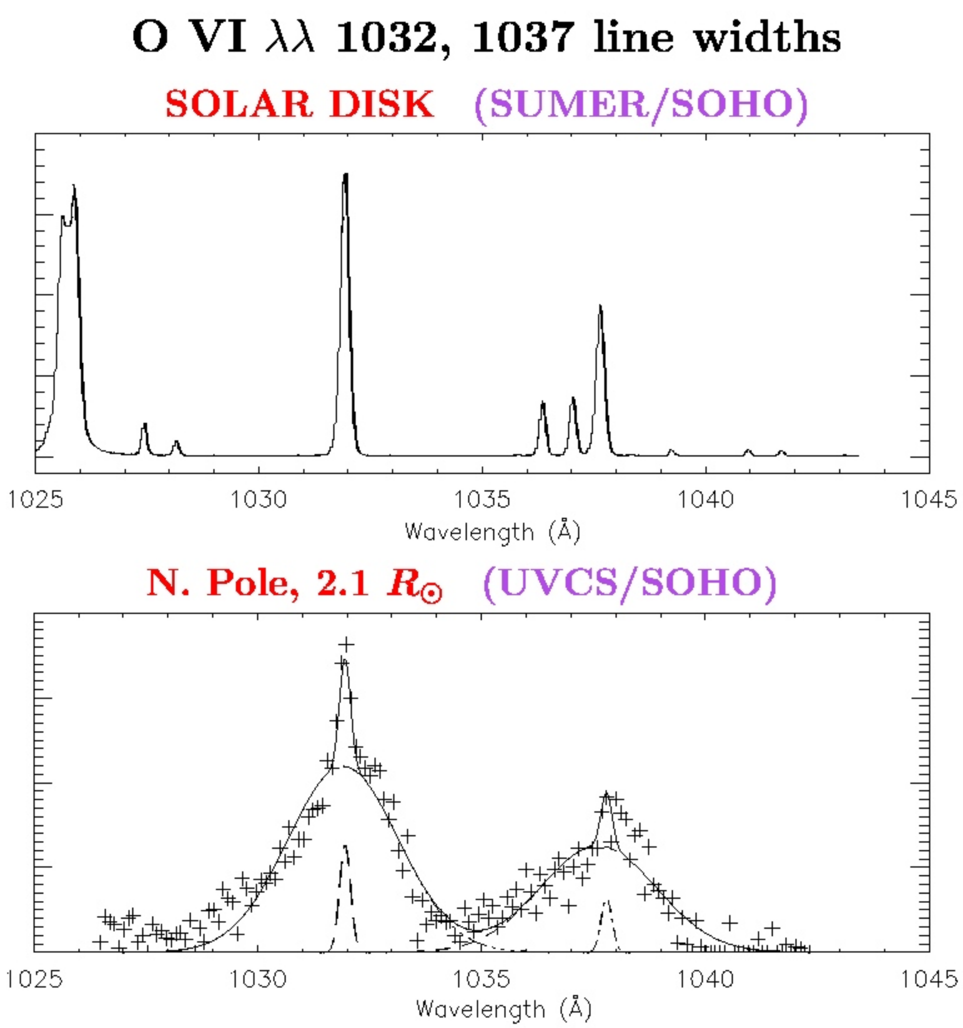
UVCS Doppler Dimming Data



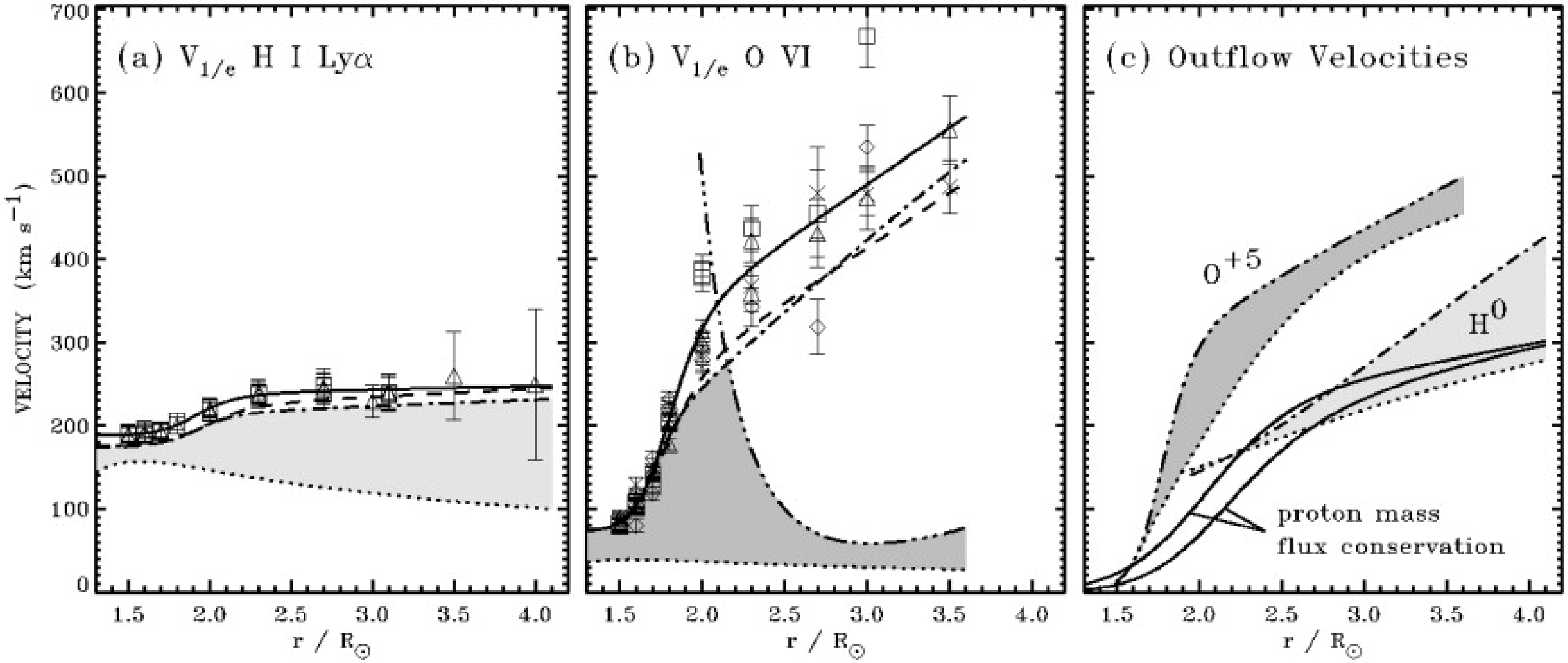
Kohl et al. (1997, Sol. Phys.)

O VI Line Widths

- Further velocity information from line widths
- O VI lines seen by UVCS extremely broad
- Temperatures 200 million K!
- Highly anisotropic velocity distribution ($v_{\perp} \gg v_{\parallel}$)



UVCS Velocity Results



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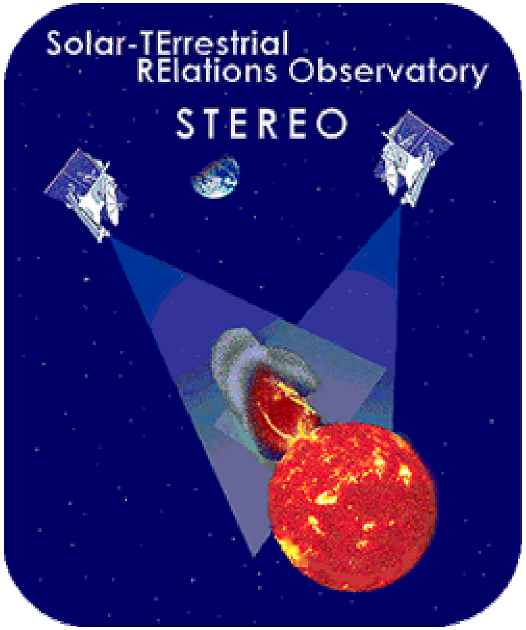
Future Solar Missions

- Exciting times ahead for solar physics!

- **STEREO**, launch Feb 2006
- **Solar-B**, launch Aug 2006
- **Solar Dynamics Observatory** (SDO), launch Apr 2008
- **Solar Orbiter**, launch 2012-13

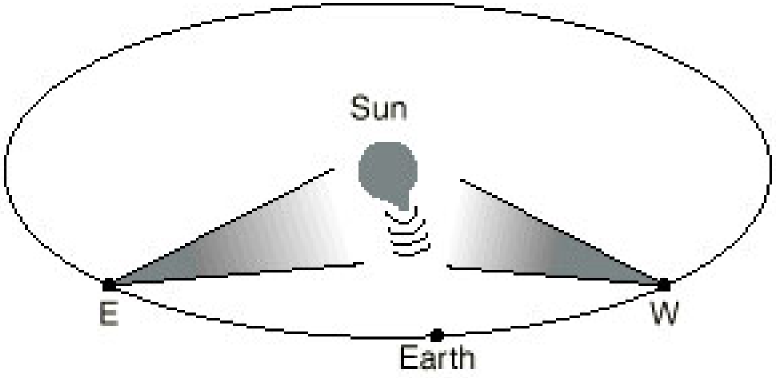
STEREO

- *Solar-Terrestrial Relations Observatory*
- Two identical spacecraft leading and following the Earth
- Launch Feb 2006
- Four instrument packages
  - SECCHI
  - PLASTIC
  - SWAVES
  - IMPACT
- Goal:
  - Understand the origin and consequences of CMEs



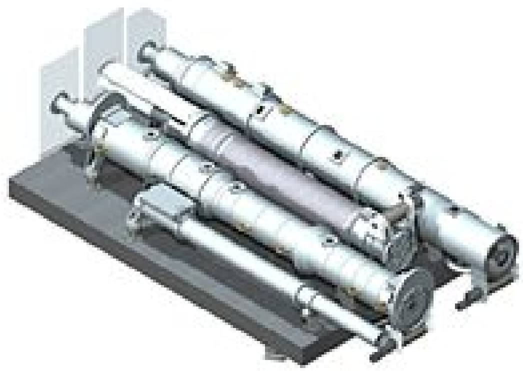
STEREO Mission Phases

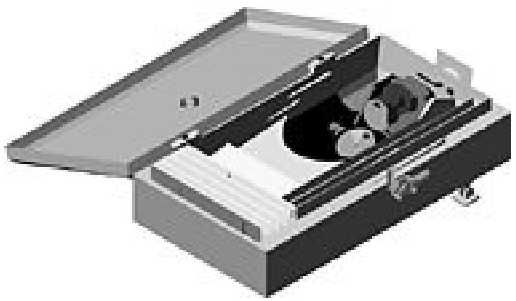
- Phase 1 (first 400 days; α≤50°)
  - 3-D structure of the corona
- Phase 2 (days 400 to 800; 50°≤α≤110°)
  - Physics of CMEs
- Phase 3 (days 800 to 1100; 110°≤α≤180°)
  - Earth-directed CMEs
- Phase 4 (after day 1100; α>180°)
  - Global solar evolution and space weather



Remote Sensing: SECCHI

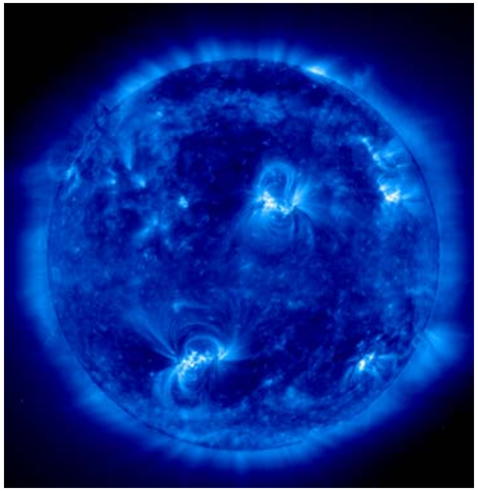
- Instruments
  - EUVI (EUV imager)
  - COR1 & COR2 (white light coronagraphs)
  - HI (heliospheric imager)
- EUVI and CORs are direct follow-ons to EIT and LASCO





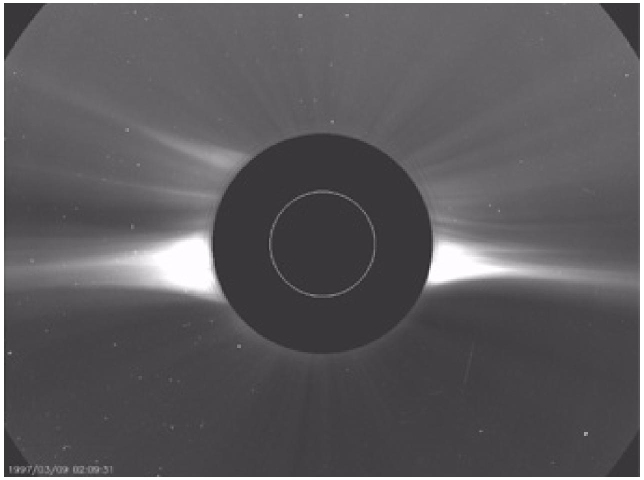
SECCHI – EUVI

- Successor to EIT
- Image channels: Fe IX 171, Fe XII 195, Fe XIV 211, He II 304
- Larger detector (2048x2048 pixels) leads to
  - Higher spatial resolution (1.6 arcsec vs. 2.5 arcsec)
  - Larger field-of-view (1.7 Rsun vs. 1.4 Rsun)
- Higher telemetry ensures higher image cadence



SECCHI – COR

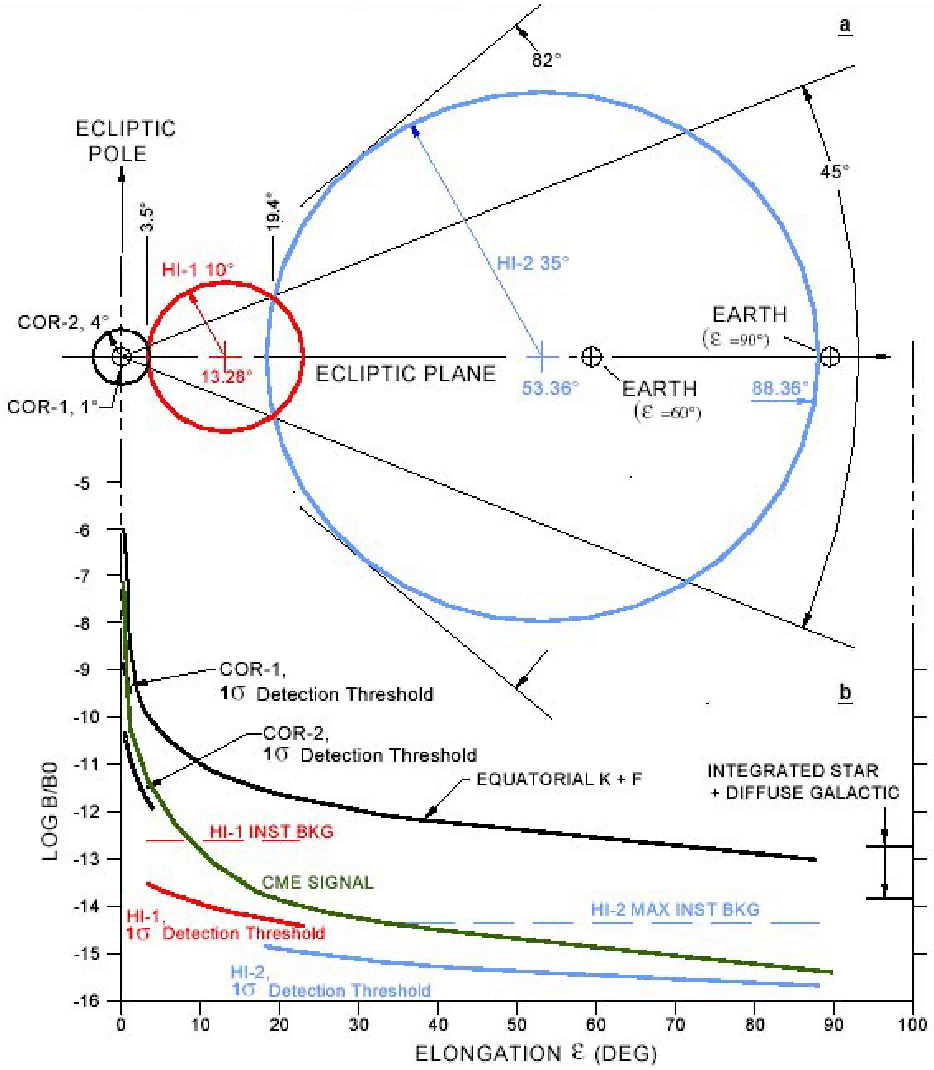
- Two coronagraphs do a similar job to the three coronagraphs of LASCO
- COR1
  - 1.1-3.0 Rsun; 7.5 arcsec pixels
  - Measures polarization
- COR2
  - 2-15 Rsun; 14 arcsec pixels
  - Higher spatial resolution and time cadence than LASCO C3



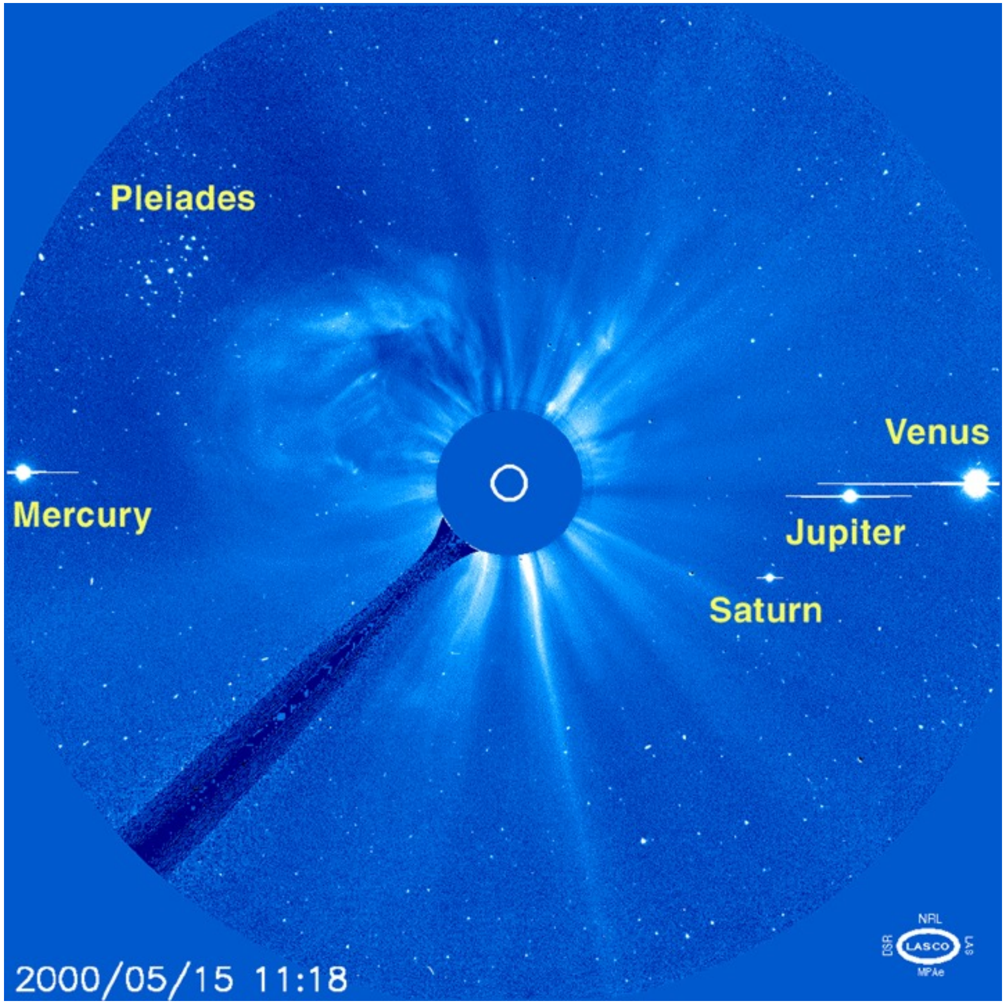
Heliospheric Imager

- UK-led instrument (PI: Richard Harrison, RAL)
- Will obtain a new type of solar data: imaging of CMEs out to 1 a.u.
- Images not Sun-centred (unlike coronagraphs)
- Two independent telescopes (HI-1, HI-2) with half-angle fields-of-view of 10º and 35º

Heliospheric Imager



Heliospheric Imager

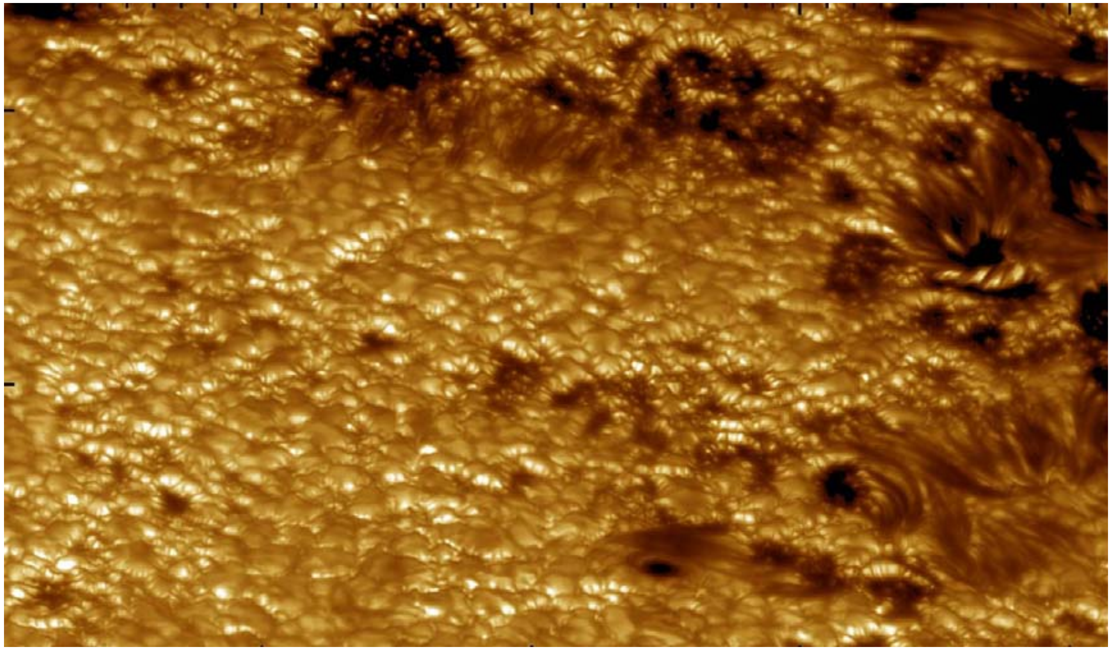


Solar-B

- Japan/USA/UK mission
- Follow-up to *Yohkoh*
- 3 scientific instruments
  - X-ray imager (XRT)
  - EUV spectrometer (EIS)
  - Optical telescope (SOT)
- Launch 2006
- Mission aim:
  - Solar-B will study the connections between fine magnetic field elements in the photosphere and the structure and dynamics of the entire solar atmosphere.
- The 'Hubble' of Solar Physics

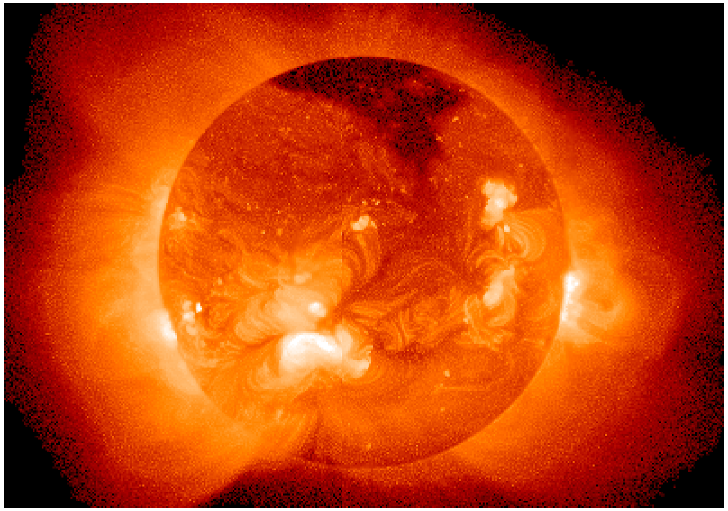
Solar Optical Telescope

- 0.5 m optical telescope feeds the Focal Plane Package (FPP)
  - Telescope diffraction-limited to ~0.25 arcsec resolution
  - Maximum field-of-view: 2.75x2.75 arcmin²
- Will measure vector magnetic field for the first time in space



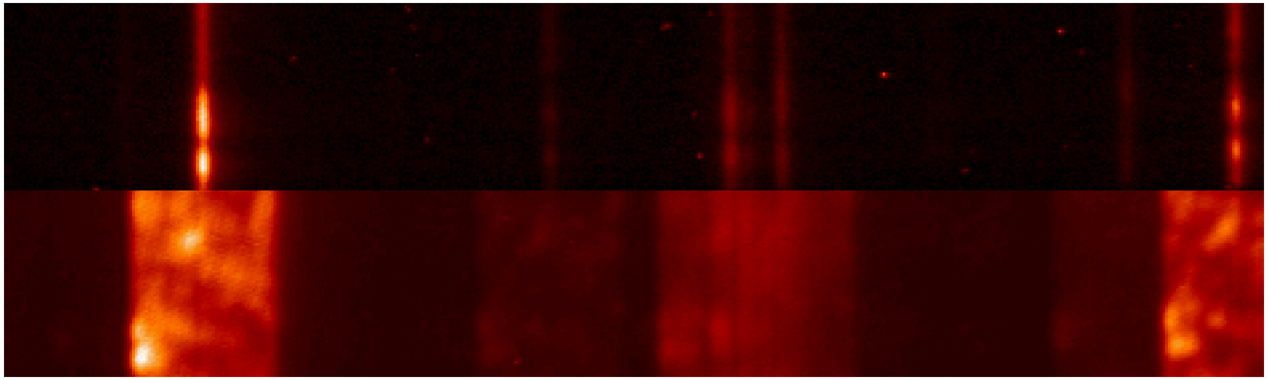
Solar-B XRT

- X-Ray Telescope
- Direct successor to the SXT on *Yohkoh*
- Key features:
  - 2 arcsec resolution (1 arcsec pixels)
  - Greater sensitivity to cool corona (1-2 MK)
  - 34x34 $arcmin^2$ field-of-view (full solar disk)



EUV Imaging Spectrometer

- UK-led instrument (PI: Len Culhane, MSSL)
- Spectra in 170-210Å and 250-290Å wavelength ranges
- Field-of-view 6 x 8 arcmin^2
- Spatial scale: 1 arcsec pixels
- Spectral scale: 0.02Å pixels
  - Line centroids ~3 km/s; line widths ~20 km/s

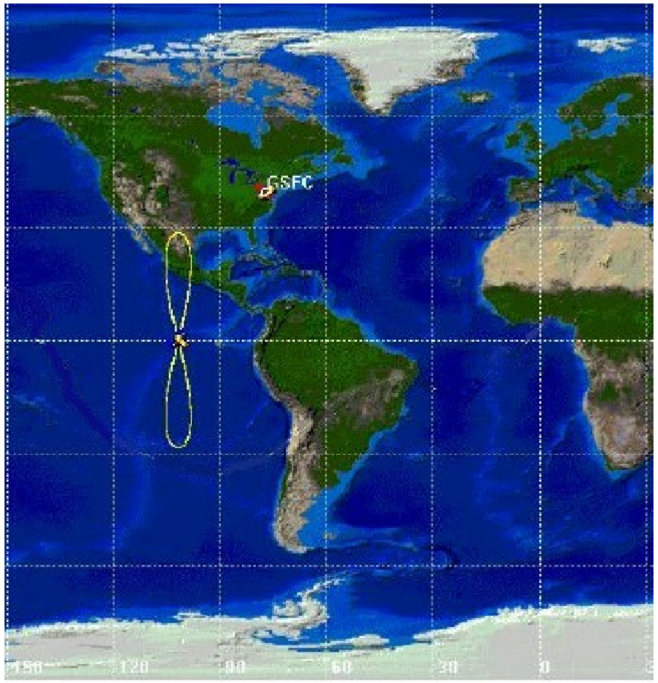


Solar Dynamics Observatory

- Launch 2008
- 3 instrument packages selected by NASA:
  - AIA (imaging)
  - HMI (magnetograph)
  - EVE (extreme ultraviolet irradiance monitoring)
- Geosynchronous orbit
  - Very high telemetry rate (160 Mbits/s)

"SOHO on Steroids"

- Telemetry rate is > 1000 times better than SOHO!
- 4 different full-disk, TRACE resolution images every 10 seconds
- 1.5 terabytes/day of data

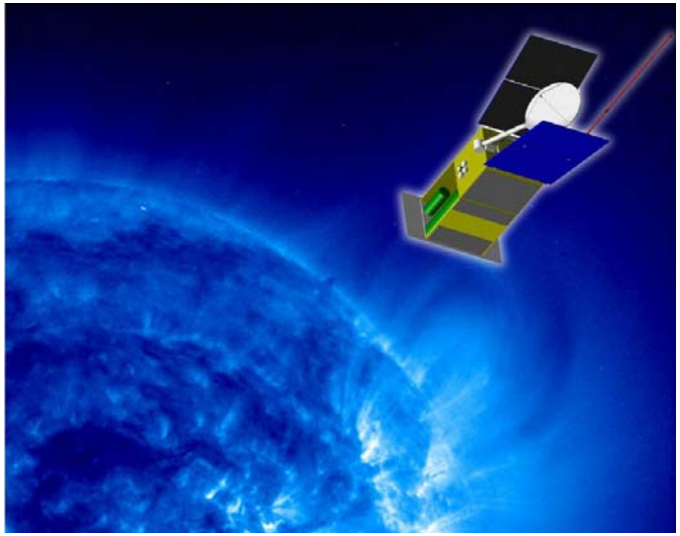


SDO Instruments

- AIA – *Atmospheric Imaging Array*
  - successor to SOHO/EIT and TRACE
  - 4 individual telescopes, with > 20 filters
  - 4kx4k CCD images covering full disk @ 0.8 arcsec resolution
- HMI – *Helioseismic and Magnetic Imager*
  - successor to SOHO/MDI
  - full disk visible light and magnetic field imager
- EVE – *Extreme ultraviolet Variability Experiment*
  - measures EUV irradiance spectrum from full Sun (no spatial resolution)

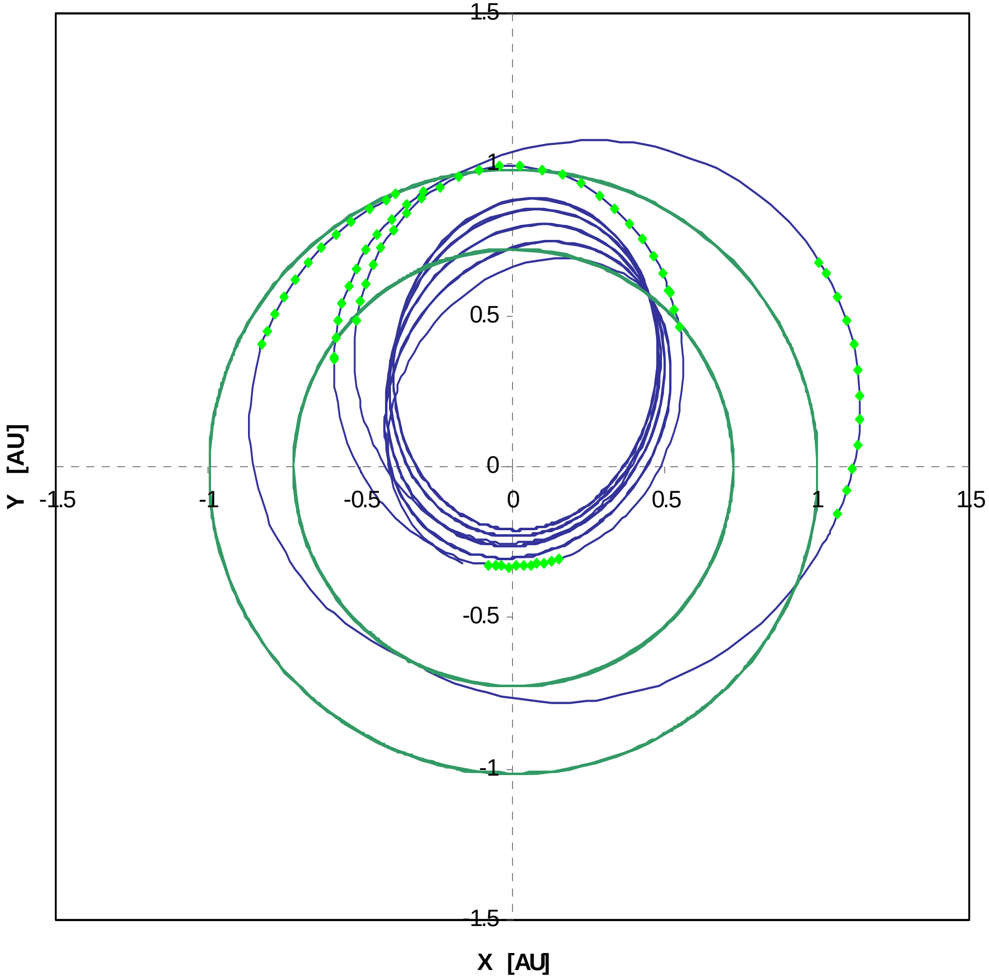
Solar Orbiter

- ESA mission to be run jointly with Bepi-Colombo
- Launch ~2012-2013
- Will get as close as 0.2 a.u.
- Both in-situ and remote sensing instrument packages
- Remote sensing:
  - Visible imager and magnetograph
  - EUV imager
  - EUV spectrometer
  - Coronagraph



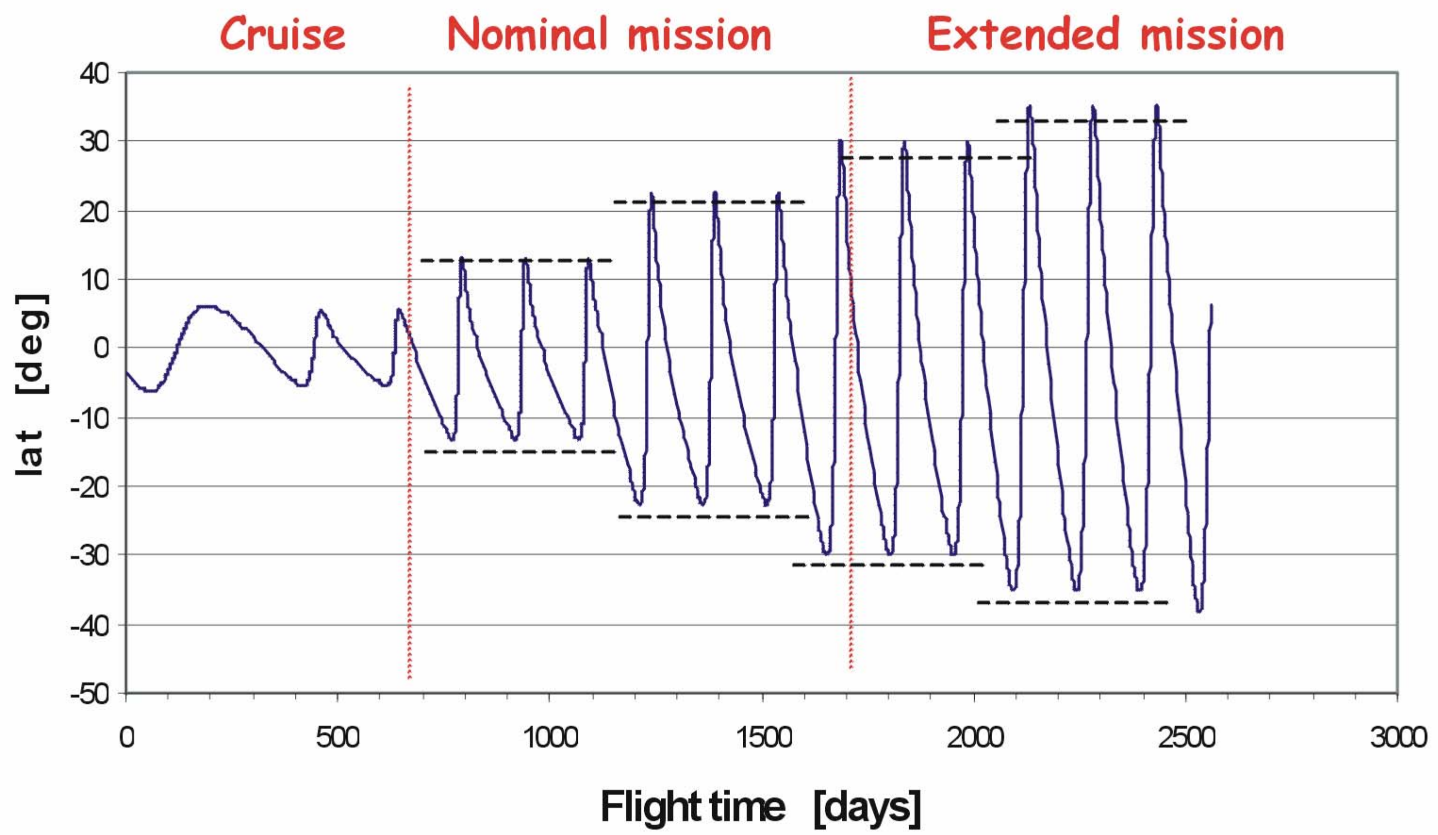
Orbit

- Each orbit is around 150 days
- Every 3rd orbit a fly-by of Venus gives an out of the ecliptic kick to the spacecraft
- Orbit reaches latitudes of ~30° during extended mission (> 4 years)



Solar Orbiter Latitude Range

- First remote sensing of the solar poles!



End of Talk

- Remote sensing imaging and spectroscopy allow detailed information about the Sun's atmosphere to be derived
- Future missions will provide even better data…
- …but must go hand-in-hand with improved atomic data and plasma modelling