

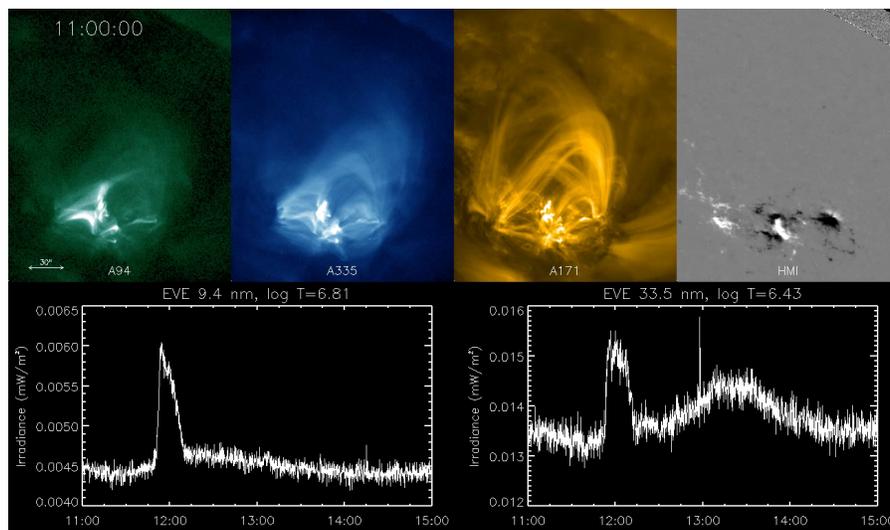
Solar Flares

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What is a solar flare?

- A sudden eruption of magnetic energy released on or near the surface of the sun, usually associated with sunspots and accompanied by bursts of electromagnetic radiation and particles.
 - *American Heritage Dictionary* (first known use of “solar flare” is 1938)



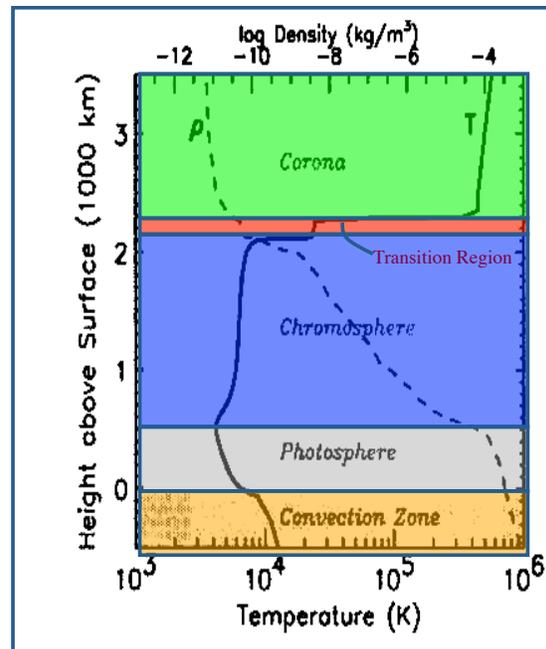
Outline of Talk about Solar Flares

- Introduction
 - movie, definitions, space weather effects, new SDO mission
- Flare Classification – X-ray magnitude
- Frequency of Flares
- Types of flares
 - 2-ribbon, confined, long decay event (LDE)
 - eruptive and non-eruptive
- 5 Flare Components/Phases
 - Onset, Impulsive Phase (IP), Gradual Phase (GP), Coronal Dimming (CD), EUV Late Phase (ELP)
- Radiation from flares
 - IP: hard X-ray (HXR), gamma ray (GR), transition region (TR) emissions
 - GP: soft X-ray (SXR), hot corona emissions
 - CD: cool corona emissions
 - ELP: warm corona emissions
- Summary of papers (homework)

REF: <references listed in handout>

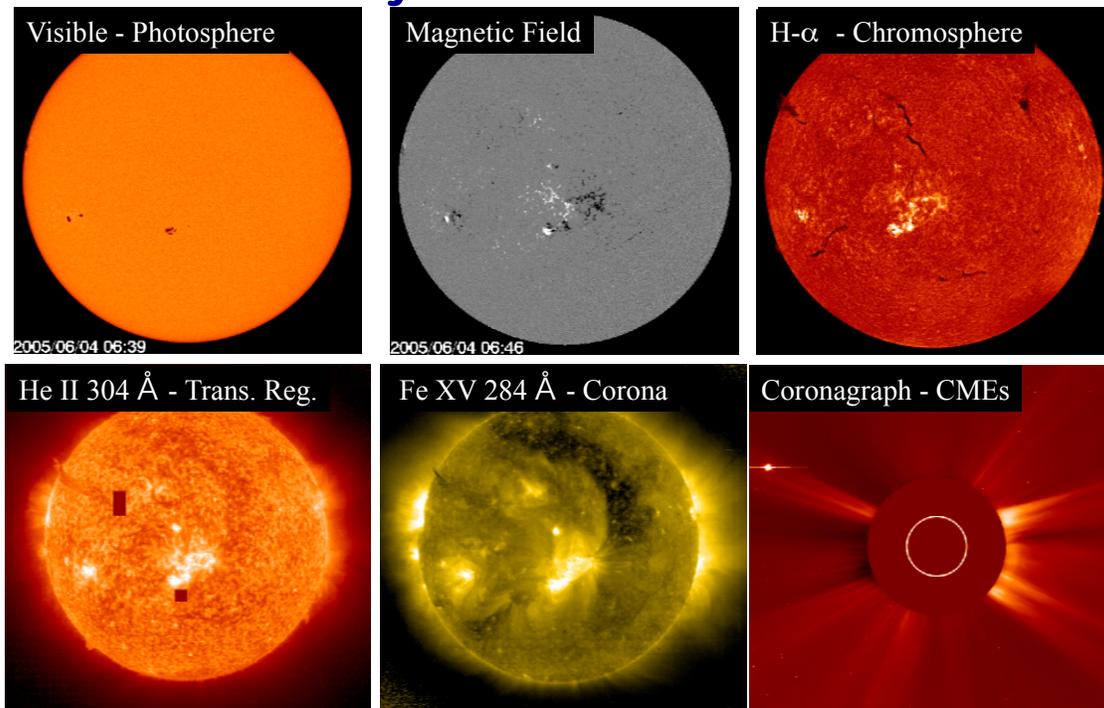
Layers of the Solar Atmosphere

- **Corona**
 - Outer layer - hot, low density
 - 0.5 to 10+ MK
- **Transition Region**
 - Thin transition layer for temperature rise, plasma, and LTE
 - 10,000 K to 500,000 K
 - neutral -> plasma
 - LTE -> non-LTE
- **Chromosphere**
 - Warmer layer
- **Photosphere**
 - “Surface” layer
 - temperature minimum: 5700 K
 - x 1000 **less** dense than air
- **Convection Zone**
 - Upper 1/3 of Sun
 - Solar dynamo
 - Source of magnetic activity



REF: Lean, A.R.A.A., 1997

Many Faces of the Sun

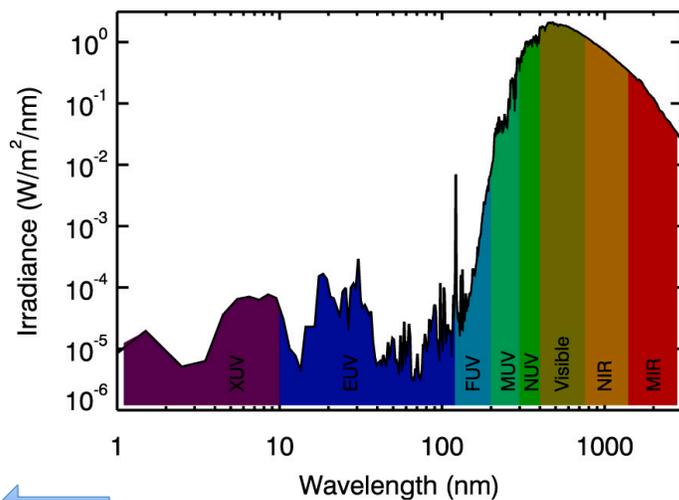


REF: Solscape (4 June 2005)

SOHO & Big Bear solar images

Spectral Ranges

- The following spectral ranges are those defined by the ISO #21348 standard concerning solar irradiance.



Range	Min - Max (nm)
Gamma ray	< 0.001 nm
Hard X-ray	0.001-0.1
Soft X-ray (or XUV)	0.1-10
Extreme UV (EUV)	10 - 120
Far UV (FUV)	120 - 200
Middle UV (MUV)	200 - 300
Near Ultraviolet (NUV)	300 - 400
Visible	400 - 760
Near Infrared (NIR)	760 - 1400
Middle IR (MIR)	1400 - 3000
Far IR (FIR)	3000 nm - 1 mm
Microwave	1 mm - 1 m
Radio	0.1 mm - 100 m

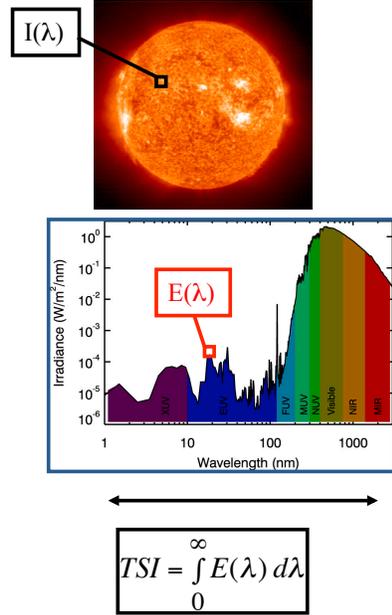
←
SXR
HXR
GR

→
FIR
Microwave
Radio

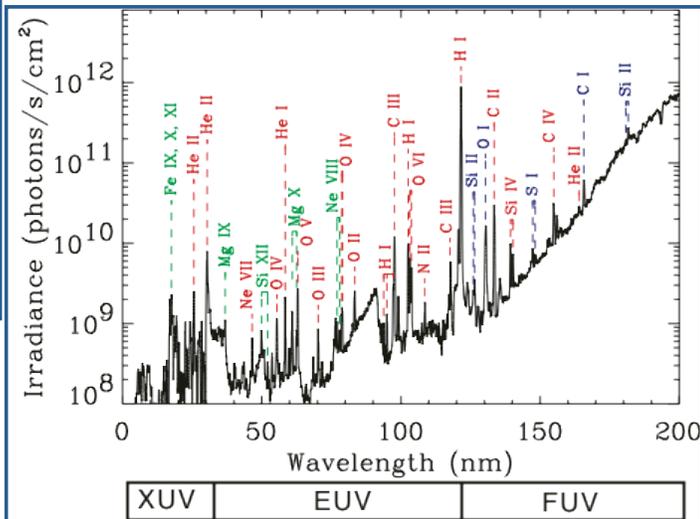
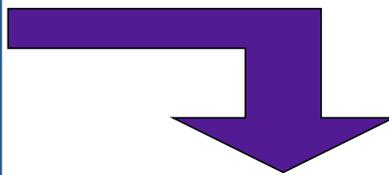
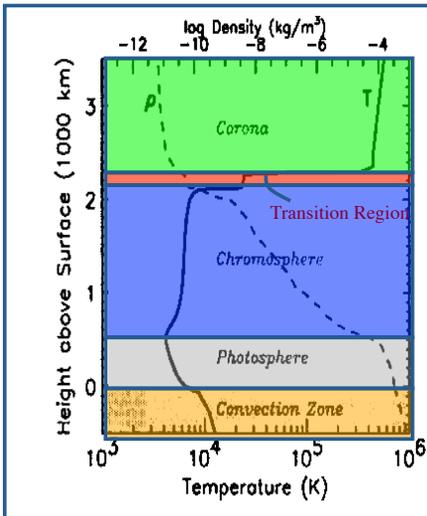
REF: <http://www.spacewx.com/ISOconfirm.html>

Radiance versus Irradiance

- Spectral Radiance, $I(\lambda)$, is the intensity from a small region on the Sun
 - Energy units of $W / m^2 / nm / steradian$
- Spectral Irradiance, $E(\lambda)$, is the solar radiance integrated over the solar disk
 - Sometimes called the full-disk radiation
 - Energy units of $W / m^2 / nm$
 - Often normalized to a distance of 1.0 AU
- Total Spectral Irradiance (TSI) is the integration of the solar spectral irradiance over all wavelengths
 - Sometimes called the solar constant
 - Energy units of W / m^2
 - Often normalized to a distance of 1.0 AU



UV Emissions are from Different Solar Layers

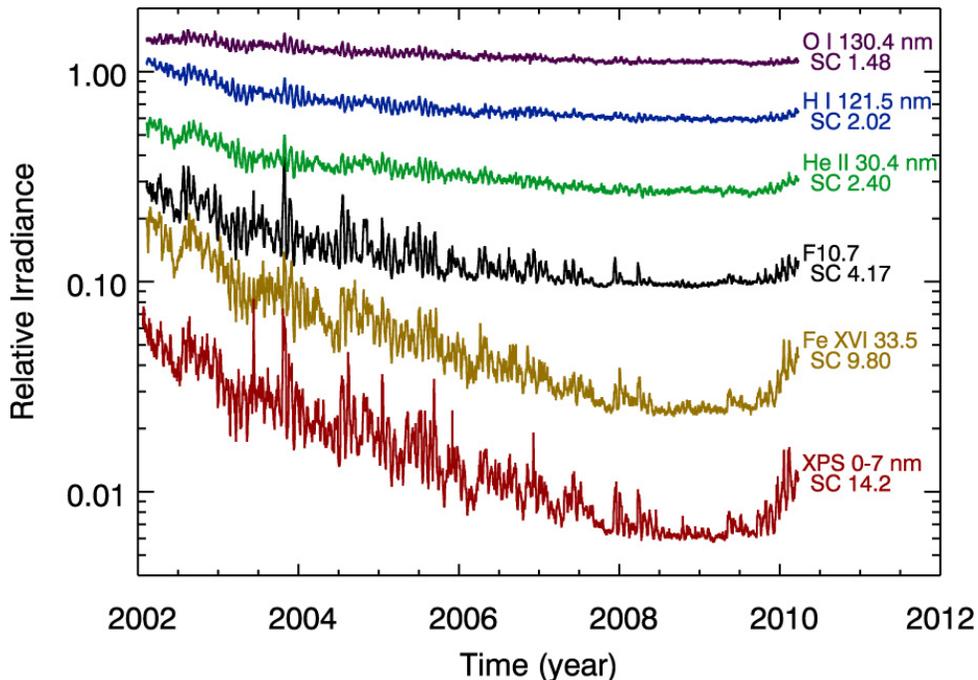


Atomic / Ions naming:

- He I = He (atom)
- He II = He⁺ (ionized once)
- C IV = C³⁺ (ionized 3 times)

EUV: The Heartbeat of Space Weather

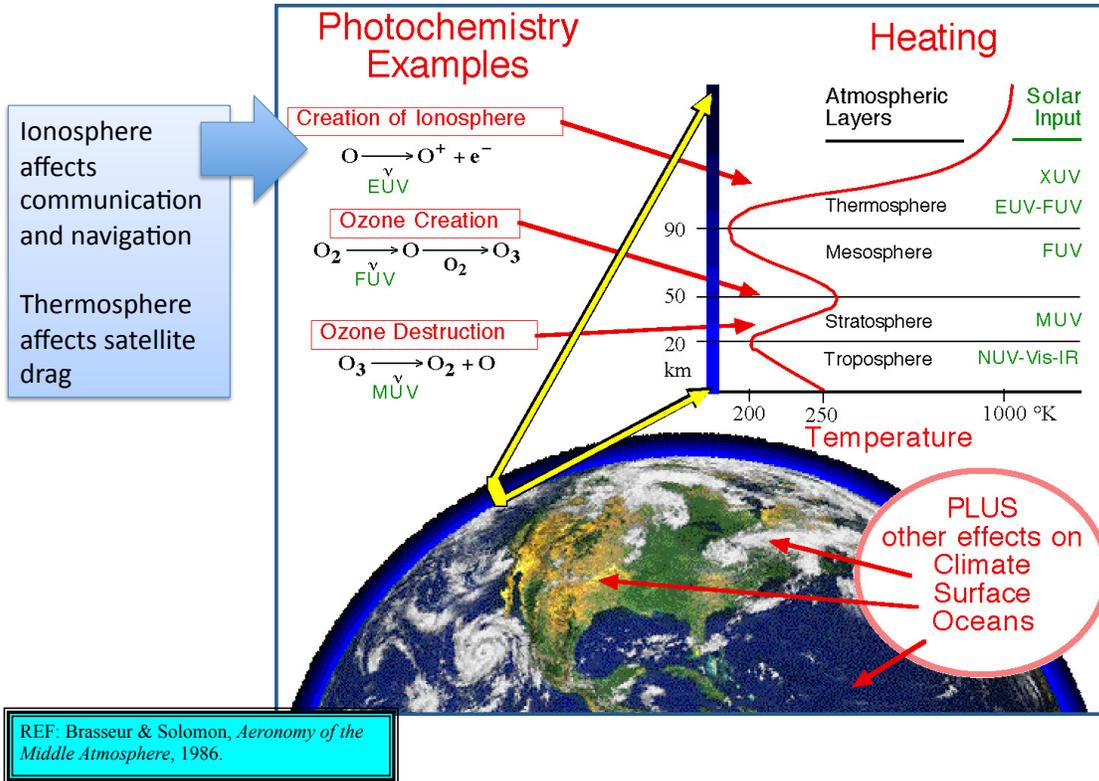
EUV variability is dominated by 27-day solar rotation
on top of 11-year solar cycle (SC) slow variation



Why are solar flares important for Earth's atmosphere and space weather?

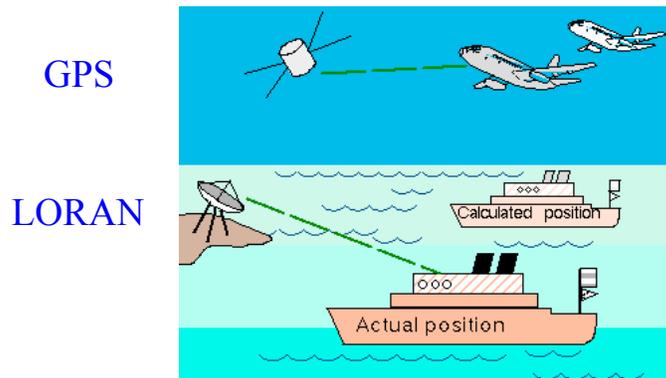
- Atmospheric Absorption
 - Ultraviolet (UV) radiation shortward of 320 nm is completely absorbed in the atmosphere
 - Solar UV radiation drives heating, chemistry, and dynamics in the atmosphere
- Space Weather Effects
 - Communication Disruption
 - Ionospheric changes can disrupt communications
 - Ground-to-ground long distance radio waves
 - Ground-to-air communication during air flights
 - Navigation Errors
 - Precision of navigation systems (GPS, LORAN, OMEGA) are impacted by ionospheric changes
 - Radiation Hazards to Humans
 - Astronauts, outside Earth's protective atmosphere, are at risk during large solar flare events due to large increase (> 1000) in X-rays
 - Satellite Orbit Degradation
 - Thermospheric density variations affect satellite drag, which causes orbit degradation, and our ability to track their locations
 - 13,000 objects tracked in orbit around Earth (NORAD)

Earth's Atmosphere Absorbs Solar UV



Navigation Errors

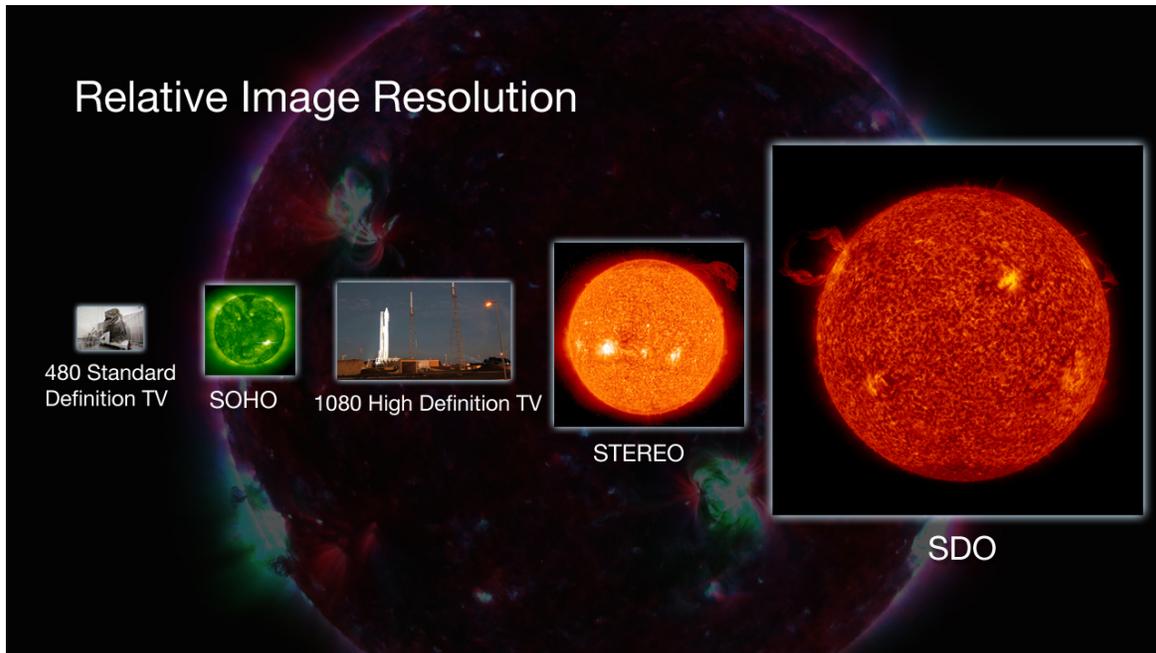
- Sudden Ionospheric Disturbances (SIDs) causes disruptions
 - loss of signal is worst case for the largest solar storms
- Solar storms cause ionospheric changes that degrades the navigation precision
 - LORAN - ground transmitters (limited coverage now)
 - Normal precision of 0.2 km degrades to 5 km during solar storms
 - Global Positioning System (GPS) - satellites
 - Normal precision of 10 m degrades to 50 m during solar storms



REF: NOAA Sp. Wx. Primer

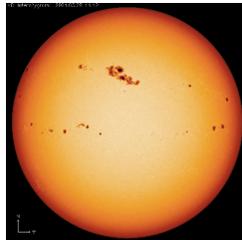
New NASA mission for studying the Sun is Solar Dynamics Observatory (SDO)

It has 8 times better resolution than HD TV



What are the SDO Instruments ?

HMI



- **Helioseismic and Magnetic Imager (HMI)**
 - Understand the origins and flow of energy from the solar interior, through various regions of the Sun, out to the solar corona
 - <http://hmi.stanford.edu/>

Magnetic Fields

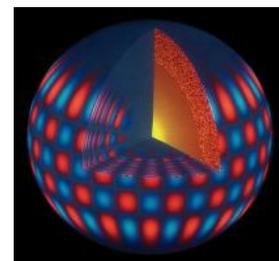
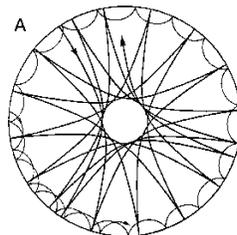
Zeeman splitting provides measure of magnetic field strength

Helioseismology

Sound waves travel around the Sun and probe into different depths of the Sun

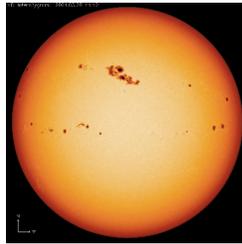
Sun has many different oscillations

Polarization provides vector magnetic fields (Stokes)



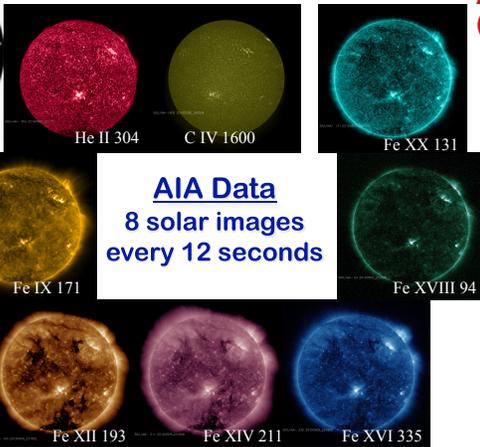
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AIA

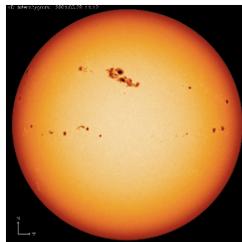
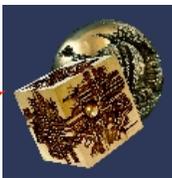


- **Atmospheric Imaging Assembly (AIA)**
 - Investigate the Sun's transient and steady state coronal plasma emissions
 - <http://aia.lmsal.com/>

Temperature Range
 Log(T) of 8 Emissions
 3.7 - 7.2

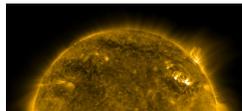
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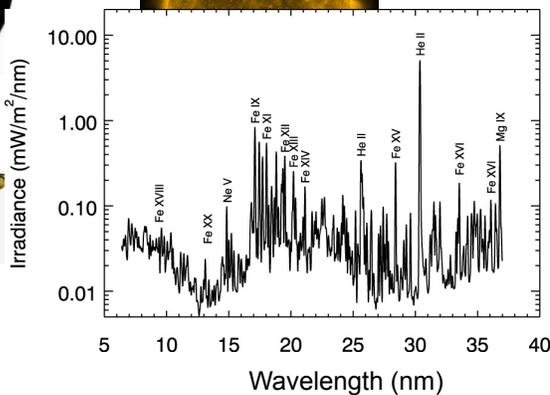
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AIA



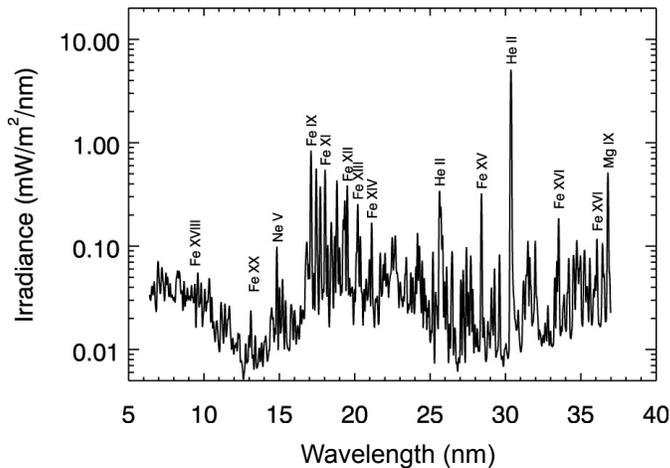
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EVE



- **EUV Variability Experiment (EVE)**
 - Understand the solar drivers of variability at Earth
 - <http://lasp.colorado.edu/eve/>

SDO EVE Provides Many EUV Lines that Probe Different Temperatures



Ion	Temp. (MK)	Corona Activity
He II, H I	0.1	Transition Region (TR)
Fe IX	0.7	<u>Cool</u> Quiet Sun CME Dimming Post-Flares
Fe X	1.0	
Fe XI	1.2	
Fe XII	1.3	<u>Warm</u> Quiet Sun Active Sun Flares
Fe XIII	1.5	
Fe XIV	1.8	
Fe XV	2.0	<u>Hot</u> Active Sun Flares
Fe XVI	2.7	
Fe XVIII	7	<u>Very Hot</u> Flares
Fe XX	10	



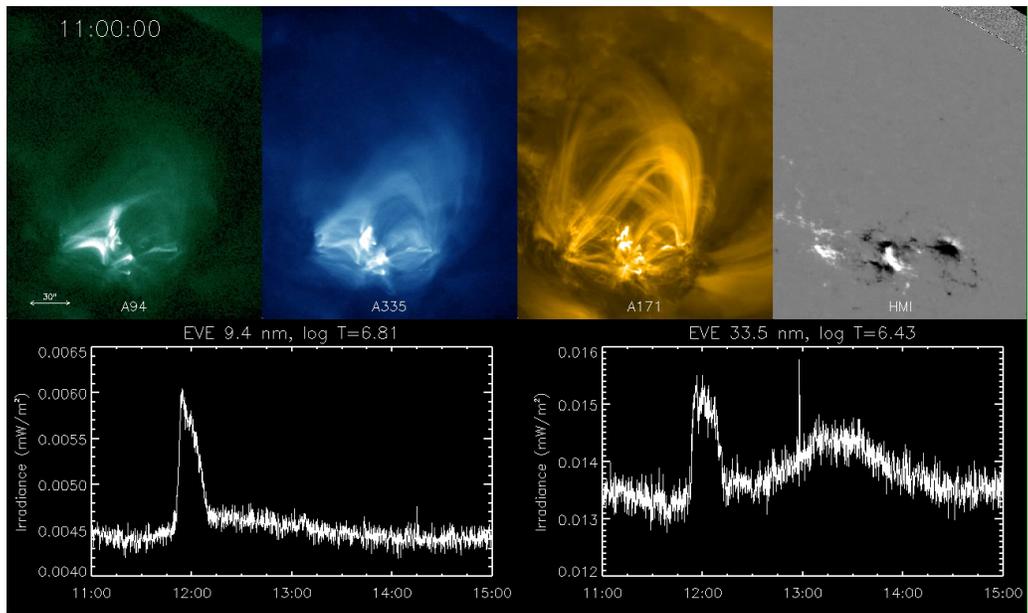
EVE Version 2 Data Products
 0.1-65 nm range, 0.1 nm res.
 10-sec, 1-min, 1-day cadence
<http://lasp.colorado.edu/eve/>

REF: Woods et al., Solar Phys., 2010

RHESSI provides info about the super hot corona ($> 20 \text{ MK}$)

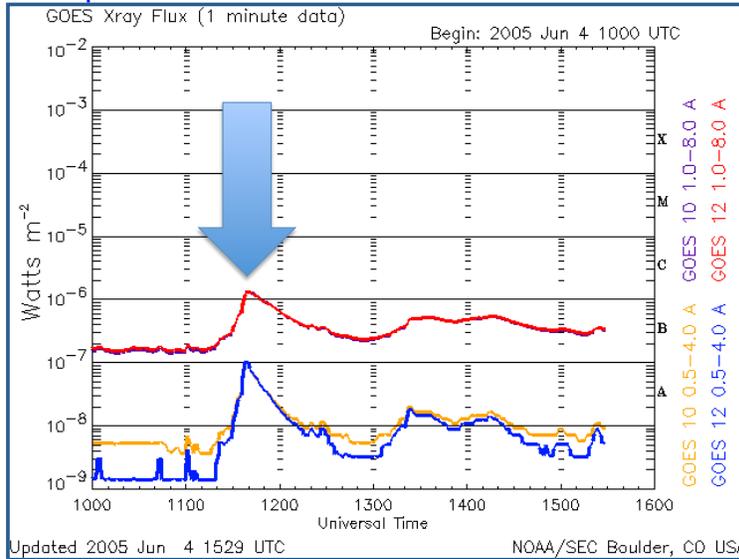
All Together: powerful probe of flare physics

- HMI: vector magnetic fields at 60-sec cadence
- AIA: coronal images at multi-temperature and 12-sec cadence
- EVE: EUV spectra at 0.1 nm resolution and 10-sec cadence



X-ray Flare Classification

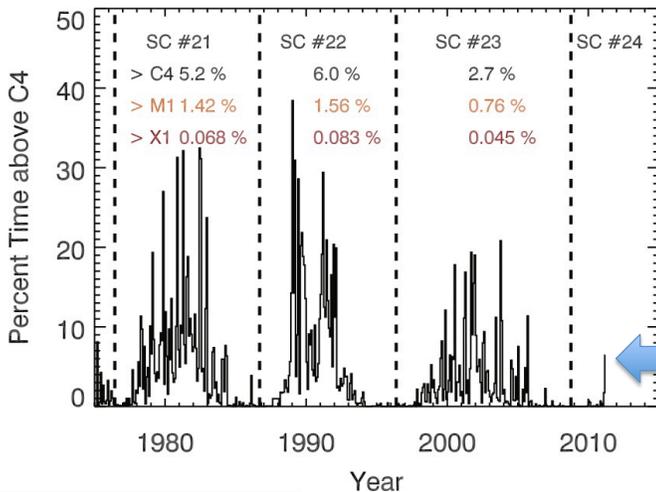
- Peak of GOES 1-8 Å irradiance
 - Letter (A, B, C, M, X) signifies magnitude
 - Number signifies value within magnitude
 - Example: C1.5 = $1.5 \times 10^{-6} \text{ W / m}^2$



REF: <http://www.sec.noaa.gov/Data/>

Frequency of Flares

- More flares during the maximum of the 11-year solar cycle
- Average over 3 solar cycles (during high activity)
 - X-class flares: once per month
 - M-class flares: every 2 days
 - C-class flares: few per day

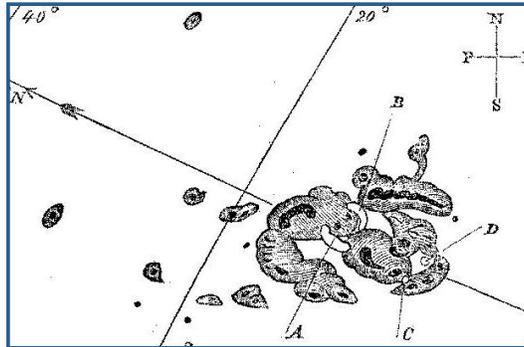


Current solar cycle (SC) 24 is expected to be low (similar to early 1900s)

REF: Garcia, Ap J Suppl, 2000

Early Detections of Solar Flares

- Routine scientific observations of the Sun began soon after the discovery of the telescope in the early 1600s
- Stephen Gary observed flash in sunspot on Dec. 27, 1705
- Richard C. Carrington noted visible light flare on Sept. 1, 1859 while making routine sunspot observation
 - Brightening started at points A & B
 - Brightening flowed along sunspot
 - Disappeared at points C & D
 - Lasted for a few minutes
 - Drawing from Carrington (*M.N.R.A.S*, 20, 13, 1860).

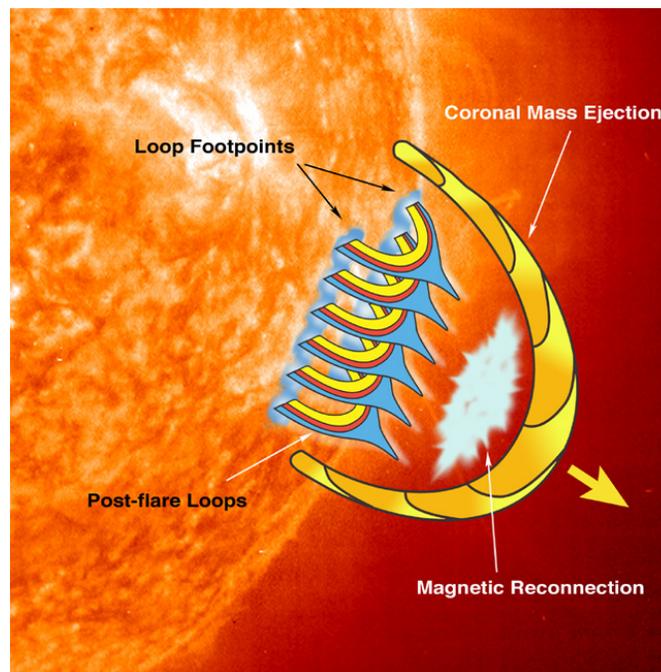


This is considered to have been an X50 flare - the largest flare observed in the past 150 years.

REF: Cliver & Svalgaard, *Solar Phy.*, 2004

Solar Flare Event

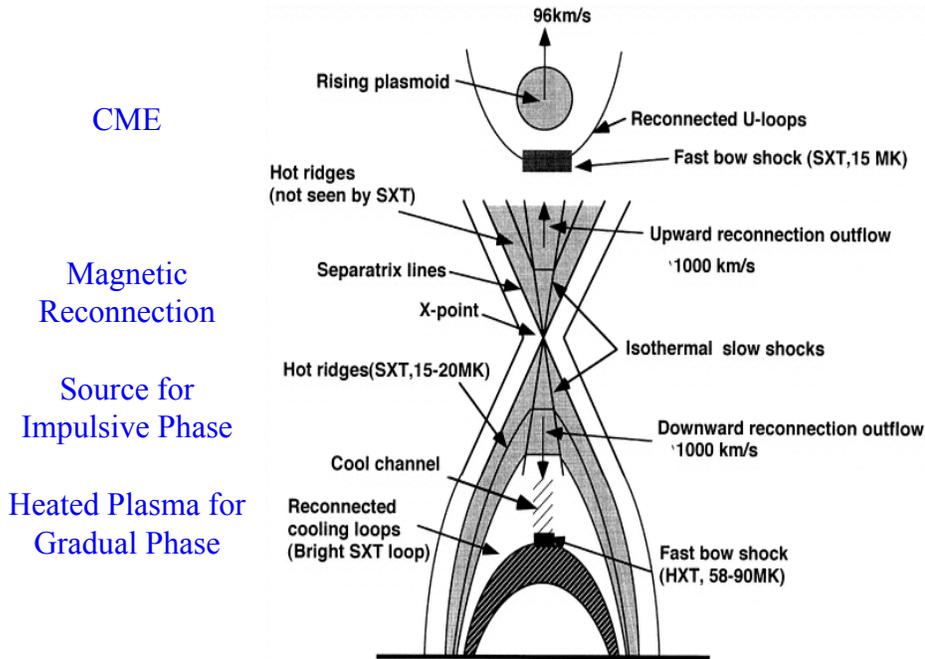
Larger flare events are usually the **two-ribbon flares** where the event starts at one end and propagates to the other end



From Hudson Flare Cartoon Site

REF: Priest, 1981

Single Loop Concept for Flare & CME



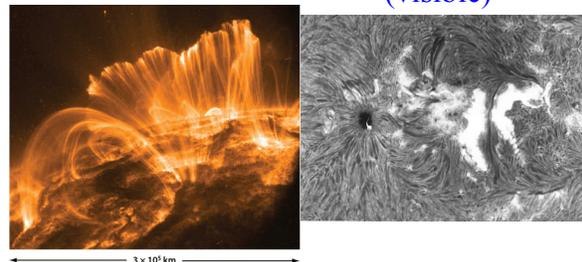
REF: Tsuneta, Ap J, 1997. Standard Flare Model = Kopp & Pneuman, Solar Phys. 1976

Types of Flares

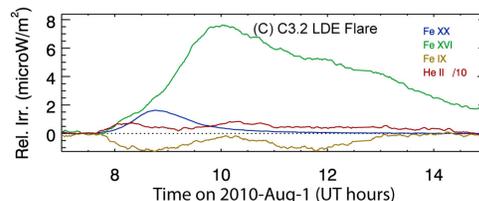
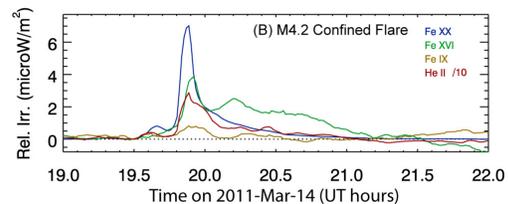
- 2-ribbon flare
 - M & X class flares usually
 - Most geoeffective flare type due to it being brighter
- confined flare
 - C class or smaller usually
 - non-eruptive, short duration
- long decay event (LDE)
 - special case of 2-ribbon flare that lasts for an hour or longer

Example in EUV

in White Light (visible)



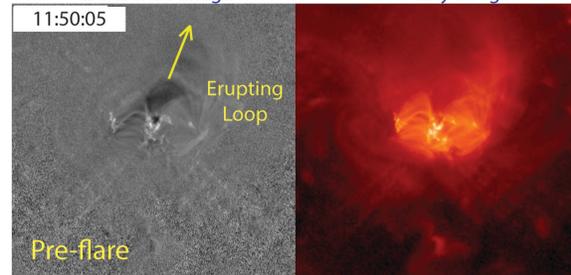
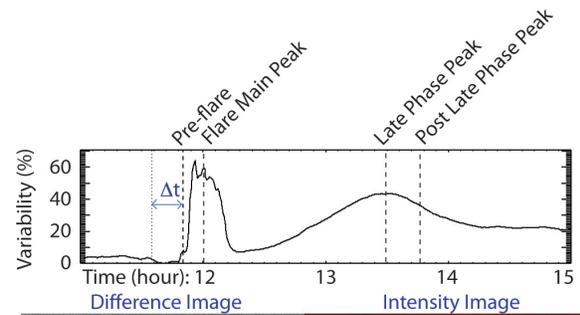
Benz AO, Güdel M. 2010.



Eruptive versus Non-eruptive

- Eruptive means corona mass seen to leave flaring region (usually detected in EUV images)
- Eruptive also usually means there is a Coronal Mass Ejection (CME). That is, the coronal mass leaves the Sun (versus falling back to Sun).
 - C-class flares: 20% have CME
 - M-class flares: 50% have CME
 - X-class flares: 95% have CME

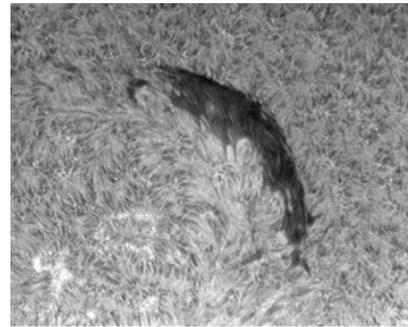
REF: Hudson, Space Sci. Rev., 2011



Difference Image shows movement from dark to light

Filament / Prominence Eruption

- Filament:
 - H- α dark band (visible)
 - Coronal loops on disk appear dark (EUV)
- Prominence:
 - EUV loops near limb are bright and huge loops
- These are very extended coronal loops that are often over a magnetic neutral line

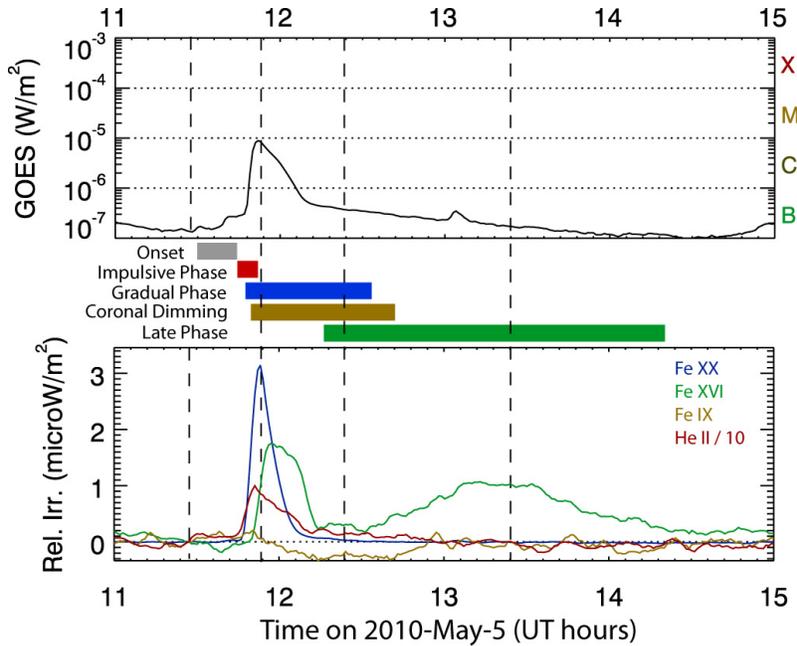


2002 06 01, 17:49 UT, Rotation 1990
filament in north hemisphere, N - up, W - right
155 mm f/9 refr. with 2X barlow, 63 mm ERF
DayStar 0.38 A. H-a filter, video frame grab
Gordon Garcia, Hoffman Estates, IL



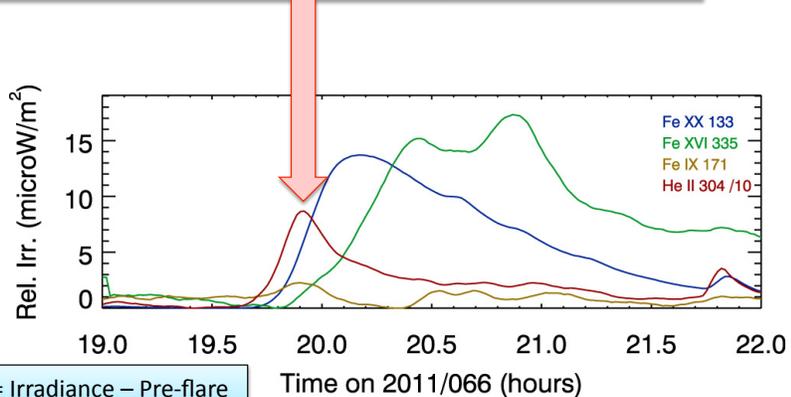
Flare Components / Phases

- Flares do not have all of these phases.
 - Gradual phase is present for all X-ray flares.



Impulsive Phase

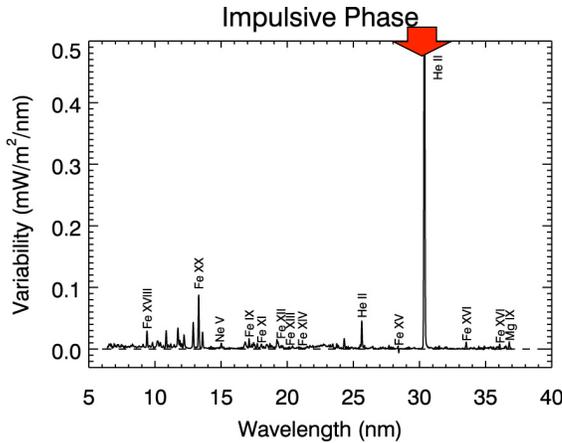
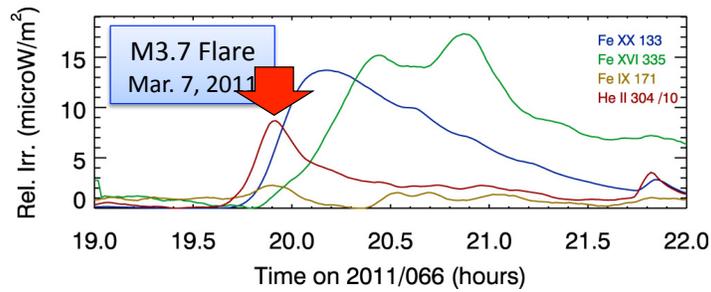
**He II 30.4 nm (0.1 MK)
Transition Region**
Usually emphasizes the flare's Impulsive Phase that peaks before the X-ray peak



Note that "Relative Irradiance" = Irradiance - Pre-flare

Flare Impulsive Phase: initial magnetic reconnection, high energy particle acceleration
Other Emissions: photosphere white light, chromosphere non-thermal Bremsstrahlung (hard X-rays) and gamma rays, and several other TR emissions like He II 30.4 nm
Space Weather Prediction Possibilities: Solar Energetic Protons (SEPs)

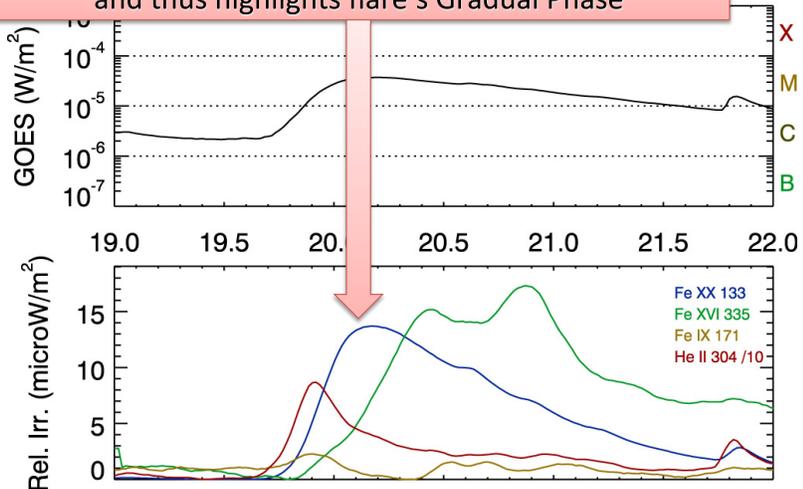
He II 30.4 nm – Transition Region Indicator for Impulsive Phase



- 35% of the flares had impulsive phase
- He II 30.4 nm dominates during impulsive phase
- Coronal lines are starting to ramp up

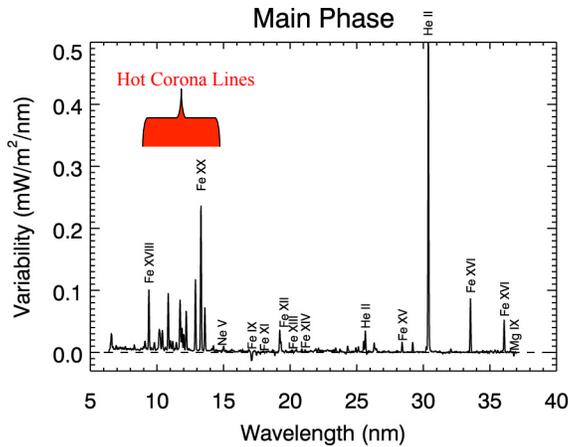
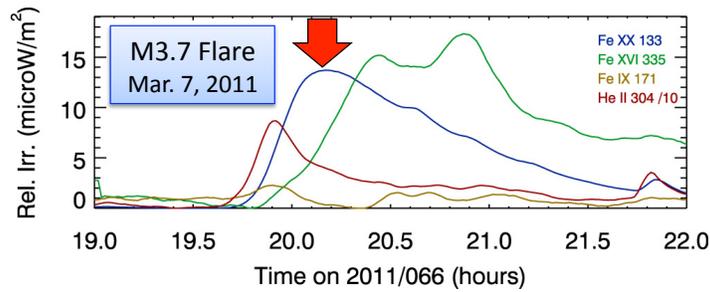
Gradual Phase

**Fe XX 13.3 nm (10 MK)
Very Hot Corona**
Behaves very much like GOES X-ray
and thus highlights flare's Gradual Phase



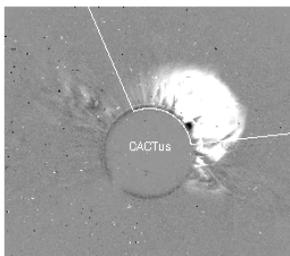
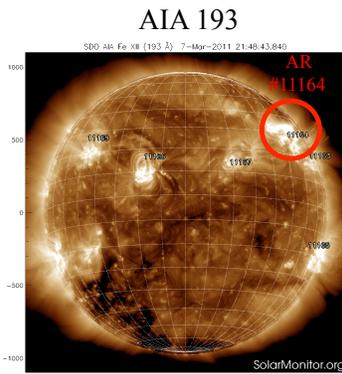
Flare Gradual Phase: chromosphere evaporation / heating from flare's energetic particles
Other Emissions: corona thermal Bremsstrahlung (soft X-ray) and several other hot corona emissions like Fe XX 13.3 nm (10 MK)
Space Weather Prediction: Proxy for GOES 1-8 Å X-ray flare magnitude

Fe XX 13.3 nm – Very Hot Corona Behaves like GOES X-ray / Gradual Phase

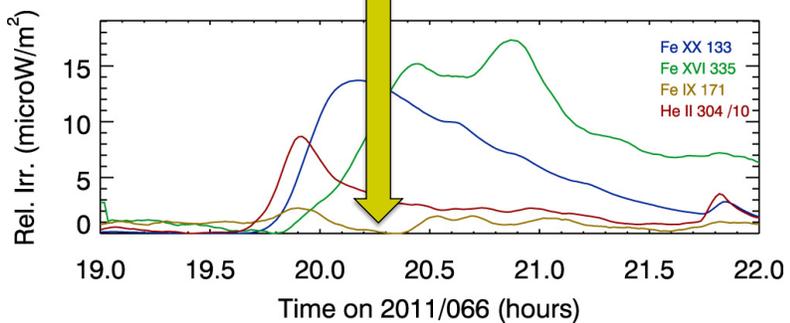


- The hot corona lines in 9-14 nm range contribute the most to the gradual phase variations.
 - Fe XX Peak = 0.17 * Xray^{1.11}
- Although He II 30.4 nm % variation from pre-flare is small, it's energy still dominates any single hot corona line.

Coronal Dimming



**Fe IX 17.1 nm (0.7 MK)
Cool Corona**
Can exhibit coronal dimming if have CME

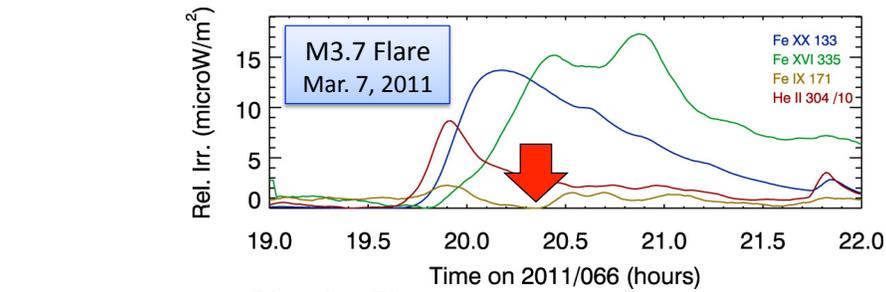


SOHO LASCO-c2

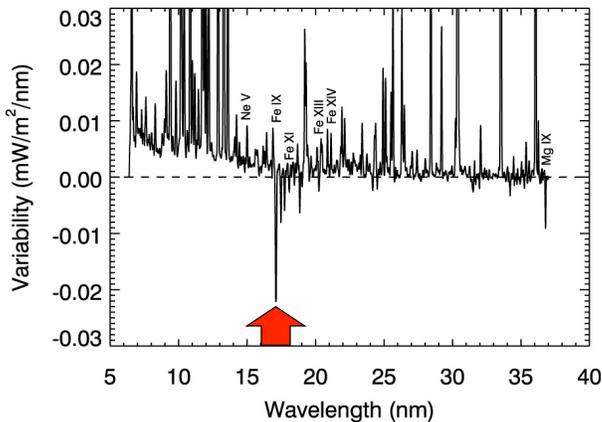
CME mass derived from EUV dimming

Flare Eruptive Events: out flowing coronal mass (some into CME, some could return)
Other Emissions: corona white light (coronagraph) and several other cool coronal emissions like Fe IX 17.1 nm
Space Weather Prediction Possibilities: Corona Mass Ejections (CMEs)

Fe IX 17.1 nm – Cool Corona Dimming after IP associated with CME



Dimming Phase



- 28% of the flares had coronal dimming
 - All coronal dimmings have Impulsive Phase
- Fe IX 17.1 nm shows the strongest dimming
 - Fe X thru Fe XIII also show dimming

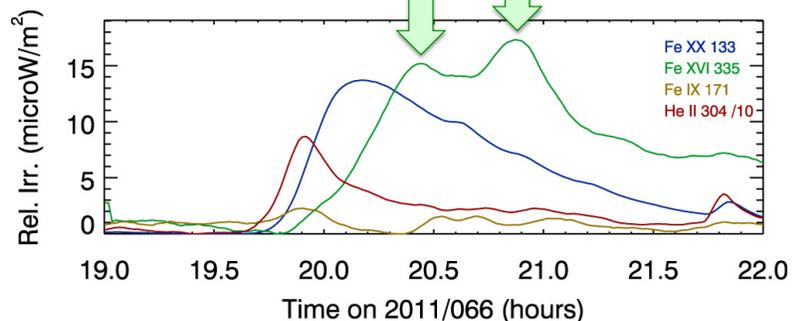
Post-flare Loops and EUV Late Phase

Fe XVI 33.5 nm (2.7 MK)

Hot Corona

Usually peaks after Fe XX 13.3 nm peak as flare's plasma cools down

Sometime peaks without X-ray peak if have weaker (cooler) reconnection

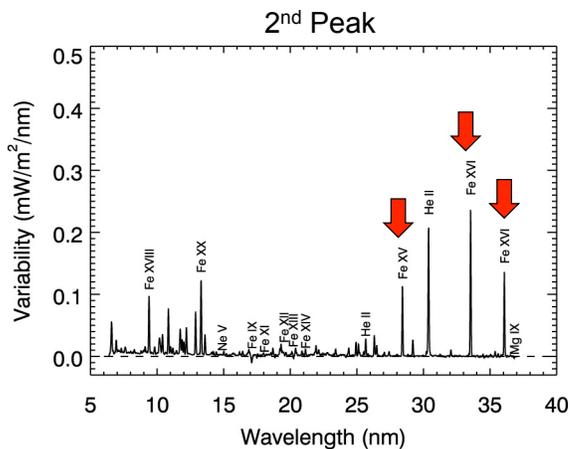
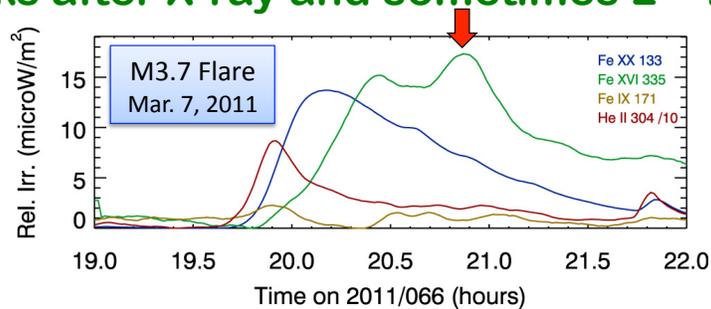


Flare Recovery Phase: post-flare loop formation and cooling (first peak), “late” phase magnetic reconnection of outer loops disrupted by CME (second peak)

Other Emissions: few other warm coronal emissions like Fe XVI 33.5 nm

Space Weather Prediction Possibilities: EUV flares (less energetic) than X-ray flares

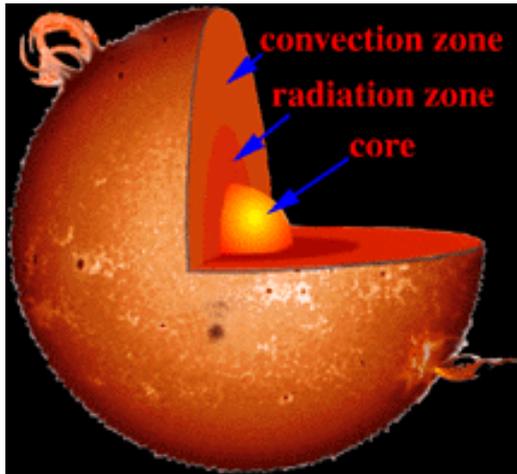
Fe XVI 33.5 nm – Hot Corona Peaks after X-ray and sometimes 2nd Peak



- 1st Peak is typically 5 min after Fe XX peak
- 15% of the flares had late phase (2nd peak)
 - 2nd Peak is on average 40 min after its 1st Peak
 - Hot coronal lines (Fe XV and Fe XVI) dominate during the 2nd peak

Additional Information

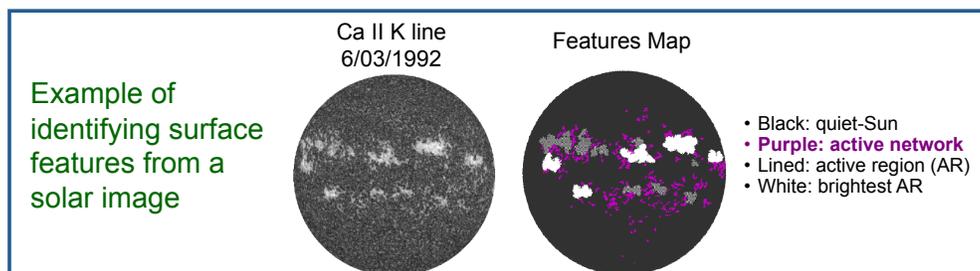
The Sun



Observation Data	
Mass	1.99 x 10 ³⁰ kg (332,950 Earths)
Diameter	1.39 x 10 ⁶ km (109 Earths)
Earth Distance	1.5 x 10 ⁸ km
Magnitude (V)	-27 (-13 moon)
Core Temp.	13.6 MK
Surface Temp.	5780 K
Surface Gravity	27.9 g (1 g Earth)
Escape Velocity	618 km/s (11 km/s at Earth)
Rotation Period (differential)	25.38 days (at equator)
Composition	H 73.5% He 24.9% O 0.8% C 0.3% Others - 0.5%

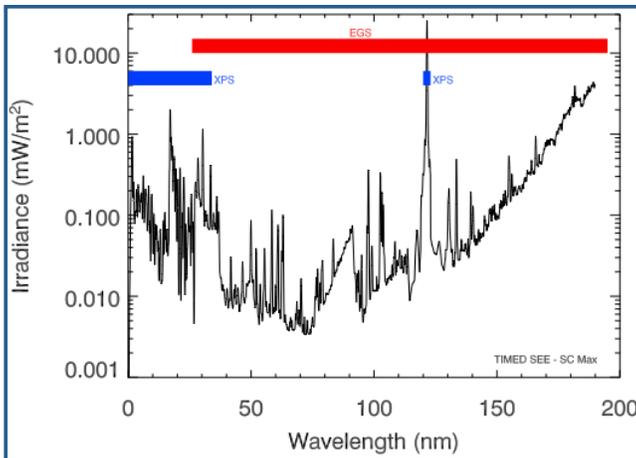
Sources of Solar Variability (surface features)

- Harvey and White (*Solar Phys.*, 1999) defined surface features based primarily on magnetic structures
 - **Quiet Sun (QS)**: quiet regions whose radiances are usually assumed to be constant, but SOHO-SUMER observations have proven this concept wrong for the EUV and FUV emissions (Schühle *et al.*, 2000, A&A)
 - **Sunspot (SS)**: dark regions that appear in the photosphere (effects irradiance > 260 nm)
 - **Faculae (F)**: bright regions in the visible (> 260 nm)
 - **Active region (AR)**: very bright regions in the UV - above the sunspots; also called **plage**
 - **Active network (AN)**: slightly bright regions in the UV (similar to faculae)
 - **Quiet network (QN)**: even less bright regions in the UV
 - **Coronal hole (CN)**: dark regions in the corona emissions



REF: Worden *et al.*, *Ap J*, 1998.

TIMED SEE Measurements



EGS:

- EUV Grating Spectrograph
- Rowland-circle grating design
- 64x1024 pixel MCP detector
- 27-194 nm at $\Delta\lambda=0.4$ nm

XPS:

- XUV Photometer System
- Set of 12 Si photodiodes
- 0.1-34 nm at $\Delta\lambda=7-10$ nm
- Ly- α (121.6 nm) at $\Delta\lambda=2$ nm



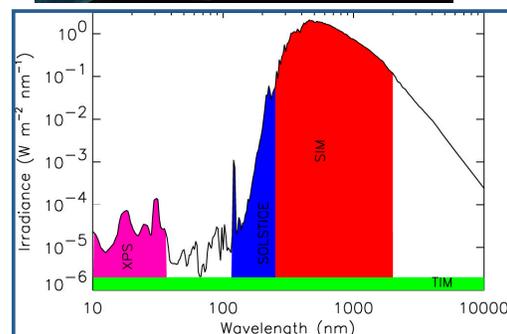
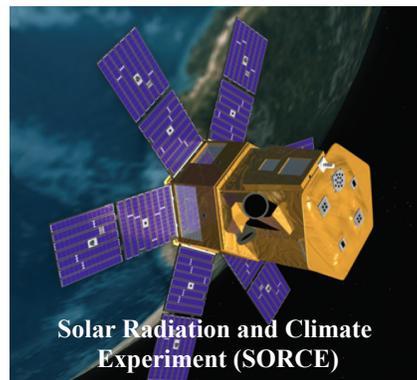
- SEE observes the Sun for ~ 3 minutes of every 97-min orbit.
- SEE has operated from 22 Jan 2002 to the present.
- [Version 7 SEE data products are publicly available](http://lasp.colorado.edu/see/)

<http://lasp.colorado.edu/see/>

REF: Woods *et al.*, JGR, 2005.

SORCE Measurements

- SORCE launched in Jan. 2003
 - Makes daily solar observations
 - PI Mission: Gary Rottman / Tom Woods
- **Total Irradiance Monitor (TIM)**
 - Measures total solar irradiance (TSI) - integrated over all λ s
- **Spectral Irradiance Monitor (SIM)**
 - Measures solar spectral irradiance from 200 - 2000 nm
- **SOLar STellar Irradiance Comparison Experiment (SOLSTICE)**
 - Measures solar spectral irradiance from 115 - 320 nm
 - Similar to UARS SOLSTICE
- **XUV Photometer System (XPS)**
 - Measures solar irradiance in broad bands from 0.1 - 34 nm and the H I Lyman- α emission

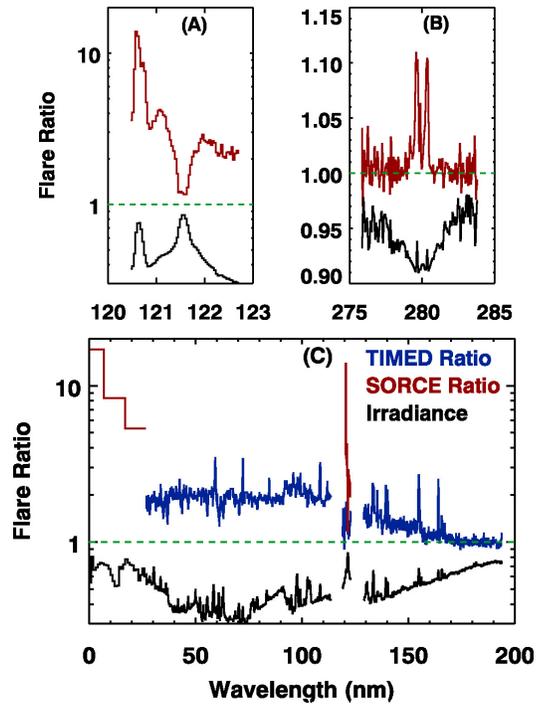


REF: Solar Physics Vol. 230, 2005

<http://lasp.colorado.edu/sorce/>

X17 Flare Variation is as Large as Solar Cycle Variation

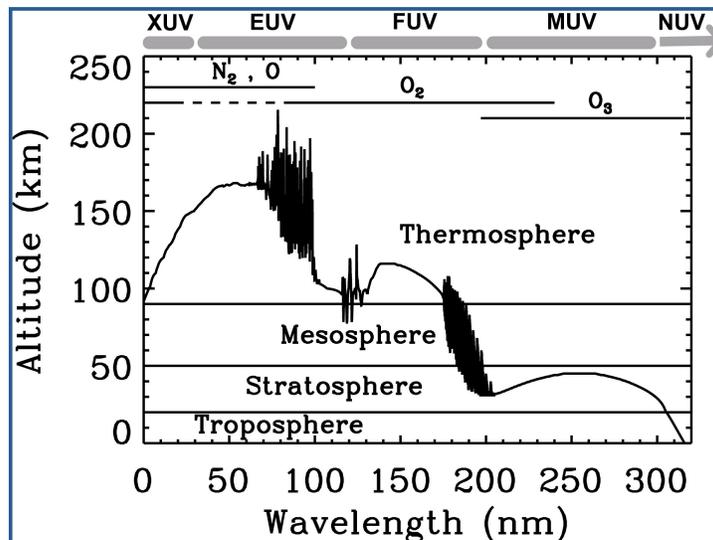
- TIMED and SORCE observations of the large X17 flare on 28 Oct. 2003
- Panel A: FUV H I Lyman- α
 - 20% at Ly- α core
 - x 2 for Ly- α wings
 - x 17 for 120.6 nm emission (Si III & Cr XX)
- Panel B: MUV Mg II
 - 12% for Mg II lines
- Panel C: VUV
 - x 2 or more for EUV and some FUV lines
 - > 10 for X-rays



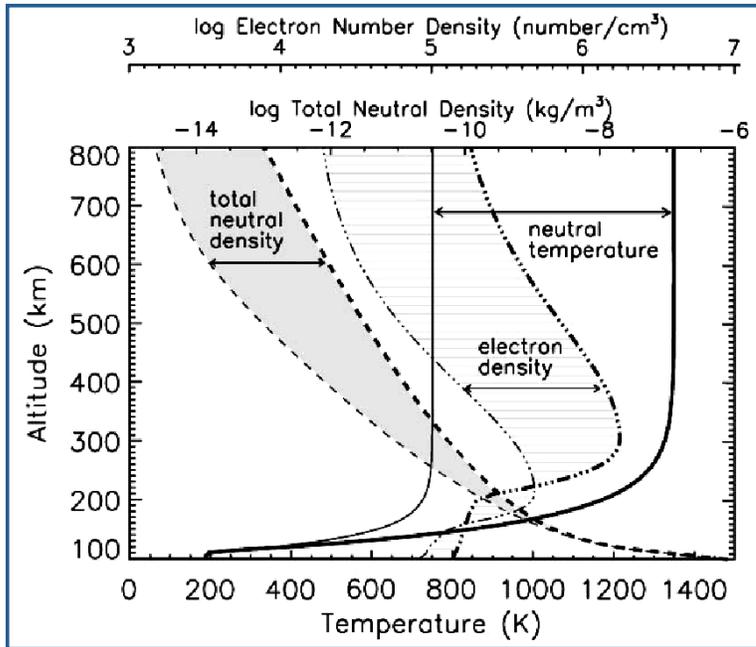
REF: Woods *et al.*, *GRL*, 2004.

Absorption is Wavelength Dependent

- Solar ultraviolet (UV) radiation drives heating, chemistry, and dynamics in the atmosphere
 - Primary absorption in the MUV range is by O₃ (dissociation)
 - Primary absorption in the FUV range is by O₂ (dissociation -> creates O₃)
 - Primary absorption in the XUV and EUV ranges is by N₂, O, and O₂ (ionization)



Solar Cycle Effects on Earth's Atmosphere



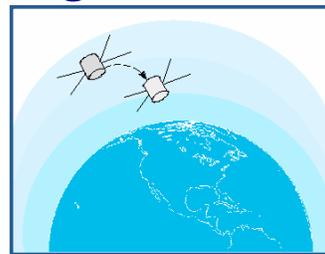
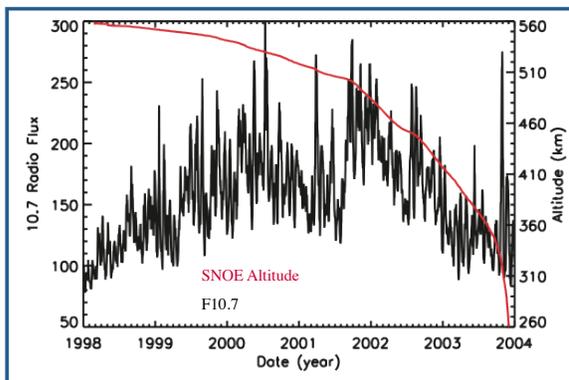
Neutral density varies by more than a factor of 10

Electron density varies by a factor of 10 over a solar cycle

Temperature varies by a factor of 2 over a solar cycle

REF: Lean, A.R.A.A., 1997.

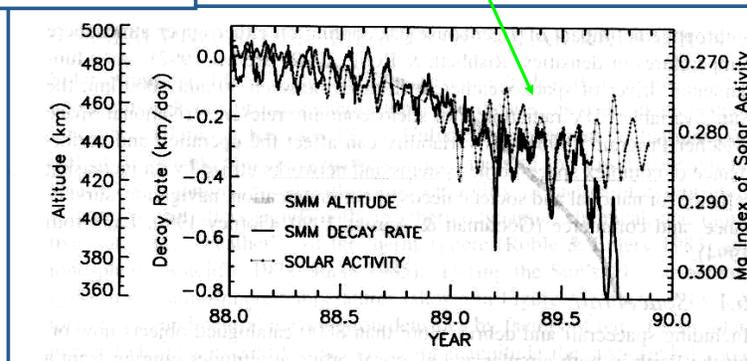
Satellite Orbit Degradation



Decay rate fluctuations match solar rotation variability

(Barth, Private Communication, 2004)

Higher altitude decay during times of higher solar activity



REF: Lean, A.R.A.A., 1997.