The Role of XUV and Soft X-ray Observations in Understanding the Solar Corona

In Celebration of the Career of Helen Mason

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Introduction and Summary

- Photon wavelength and energy ranges
  - XUV/EUV: 100 Å – 1200 Å or 0.1 keV – 0.01 keV
  - Soft X-ray: 1 Å – 100 Å or 10 keV – 0.1 keV

- Solar emission in these ranges is from plasma with 0.1 MK $\leq T_e \leq$ 50 MK

- Talk mainly about Coronal phenomena
  - discuss roles of X-ray and EUV imaging and spectroscopy in advancing knowledge

- Topics will include:
  - magnetic field involvements
  - solar cycle activity evolution and shorter term variability
  - coronal heating and the possible role of nanoflares
  - waves and coronal seismology
  - solar flares and magnetic reconnection
  - near-surface manifestations of CMEs

Solar Corona

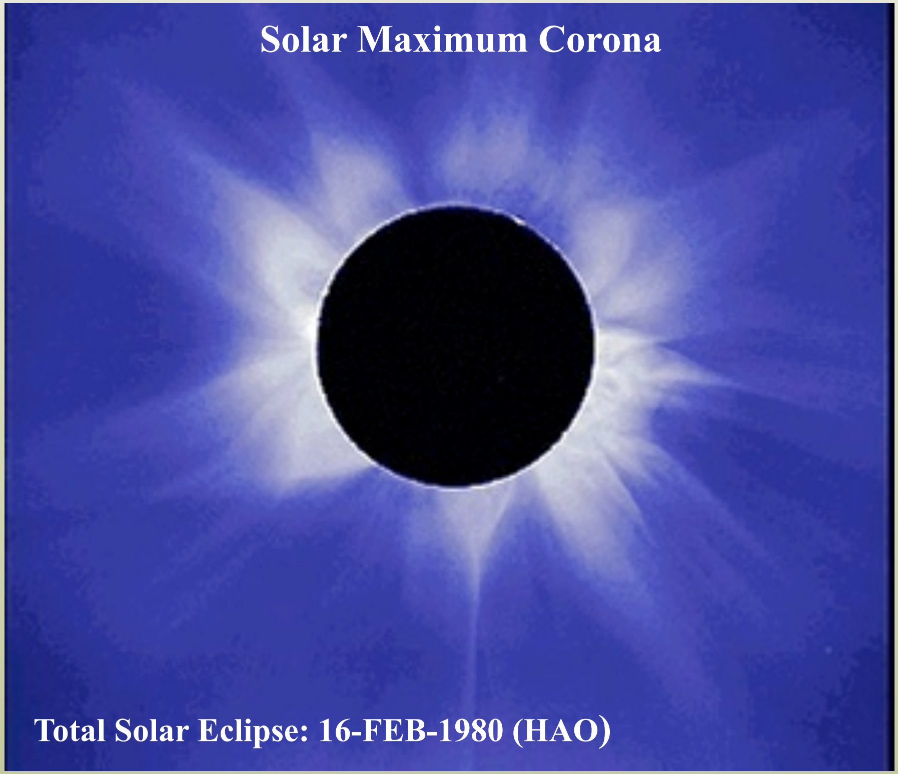
- Identification of the Corona was from visible light ***images*** during total eclipses

- First real clues to its physical nature were from visible ***spectroscopy***
  - Edlén (1942) identified the forbidden lines of Fe X , Fe XIV, Ca XV
  - suggests low density high T_e plasma with T_e ~ 1 MK

- Burnight (1949) found evidence for coronal ***X-ray*** emission in a V-2 rocket flight of photographic emulsion behind thin metallic filters

- Continuing NRL work by Friedman and colleagues supported this

- Early ***EUV*** focus was on H I Lyman-α and He II 304 Å emission



Magnetic Structures in the Corona

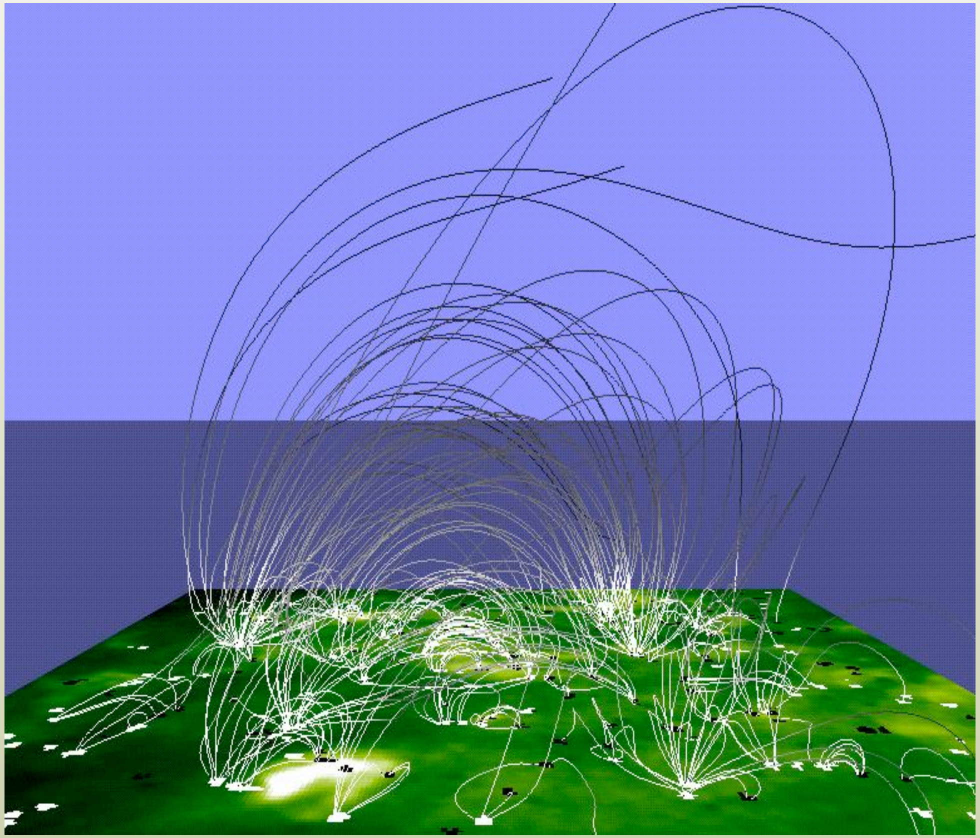
- $\beta << 1$ so Coronal magnetic structures contain the high-T_e plasma

- Structures include:
  - Bipolar Bright Point loops
  - Active Region (AR) loops
  - AR to AR or transequatorial loops
  - Coronal Streamers (Field partly open)
  - Coronal Holes (Field open)

- Coronal open field structures are sources of fast and slow solar winds

- All of the above relate to emerging flux
  - $\Phi = \int B.dA$
  - B is generated by dynamo action in the convection zone

Magnetic Carpet



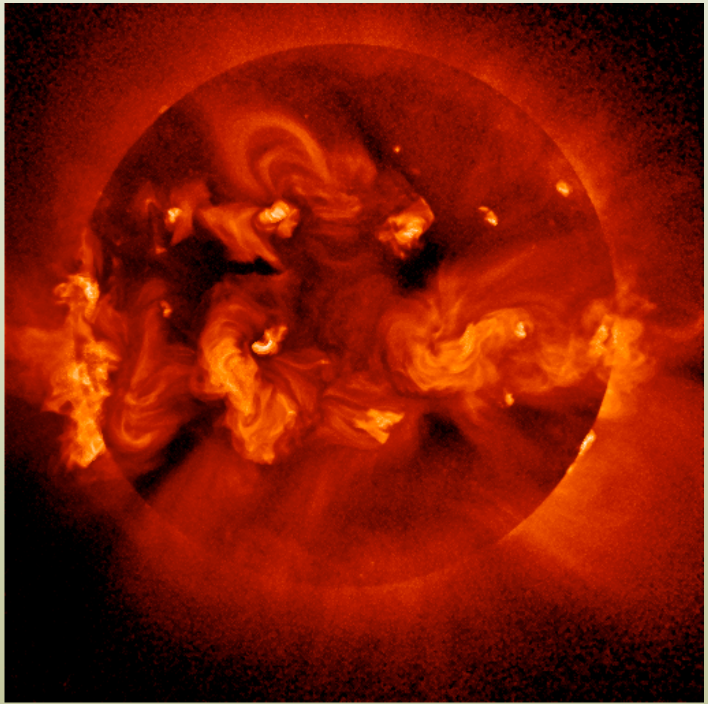
- Field lines from potential field extrapolation of Photospheric LOS fields from SOHO/MDI observations

X-ray Corona – Yohkoh SXT Images

Yohkoh X-ray image near Solar maximum - January,1992

Note:

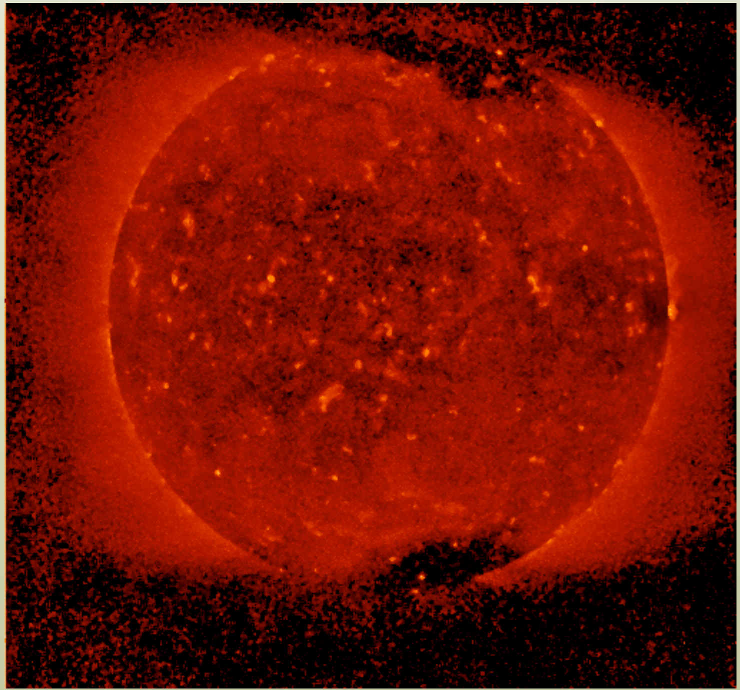
- Complex AR loop structures
- Streamers around the limb
- Distributed Coronal Holes



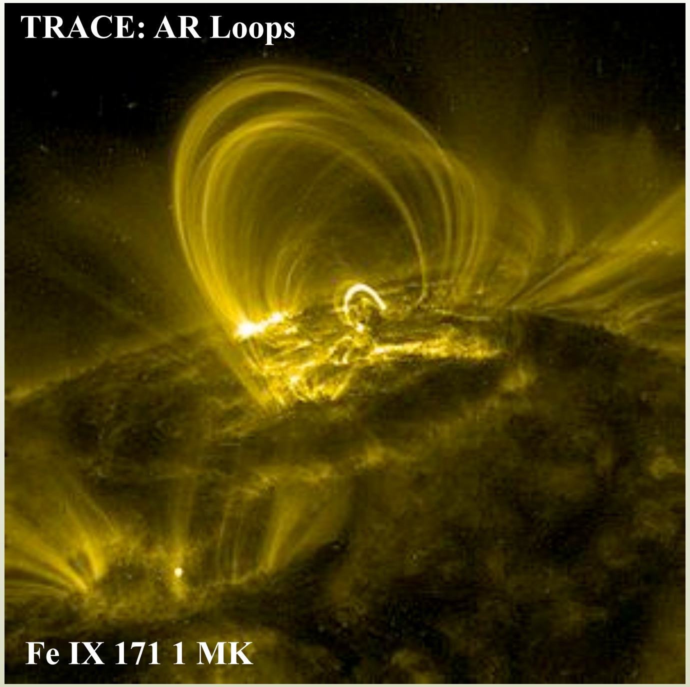
Yohkoh X-ray image at Solar minimum - April,1996

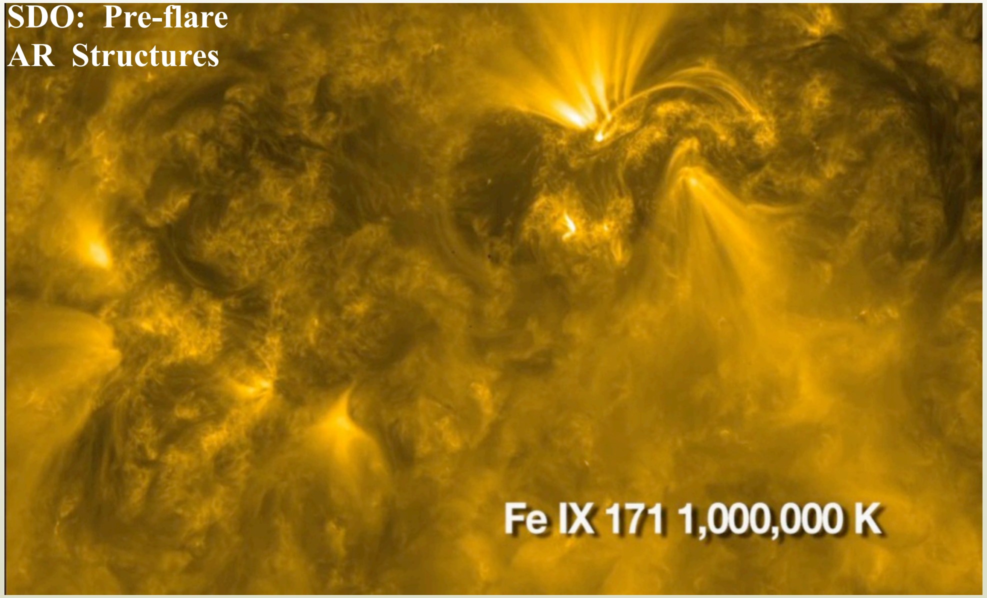
Note:

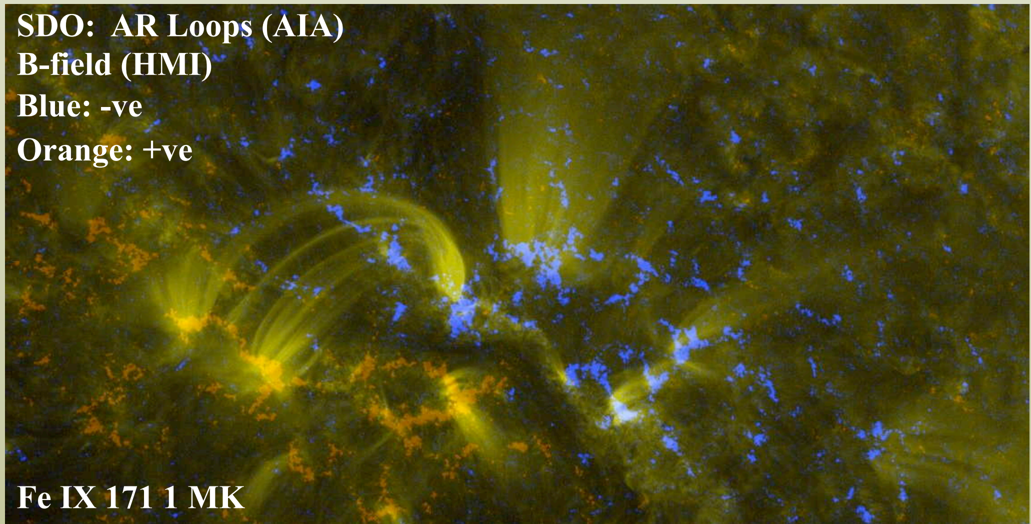
- Few AR
- Many visible Bright Points
- North- and South-polar Coronal Holes

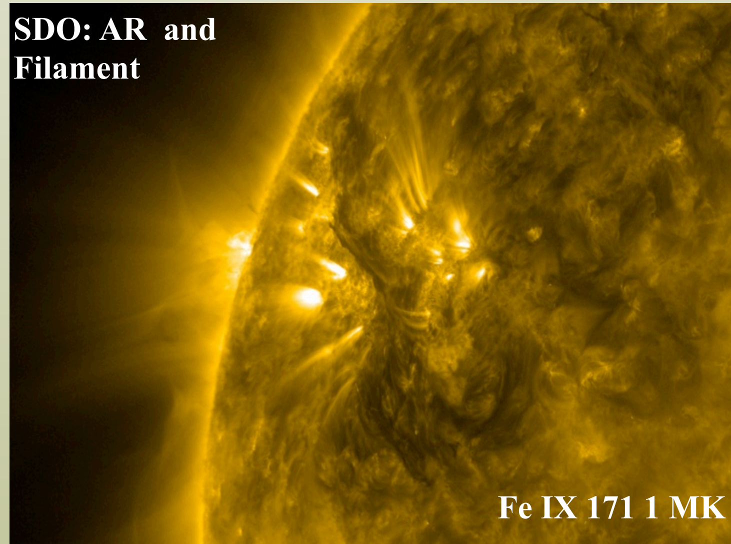


EUV Corona – TRACE and SDO Images





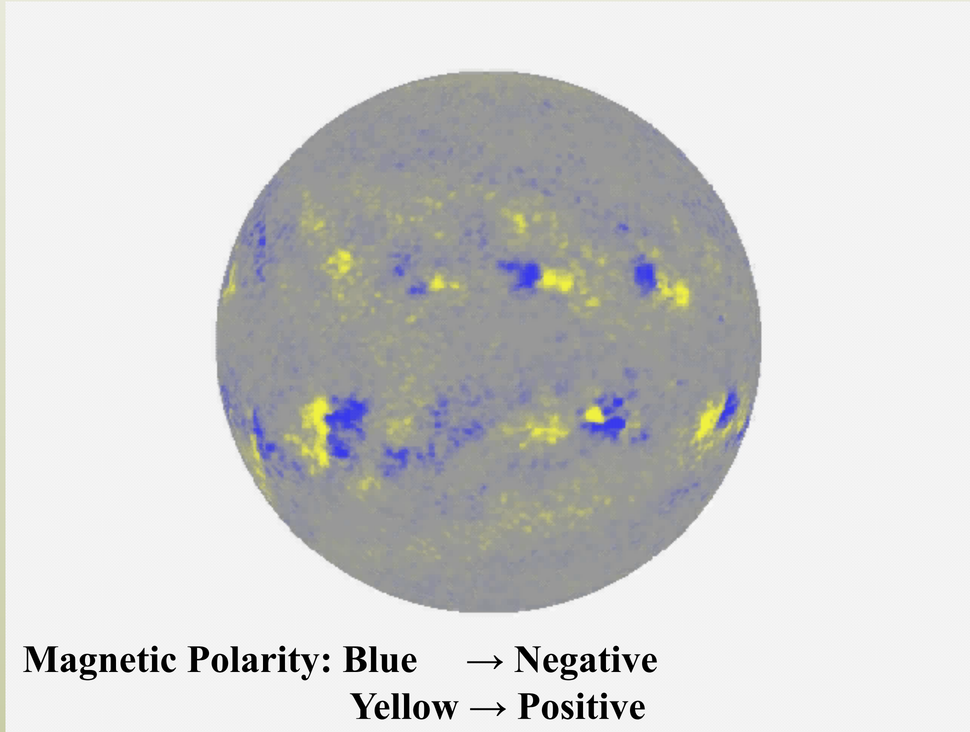


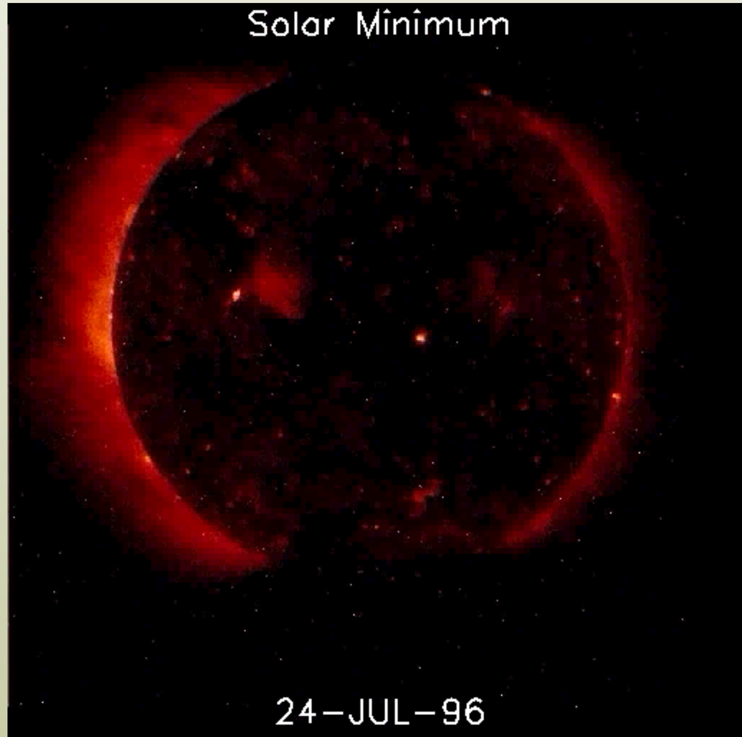


Solar Cycle Activity Evolution

- KPNO Magnetogram Movie (Hathaway)
  - shows photospheric magnetic field evolution for 1980 to 2003

- Yohkoh SXT Movie (Acton)
  - shows coronal X-ray evolution from cycle 23 minimum (2006) towards next maximum



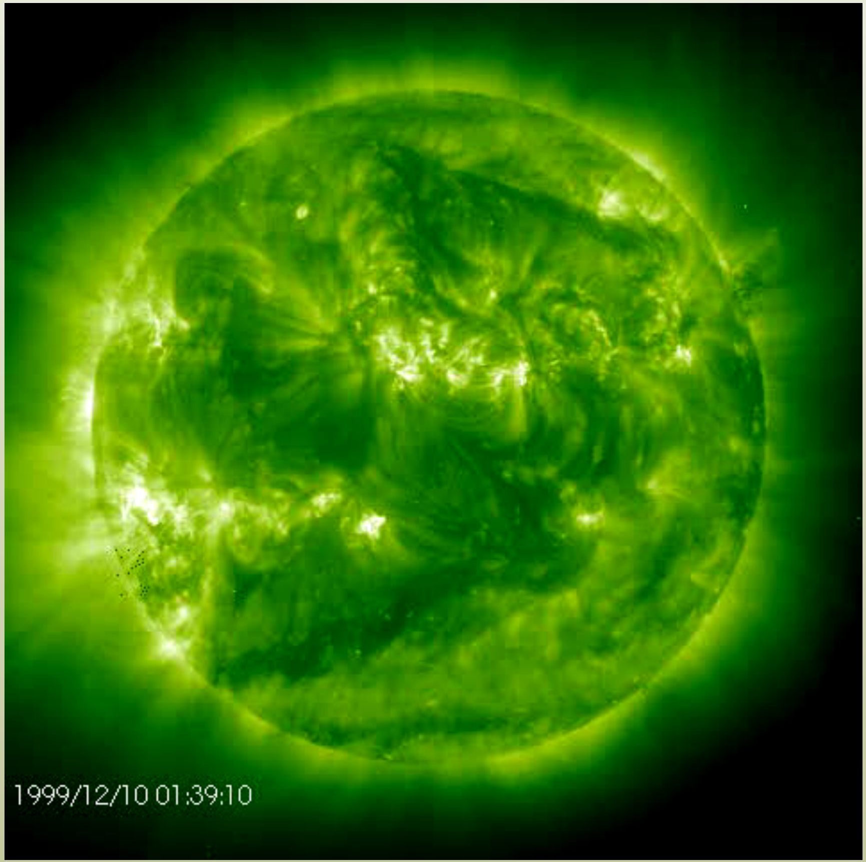


Coronal Structure Variability

- EUV observations have proved most valuable for many long term observations of chromospheric and coronal variability

- Coronal structures in particular vary on timescales of minutes through hours to months

- Movie shows SOHO/EIT 195Å images of the corona for the interval 10 – 23 December, 1999



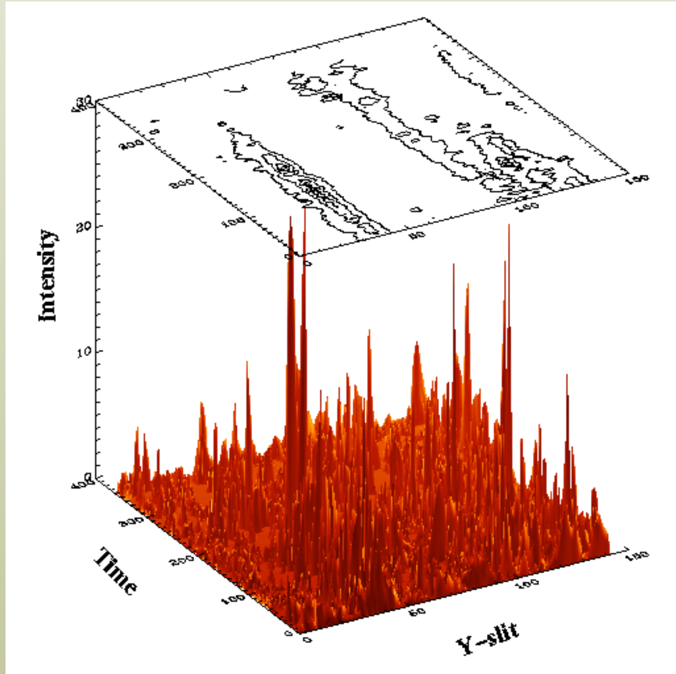
Coronal Heating - Flare-like EUV Brightenings in the Quiet Sun

- Flare occurrence is distributed with total energy/event, W as $dN/dW = AW^{-\alpha}$
  - nanoflare **coronal heating** requires $\alpha \geq 2$ (Hudson, 1991) ***assuming*** power law extends to small W
- Class of microflares – “blinkers”, found by Harrison (1997) at network junctions with SOHO/CDS
  - concluded available energy not sufficient to heat the corona
- Brightenings observed in quiet Sun with CDS, both in network and cells (Harra et al., 2000)
  - for: network α = 1.5; cells α = 2.5; whole Sun α = 1.7

O V

45,000km

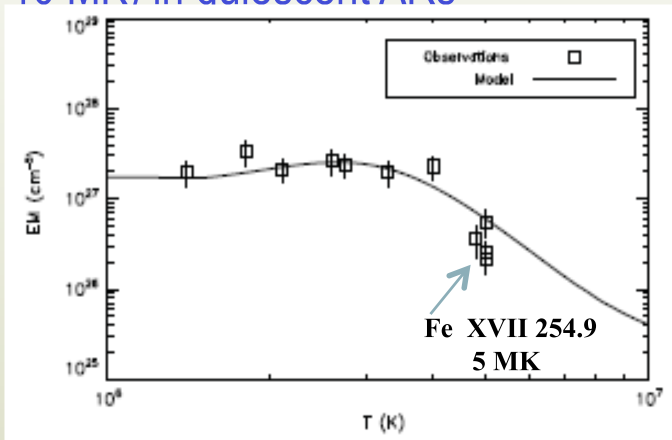
7,500 km

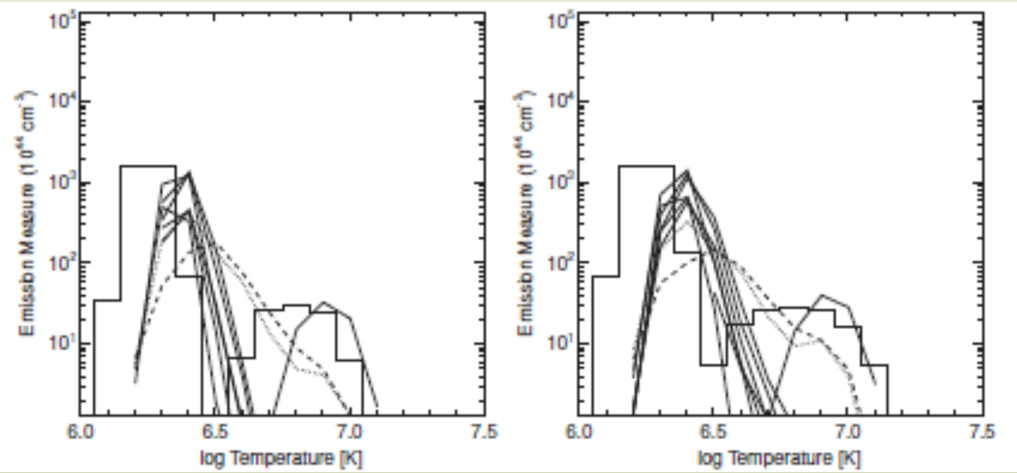


- Whole Sun values $1.3 < \alpha < 2.6$ reported from EIT and TRACE observations
- Difficult to reliably estimate W for small events

Coronal Heating – High T_e Plasma in Non-flaring Active Regions

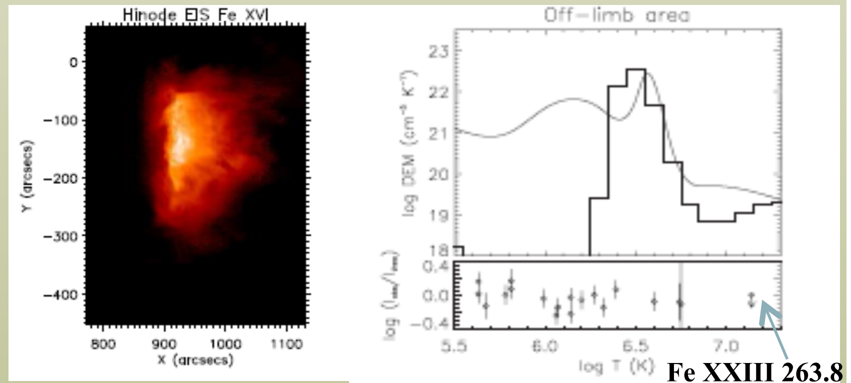
- Nanoflare heating in unresolved AR loop strands also possible (Cargill, 1993, Klimchuk, 2006)
  - need to find evidence for very small amounts of hot material (T_e ~ 10 MK) in quiescent ARs
- Patsurakos & Klimchuk (2009) found a nanoflare model fit to EIS AR emission measure observations for T_e ~ 1 to 5 MK
  - model better constrained if higher T_e lines observed





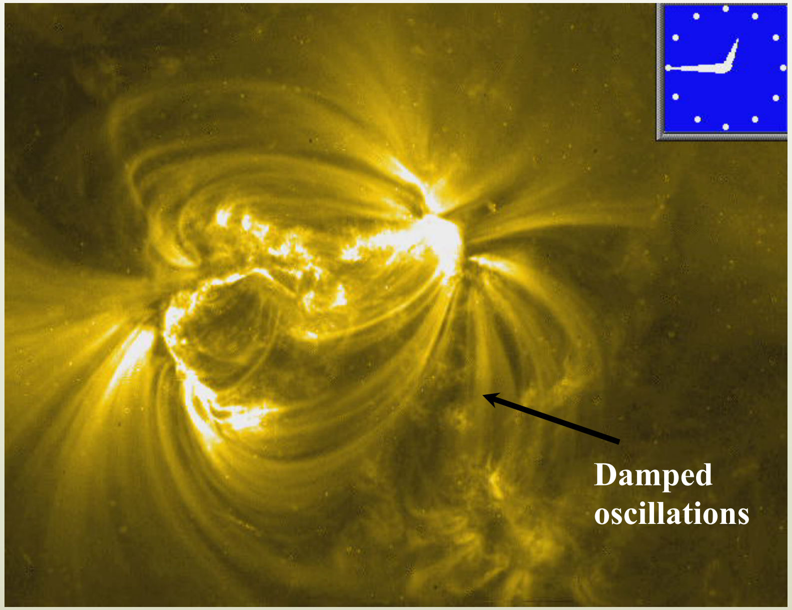
- Reale et al. (2009) found T_e ~ 10 MK plasma in an AR using Hinode XRT filter ratios
  - note that $EM_{10\,MK} \leq 0.03\ EM_{3\,MK}$

- O'Dwyer et al., (2010) constructed DEM plots for an off-limb AR segment using EIS and XRT observations
  - good agreement for T_e ~ 3 to 5 MK
  - Fe XXIII upper limit consistent with both DEM curves
- Important to detect the weak high-T_e lines at ~ 10 MK



Observations of Coronal Loop Oscillations

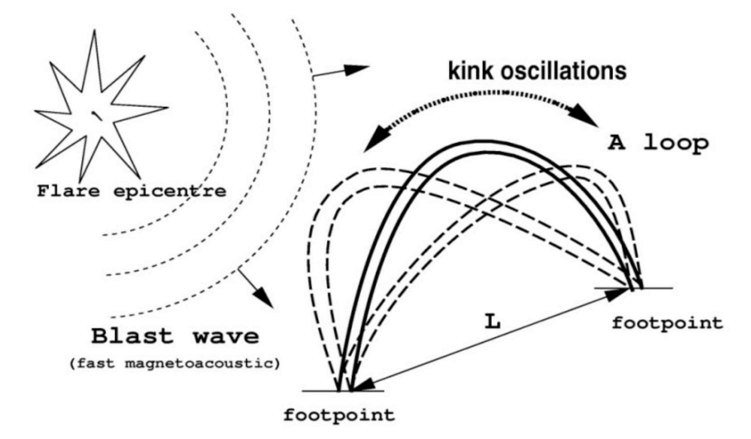
- TRACE Observations in 171 Å channel (T_e ~ 1.3 MK) during a flare on 14-JUL-1998:
  - Aschwanden et al. 1999, Nakariakov et al. 1999



- Damped transverse spatial oscillations of loops seen
  - f ~ 3.9 mHz with ~ 12 ± 6 min decay time

- Global kink mode oscillation triggered by flare

- Later use of the STEREO EUVI-A and -B instruments (Verwichte et al., 2009) allowed
  - polarization identification and measurement of loop length
  - magnetic field estimate of B = 11 ± 2 Gauss



- Improved density measurements required e.g. from EIS

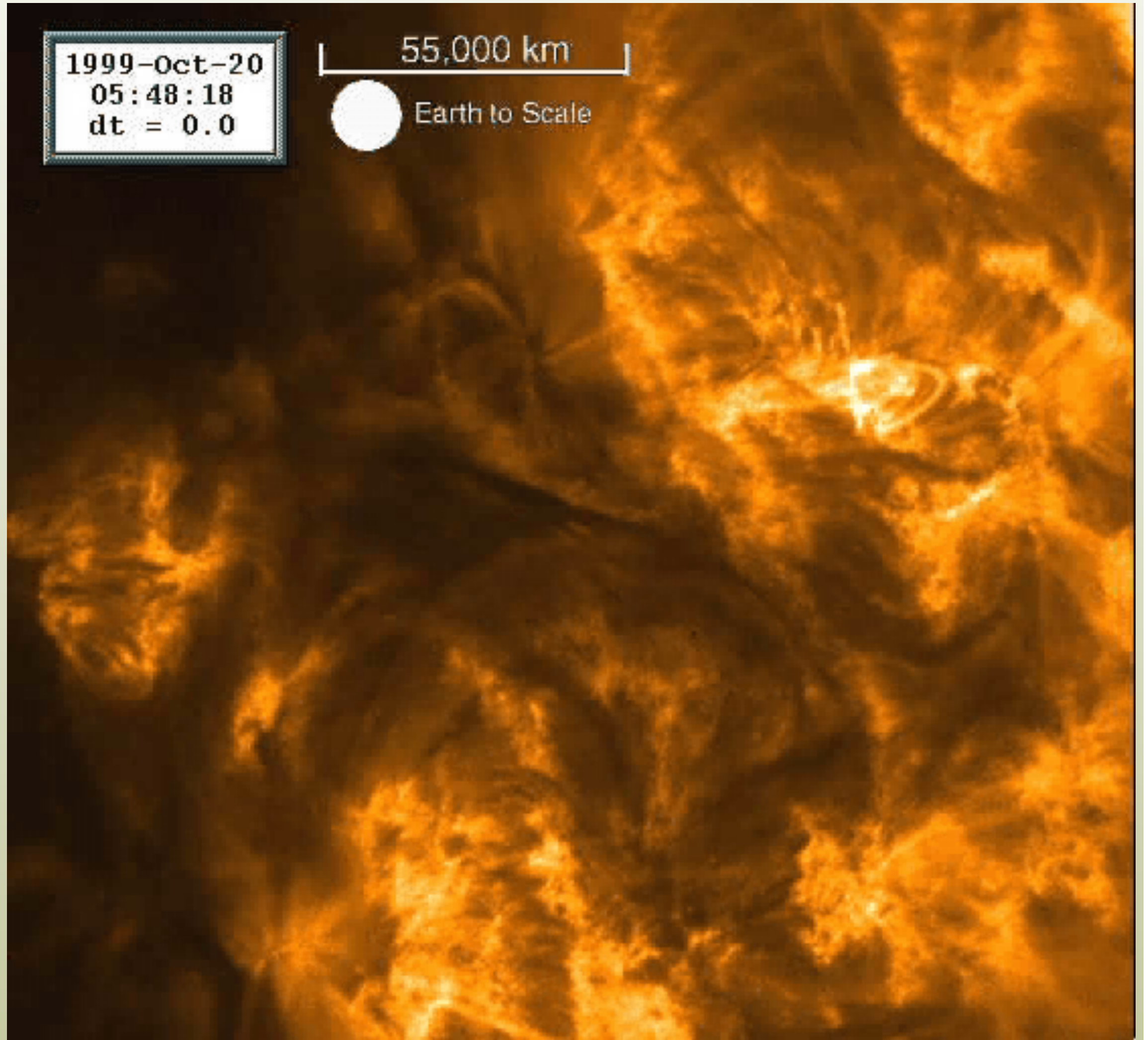
- Coronal Seismology will surely be transformed by SDO/AIA observations!

Solar Flares in the Corona

- Movie shows a coronal flare seen in EUV by TRACE

- Unstable magnetic field relaxes to a lower energy state with released energy
  - accelerates particles
  - forms two bright ribbon in the Photosphere
  - heats plasma
  - related to filament eruption and mass ejection?

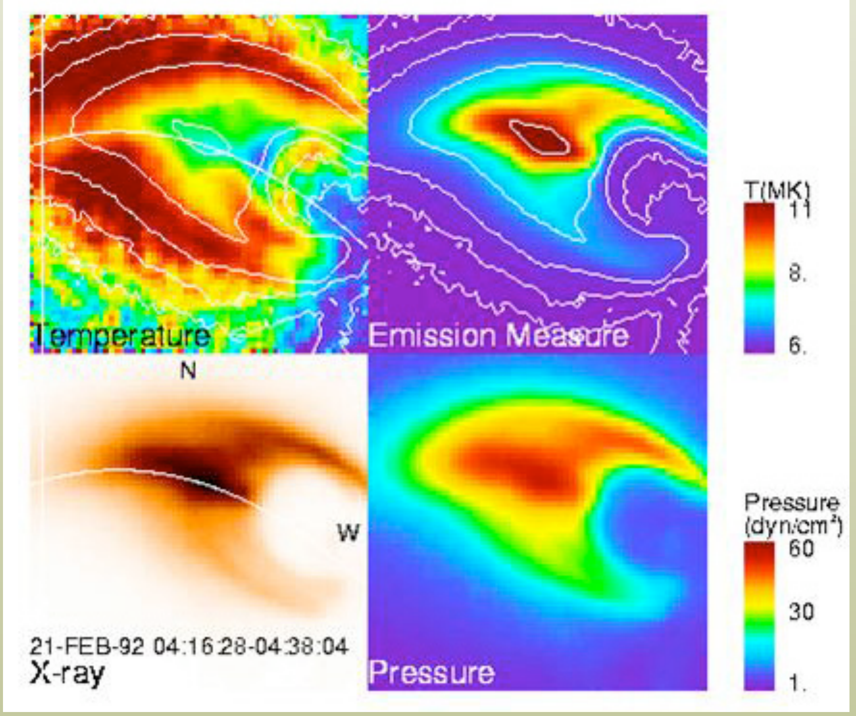
- After reconnection loops filled with hot Chromospheric plasma formed and later cool

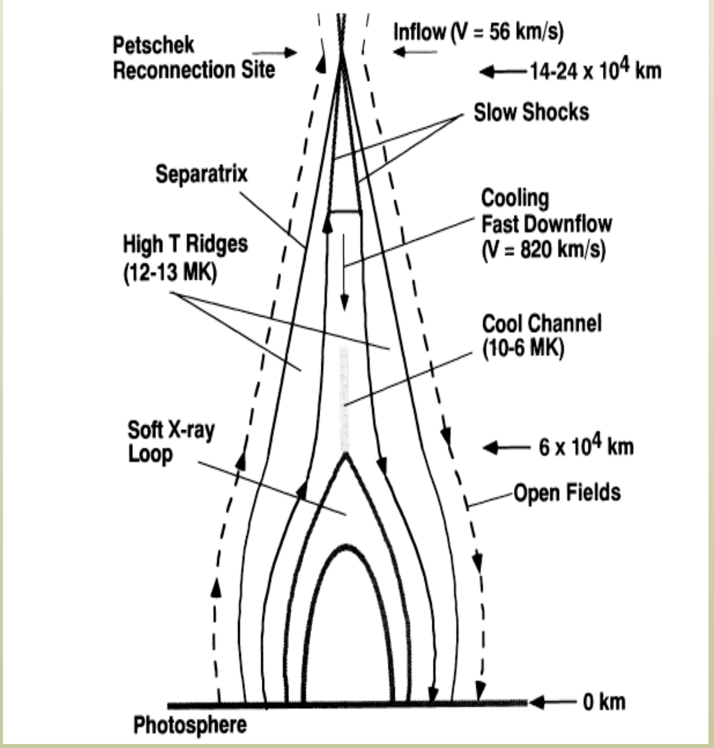


Flares and Magnetic Reconnection – X-ray Observations

- For a major two-ribbon flare (Yohkoh SXT), Tsuneta (1996) showed large–scale reconnection occurred consistent with the CHSKP model
  - compared observed structure and temperatures to model but no evidence for fast shock
  - no spatially resolved velocity measurements

- Later imaging observations identified reconnection-related flows
  - downflow observed in Yohkoh/SXT images (Mckenzie & Hudson, 1999)
  - inflow observed in SOHO/EIT images (Yokoyama, 2001)





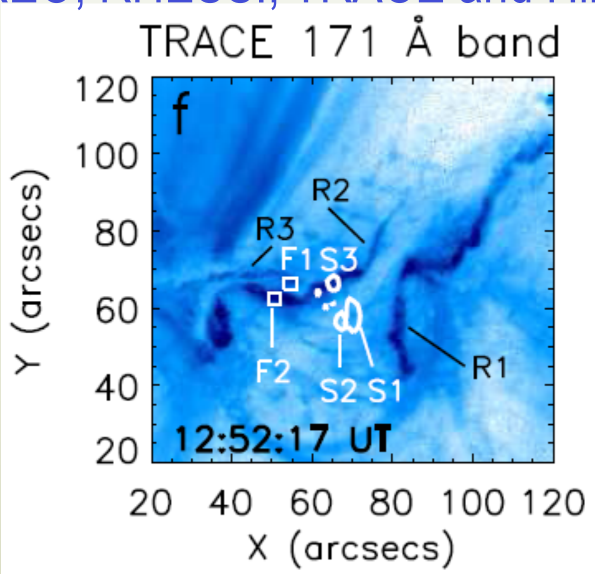
Flares and Magnetic Reconnection – EIS EUV Spectra

- B9.5 long duration flare on19-MAY-2007 (Hara et al.): Impulsive phase peak 12:51:20 UT
  - STEREO, RHESSI, TRACE and Hinode/XRT imaging used along with Hinode/EIS spectra

EIS

S1, S2:
T_e ~ 12 MK

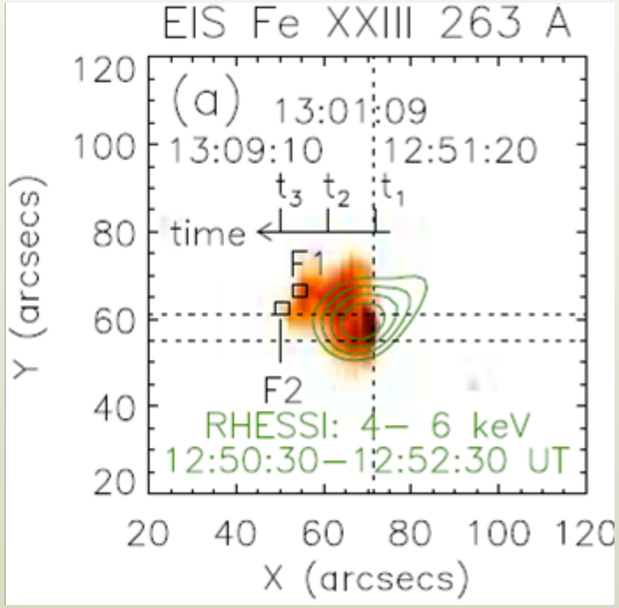
F1, F2: Loop footpoints



T_e ~ 11 - 12 MK
from $I_{Fe\ XXIV}$ / $I_{Fe\ XXIII}$

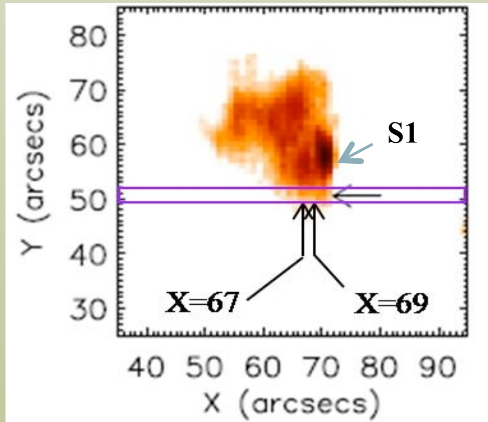
RHESSI thermal source has
T_e ~ 12 MK

EIS slit at S1 for impulse peak

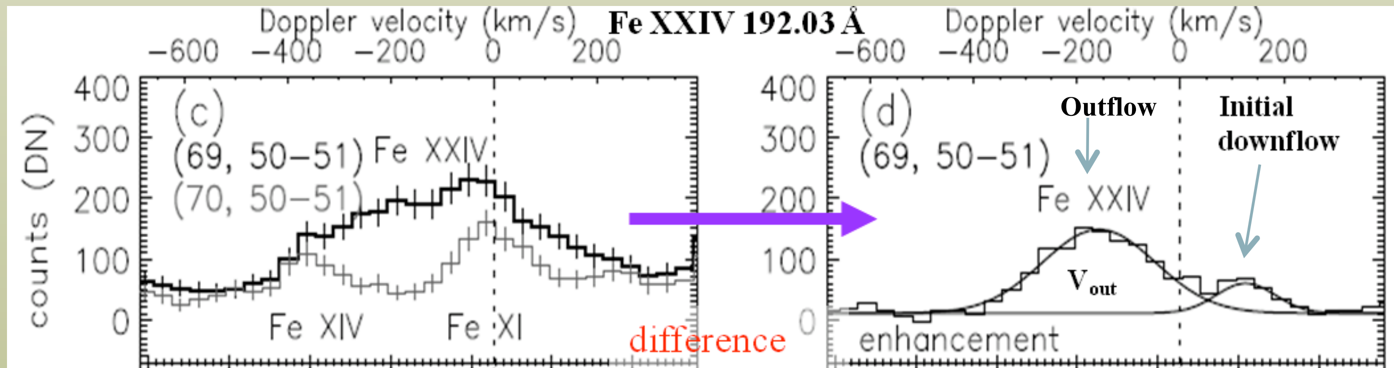


X = 69: Flow
X = 67: No flow

Flow width ~ 3 arcsec

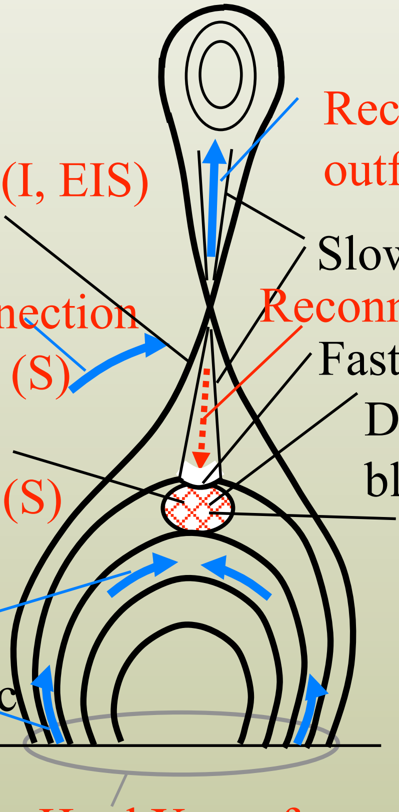


Difference of spectra gives V_{FLOW} estimates: V_{OUT} ~ 200 km/s; V_{DOWN} ~ 100 km/s



Flares and Magnetic Reconnection – EUV Spectra (Cont.)

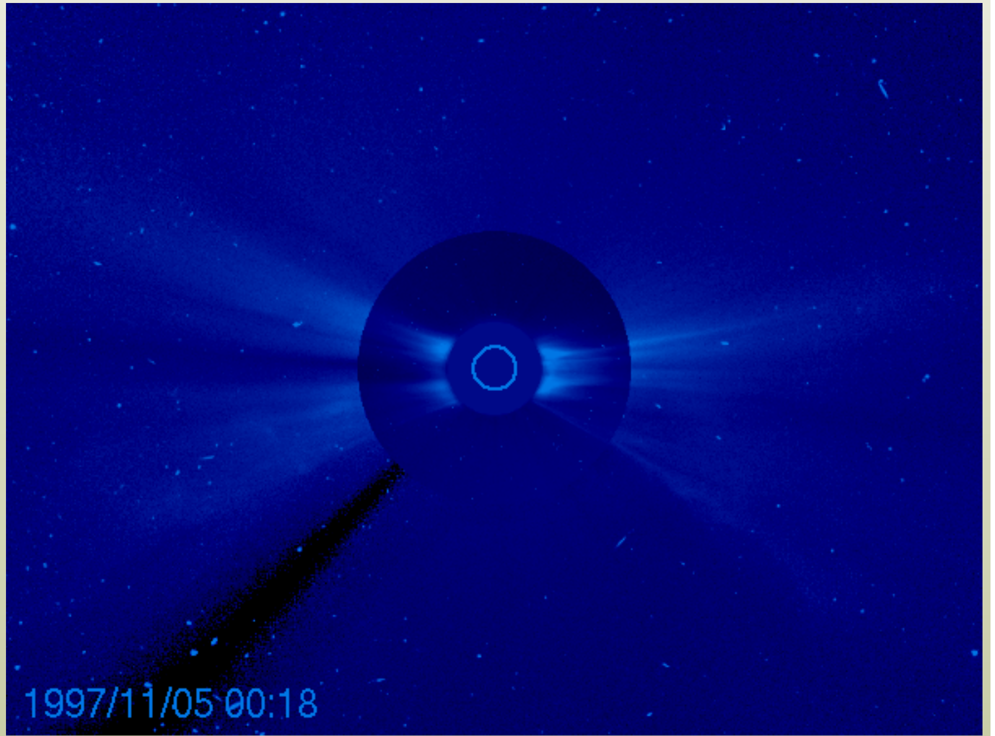
- All of the EIS observations summarised on a CHSKP diagram
- Observations show many features of the standard flare reconnection model
- EIS emission line data provide T_e, n_e and plasma velocity measurements
- Isolated Fe XXIII / XXIV 12 MK source located high in the corona
  - enhanced line broadening suggests source turbulence
  - heating, outflows and inflow observed
  - evaporation upflow seen following non-thermal energy release
- Standard Flare Model?
  - complexities require consideration of 3-D structure



Coronal Mass Ejections - CMEs

- Observed in white light – electron scattered photospheric emission
  - first systematic studies from coronagraphs in space e.g. Skylab ATM, SMM
- Corona viewed at ~ $R \geq 1.5 – 2.0\ R_{\odot}$
- Ejected mass ~ 10^{15} gm
- Key questions include:
  - launch site location e.g. front- or back-side
  - associated near-surface coronal features
  - eruption trigger
  - magnetic configurations involved
  - launch forecast possibility

SOHO LASCO - 05-NOV-1997



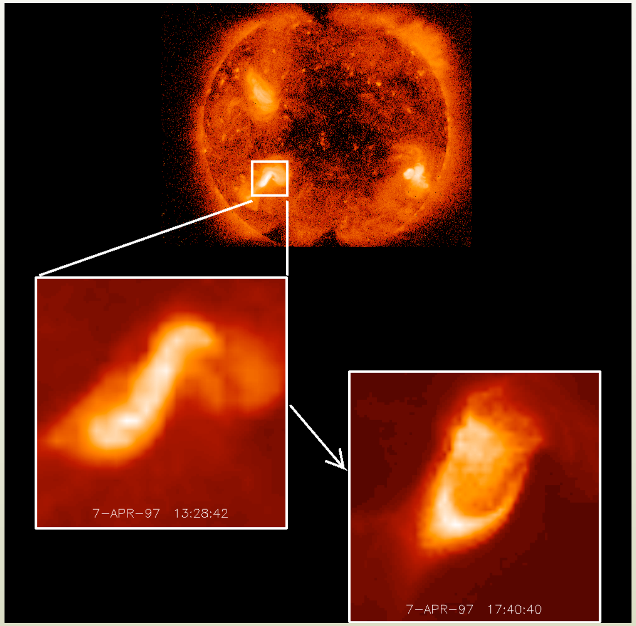
Surface Manifestations of CME Launching

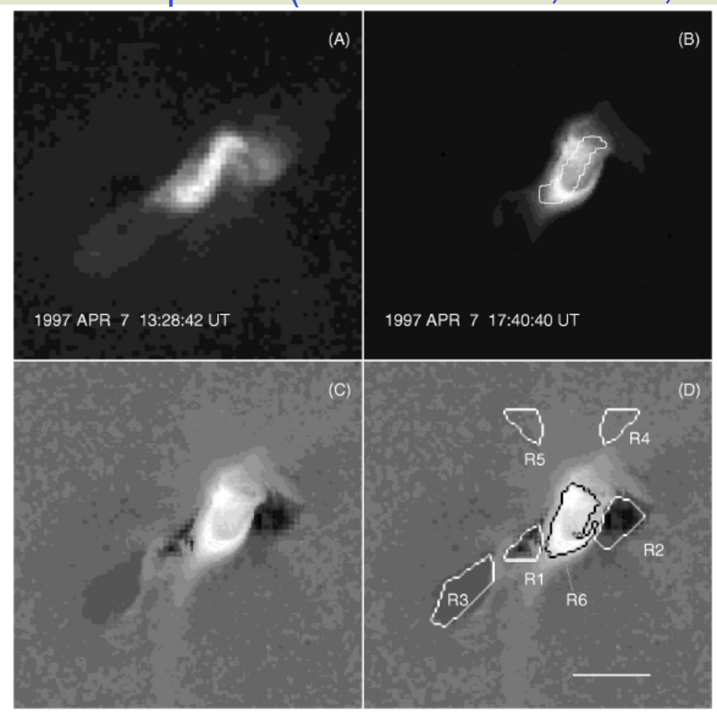
1. Sigmoid Magnetic Structures

- Yohkoh observations at the launch-site of the 07-April-1997 CME

- Sterling and Hudson (1997) found a pre-event sigmoid or S-shaped structure followed by a post-event cusp

- S-shaped structures have a high probability of association with eruptions (Canfield et al., 1999; Glover et al., 2000)





- Such magnetic flux-ropes may have a fundamental role in energizing mass ejections (Williams et al., 2005, Török et al., 2005)

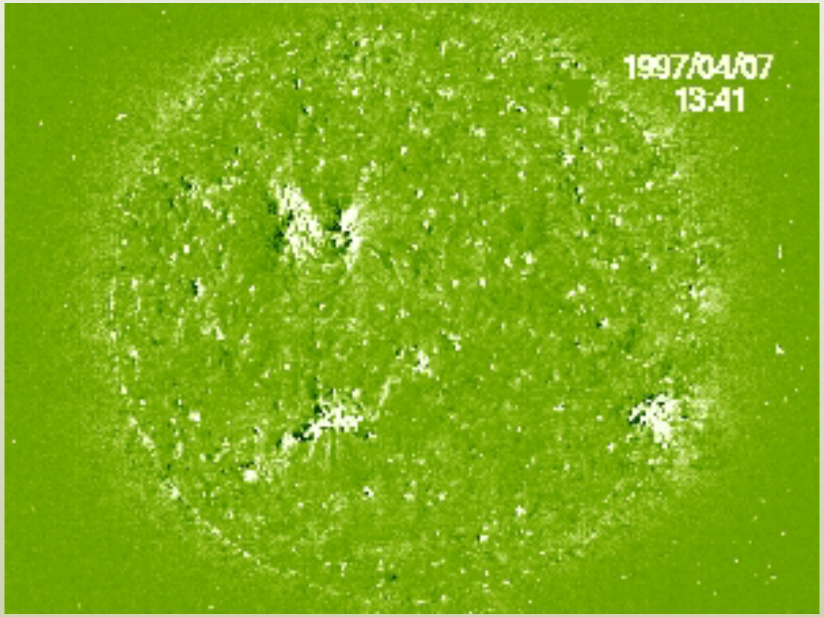
2. Coronal Dimming

- Sterling and Hudson (1997) also made the first association of "coronal dimming" with a halo CME
  - dimming regions seen in R1, R2 and R3
  - associated mass loss ~ 1. – 3. x 10^{14} gm
  - $\geq 10^{15}$ gm lost mass concealed by the flare?

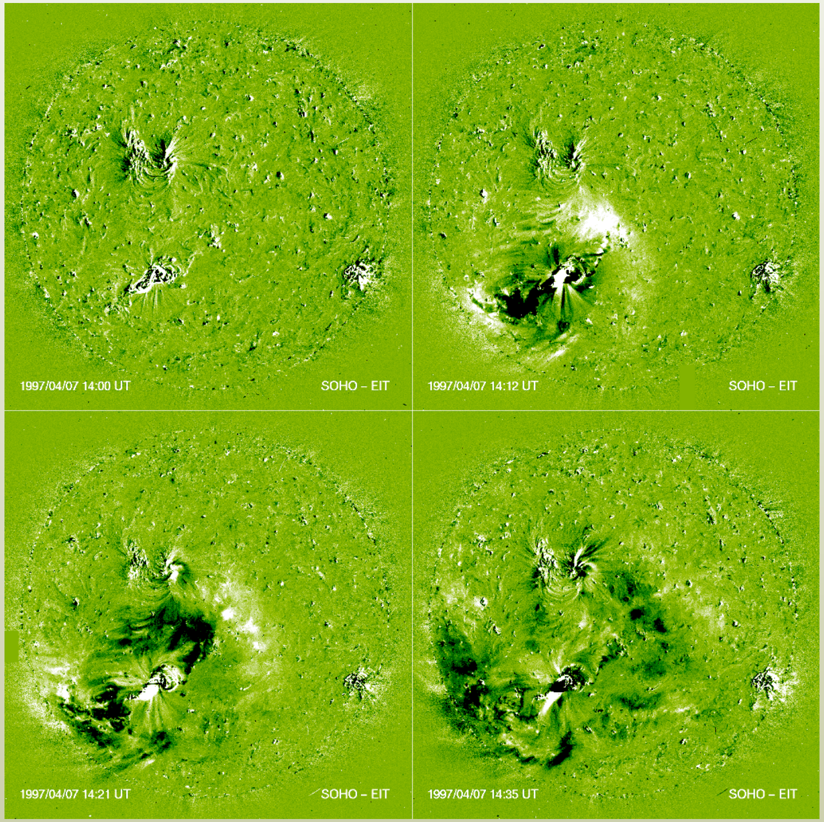
Surface Manifestations of CME Launching (Cont.)

3. Coronal Waves Detected by SOHO EIT – Fe XII, T_e ~ 1.2 MK

- First observed by Thompson et al. (1998)
- Frequently associated with CMEs



Wave seen with 7-APR-97 CME

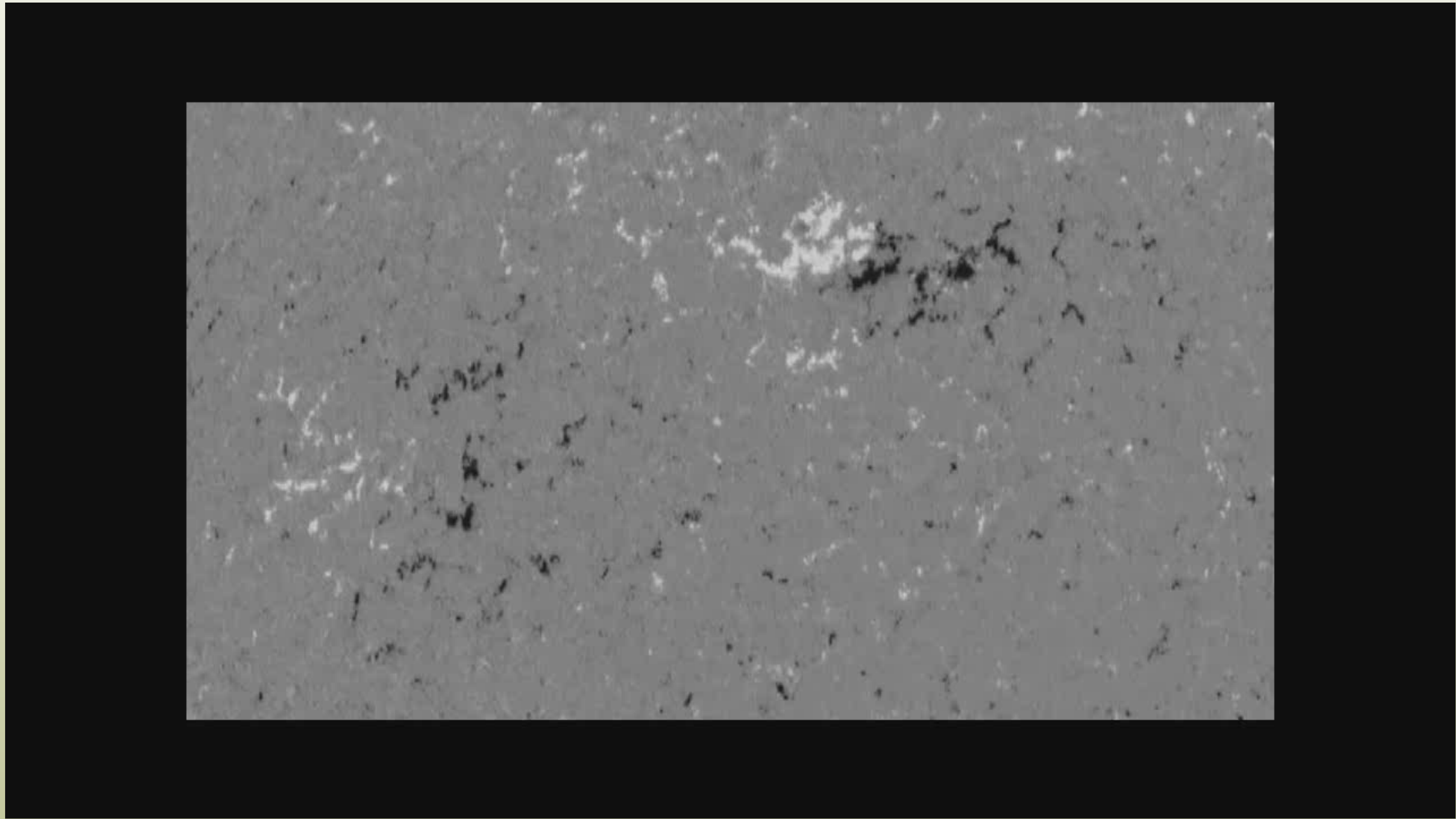


- Related to Photospheric Moreton Waves?
- Consequence of CME footprint?

→ SDO/AIA 10s cadence images must solve this!

SDO Sequence for Flare and Eruption – April 2010

- HMI magnetogram, He 304, Fe IX 171, Fe XII 193, Fe XX 131
- Chromospheric flare, Wave, Eruption, Dimming regions
- Flare plasma and arcade



Conclusions

- Although discovered through visible observations, X-ray and EUV imaging and spectroscopy have had the major impact on our knowledge of the Corona

- Dynamo-generated magnetic fields control the character of the plasma but its properties and evolution are best studied at EUV and X-ray wavelengths
    - **imaging** allows structure studies on timescales from 11 years to seconds
    - plasma properties and dynamics – T_e, n_e and v, best addressed by **spectroscopy**

- Areas advanced in several decades by X-ray and EUV observations include:
    - structure and activity in the corona
    - coronal plasma heating
    - energy transfer by and diagnostic role of coronal waves
    - solar flares
    - nature and origins of coronal mass ejections

- Much remains to be done – X-ray and EUV observations will continue to have a key role

Final Words

- This meeting is in Helen's honour
  - many facets of Solar Plasma Spectroscopy are being addressed
  - her field of major contribution

- I want to acknowledge her role as a leading UK Co-Investigator for Hinode/EIS
  - along with Peter Cargill and Eric Priest, she helped convince PPARC that they should fund substantial UK involvement in this mission

- More than three years post-launch, she and her group are major users of EIS data with many successful observations

Thank you H