Solar Corona

Rutten 8.3

Solar Corona

Rutten 8.3

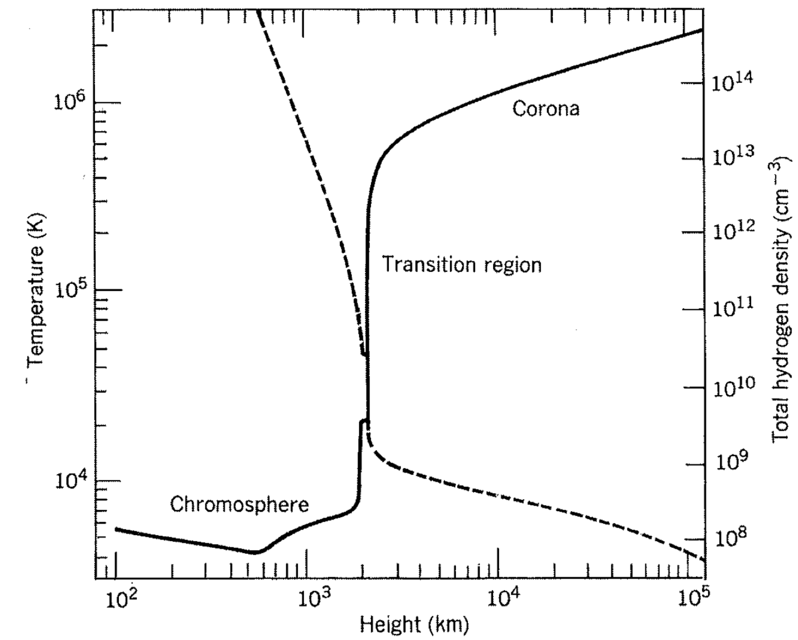
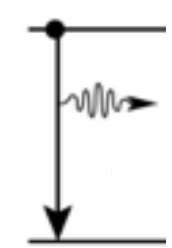


Fig. 9-17 Plots of temperature (solid line) and density (dashed) from a model of the quiet network. Reproduced with permission from A. Gabriel, *Phil. Trans. Royal Soc. London*, **281**, 339 (1976).

- very hot $T_e \geq 10^6$ K
- low density (tenuous) $N_e \leq 10^7\ \mathrm{cm}^{-3}$
- optically thin $\lambda \leq 10$ cm
- far from LTE

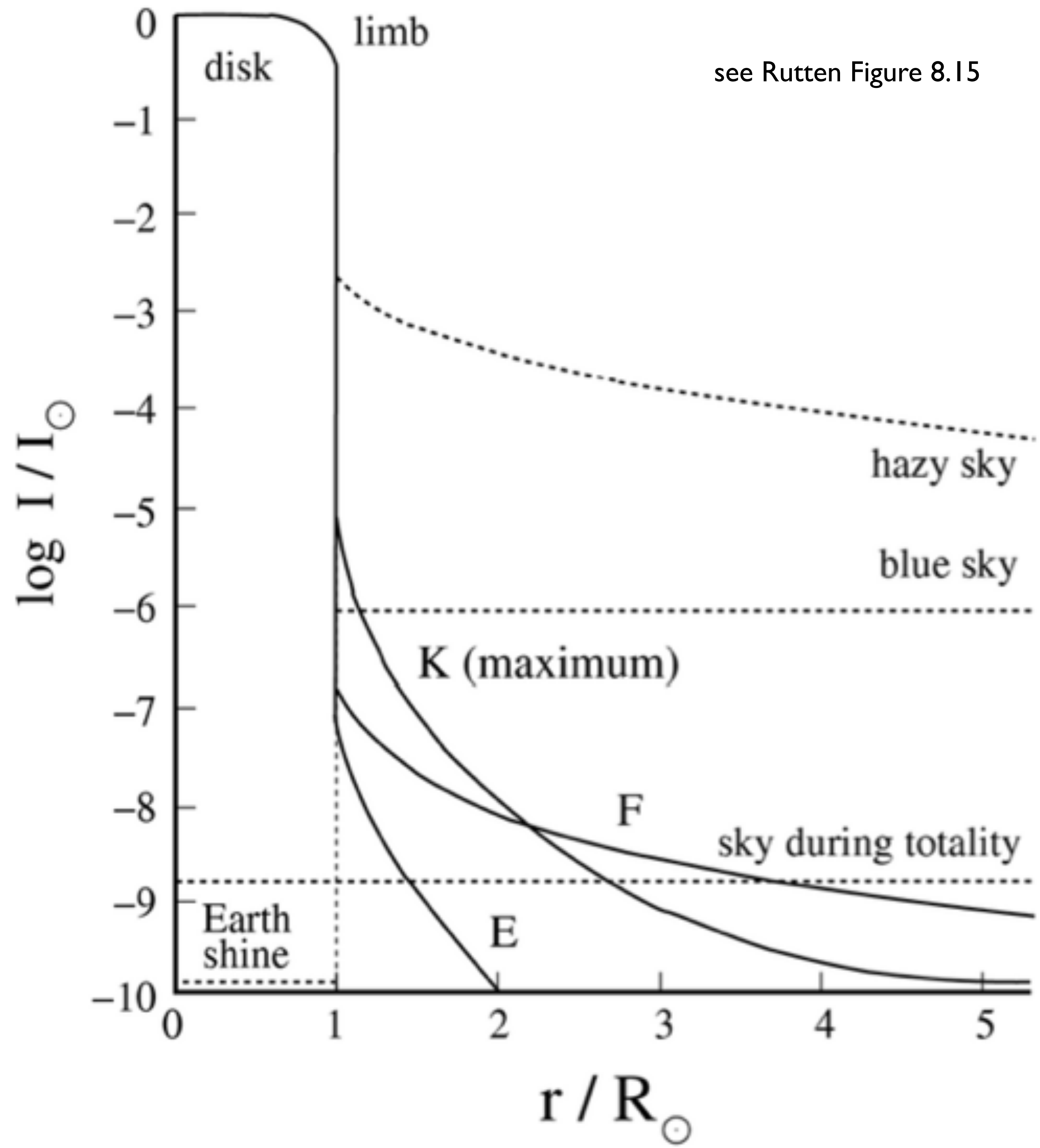
C_{lu}

- excitation/ionization: **collisional**
  ignore radiative excitation



A_{ul}

- de-excitation/recombination: **spontaneous radiative**
  ignore collisional and induced de-excitation

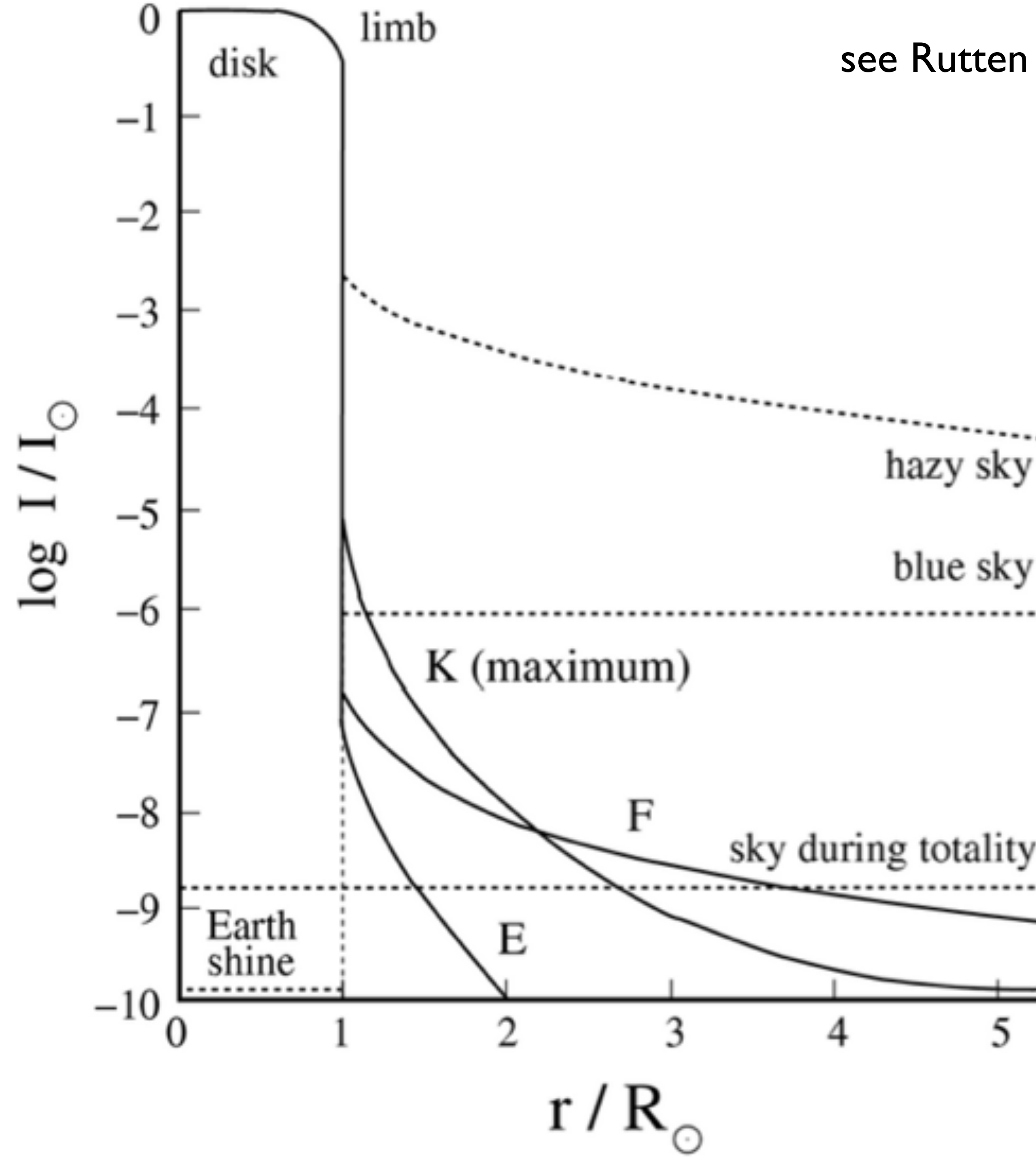


see Rutten Figure 8.15

•**K corona**: "<u>K</u>ontinuum", mostly Thomson scattering by hot electrons → elastic but large Doppler shifts →spectral lines washed out, except strongest lines
•**F corona:** "<u>F</u>raunhofer", scattering by interplanetary dust, elastic →spectral lines preserved, strong forward scattering
•**E corona:** "<u>E</u>mission", emission lines from hot plasma

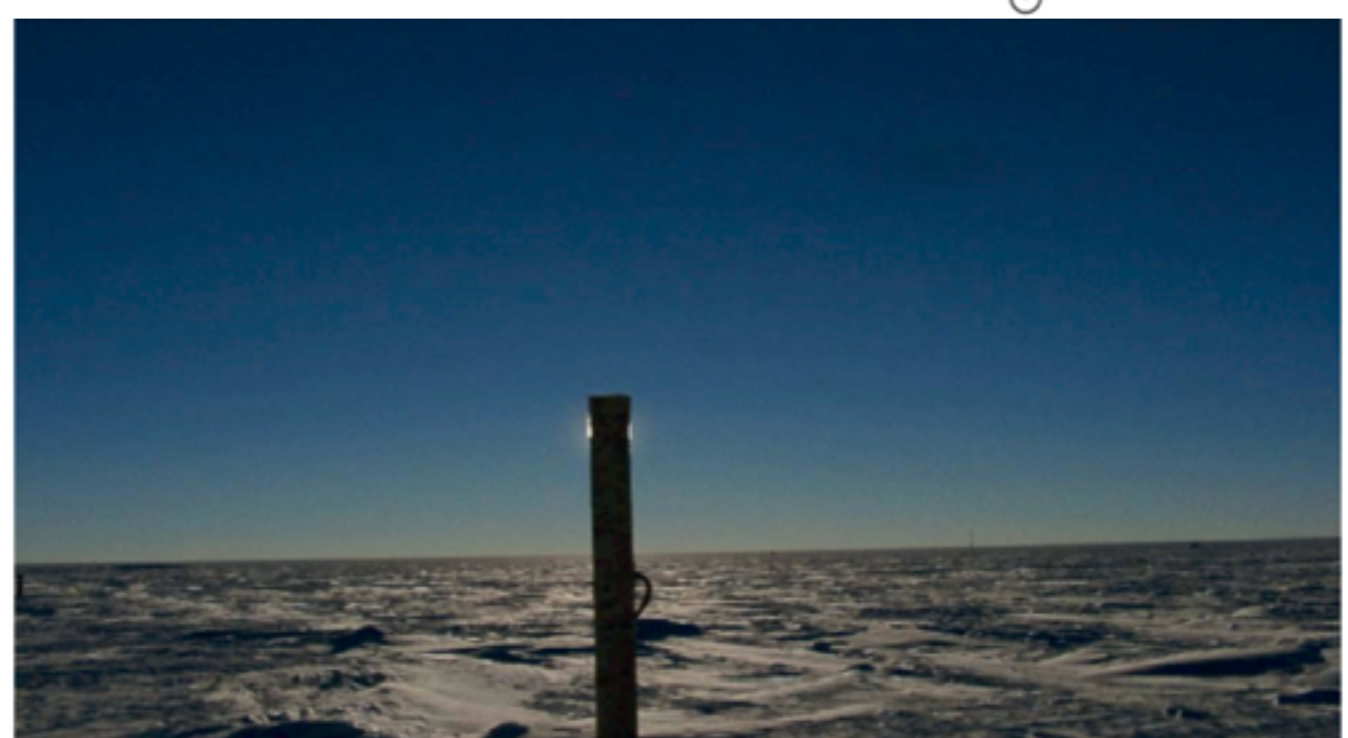
K corona: Thomson scattering on hot coronal electrons
F corona: scattering on interplanetary dust
E corona: emission lines from coronal ions
Earth shine:

K corona: Thomson scattering on hot coronal electrons: loop structures
F corona: scattering on interplanetary dust: brightness gradient
E corona: emission lines from coronal ions
Earth shine: sunshine reflected from Earth to Moon and back again



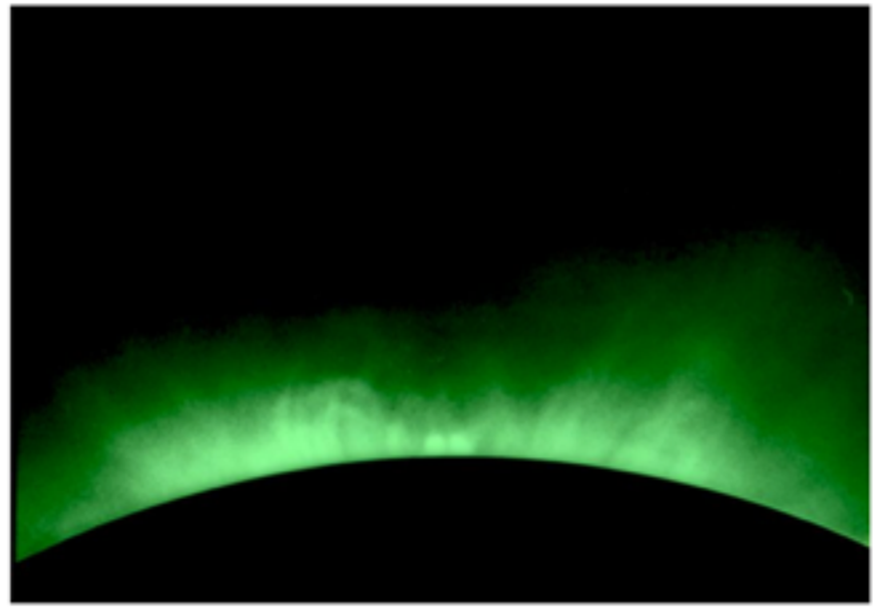
see Rutten Fig 8.15

Coronal sky at Dome C
at the South Pole



"CORONIUM" LINES

Stix section 9.1.3 *http://laserstars.org/spectra/Coronium.html*



Grotrian, Edlén 1942: forbidden lines high ionization stages (Stix Table 9.2 p. 398)

name	wavelength	identification	$\Delta\lambda_D$	$\overline{v}$	A_{ul}	previous ion	$\chi_{\rm ion}$
green line	530.29 nm	[Fe XIV]	0.051 nm	29 km/s	60 s^{-1}	Fe XIII	355 eV
yellow line	569.45	[Ca XV]	0.087	46	95	Ca XIV	820
red line	637.45	[Fe X]	0.049	23	69	Fe IX	235

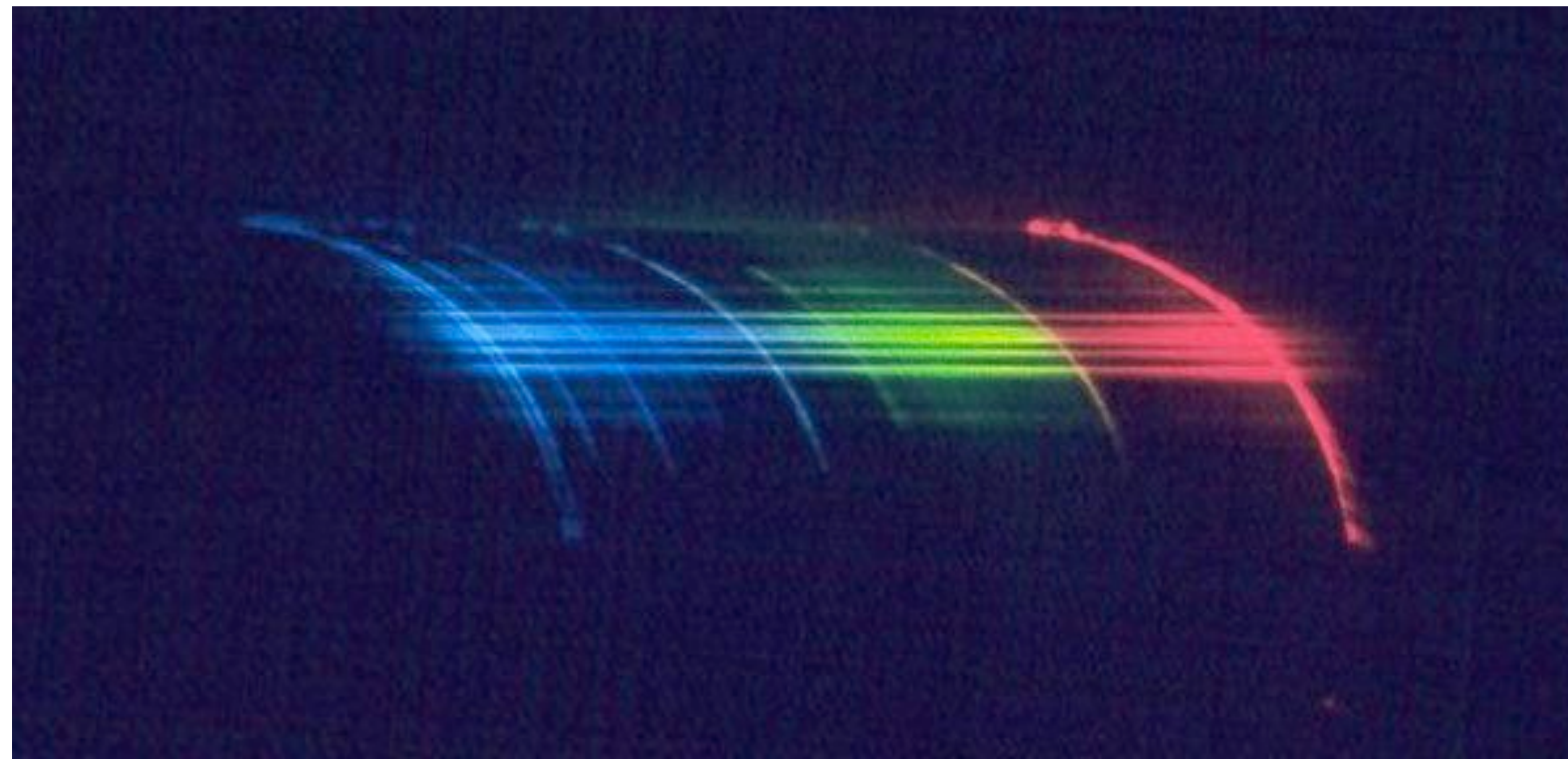
Doppler width $\Delta\lambda_{\rm D} \equiv \sqrt{\frac{2kT}{m}}$ $\quad \rightarrow \quad T \approx 2 - 5 \times 10^6 \ \rm K$

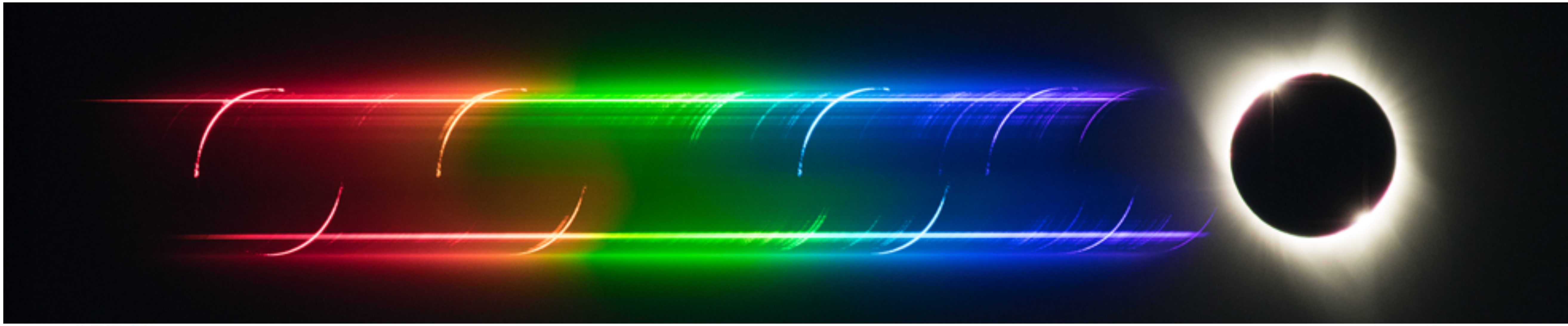
permitted transitions: $A_{ul} \approx 10^4 - 10^8 \ \rm s^{-1}$

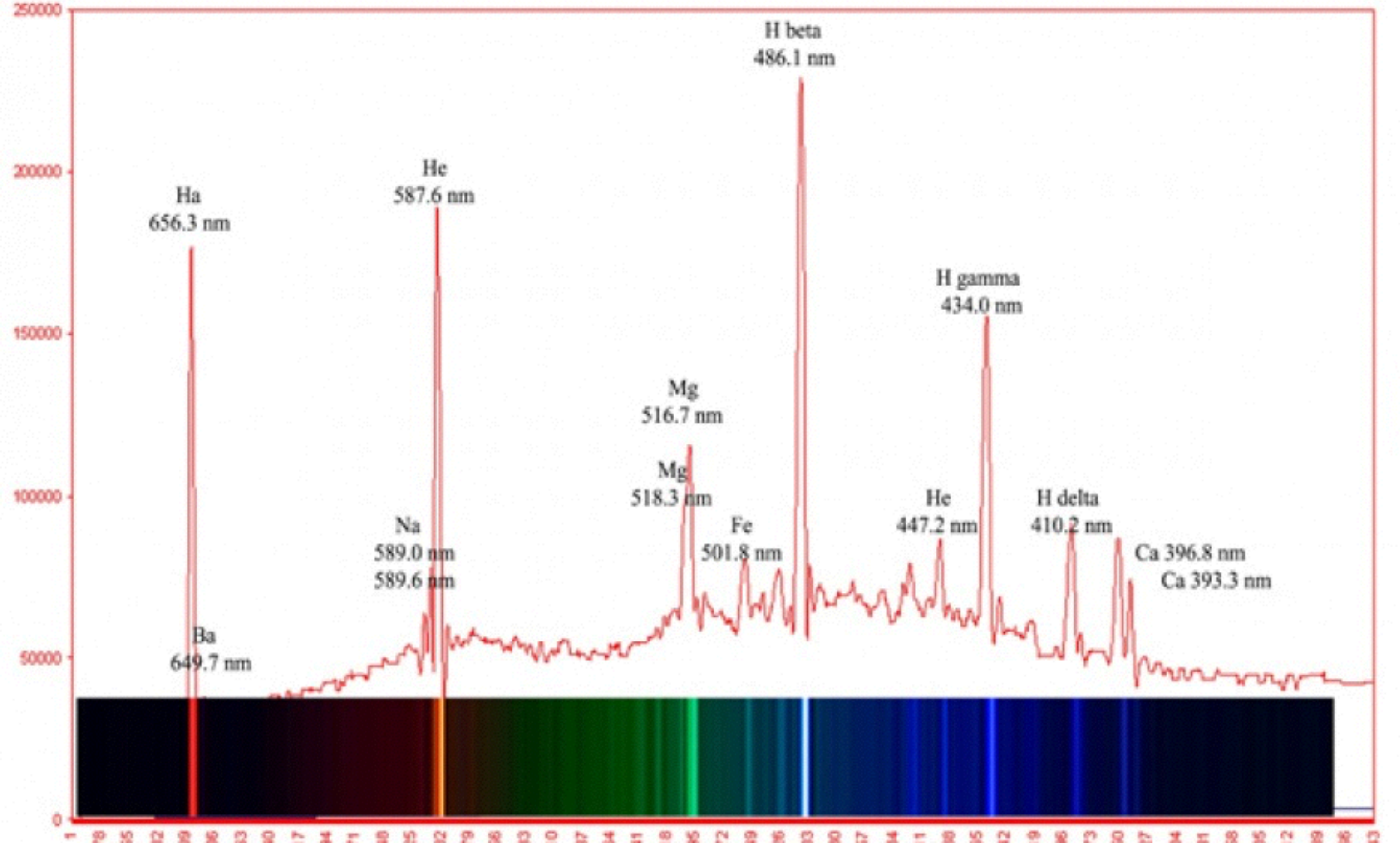
diamond ring before totality

chromosphere

flash spectrum: narrow band works as slit

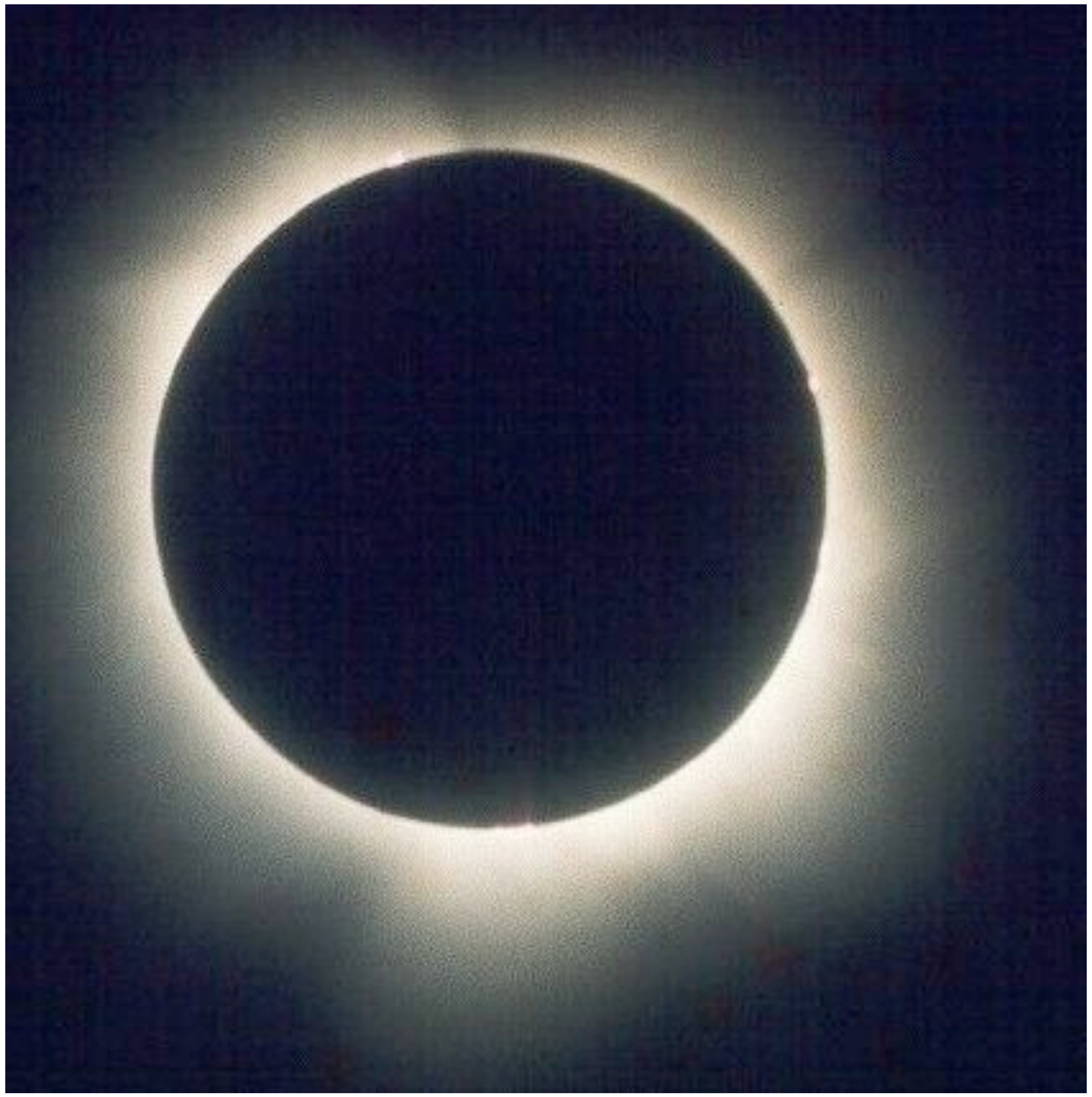




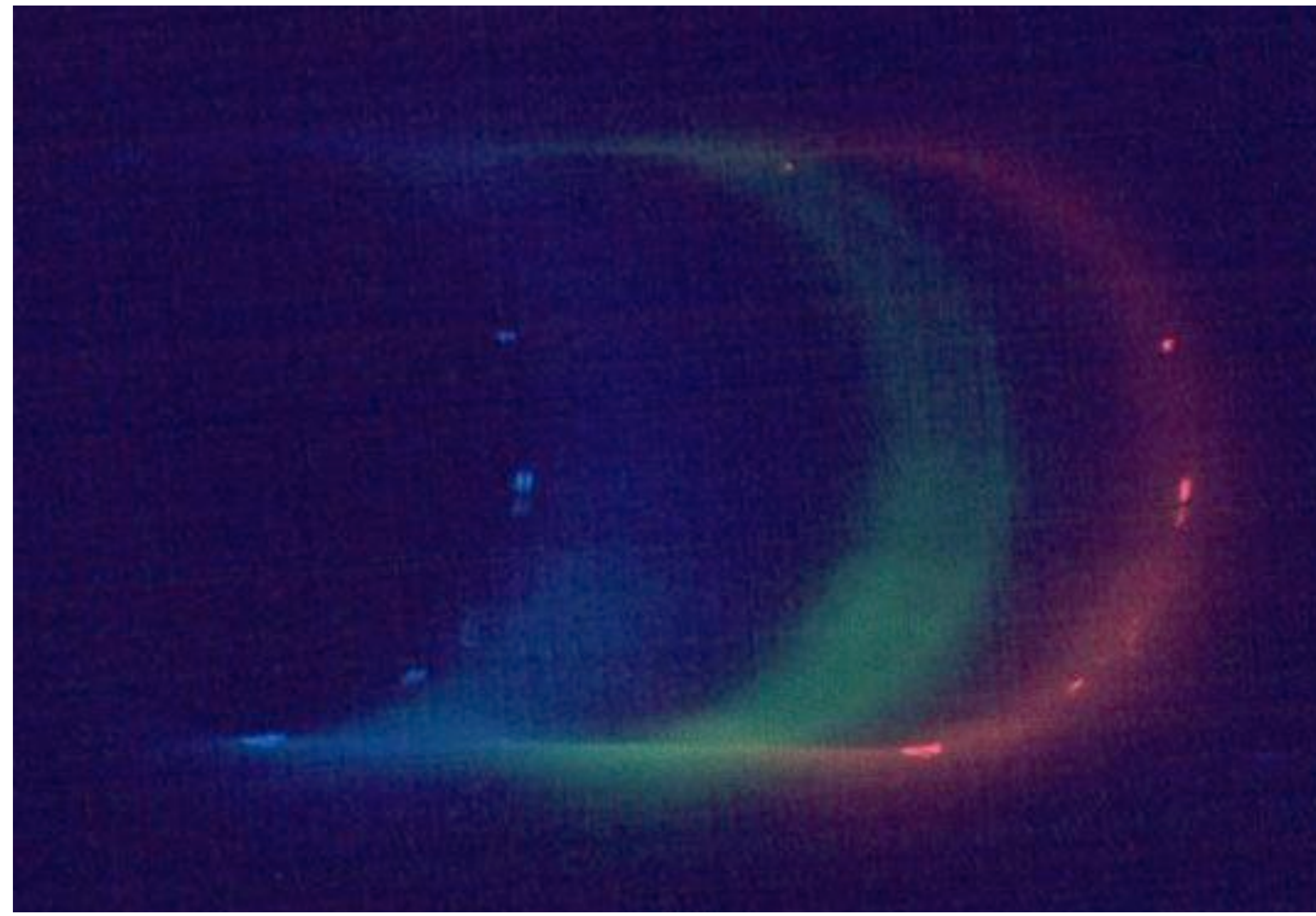


250000
200000
150000
100000
50000
0
H beta
486.1 nm
He
587.6 nm
Ha
656.3 nm
H gamma
434.0 nm
Mg
516.7 nm
Mg
518.3 nm
Fe
501.8 nm
Na
589.0 nm
589.6 nm
He
447.2 nm
H delta
410.2 nm
Ca 396.8 nm
Ca 393.3 nm
Ba
649.7 nm

lunar disk covers chromosphere



coronal lines



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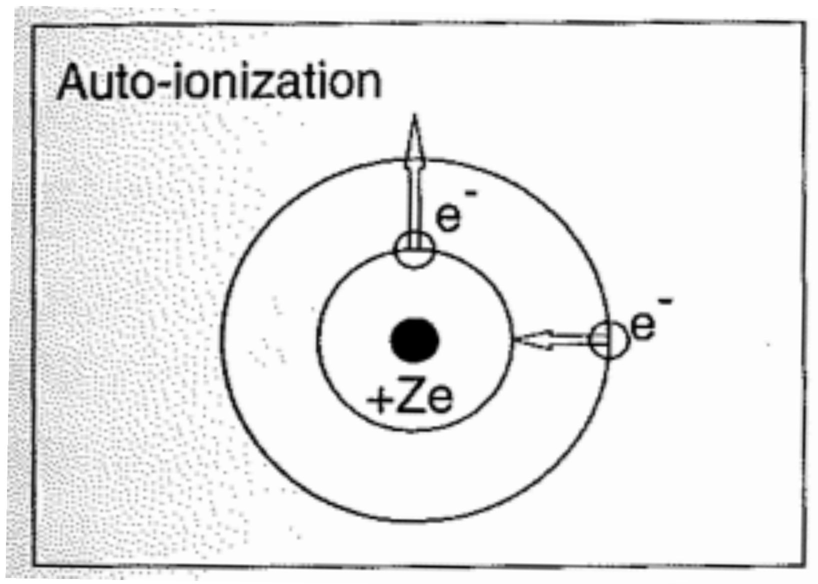
red line	637.45	[Fe X]	0.049	23	69	Fe IX	235

Process	Incoming	Outgoing	Rate
Absorption	photon + atom	excited atom	$u_\nu B_{mn} N_m$
Stimulated emission	phot. + excited atom	2 phots. + atom	$u_\nu B_{nm} N_n$
Spontaneous emission	excited atom	photon + atom	$N_{nm} A_{nm}$
Photo-ionization	photon + atom	ion + electron	$u_\nu N_m B_{m\kappa}$
2-Body recombination	electron + ion	photon + atom	$N_e N_i A_{\kappa m}$
→ Dielectronic Recomb.	electron + ion	phot. + excited atom	$N_e N_i \alpha_{diel}$
→ Dielectronic Absorption (Auto-ionization)	phot. + excited atom	ion + electron	$N_n u_\nu \kappa_{diel}$
Thomson scattering	photon + electron	phot. + electron	$\sigma_T N_e$
Free-free emission (Bremsstrahlung)	electron + ion	elec. + ion + phot.	$N_e N_i \kappa \kappa'$
Free-free absorption	phot.+electron+ion	ion + electron	$N_e N_i B_{\kappa' \kappa} u_\nu$
Collisional excitation	electron + atom	elec. + excited atom	$N_m N_e C_{mn}$
Collisional de-excitation	elec.+ excited atom	electron + atom	$N_n N_e C_{nm}$
Collisional Ionization	electron + atom	2 electrons + atom	$N_m N_e C_{m\kappa}$
3-Body Recombination	2 elecs. + atom	electron + atom	$N_e^2 N_i C_{\kappa m}$

Table 8.1: *Atomic processes. After Zirin.*

Auto-ionization



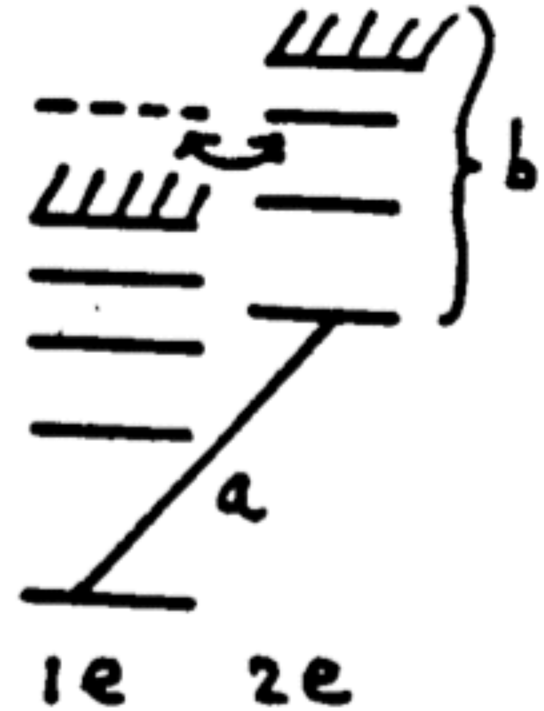
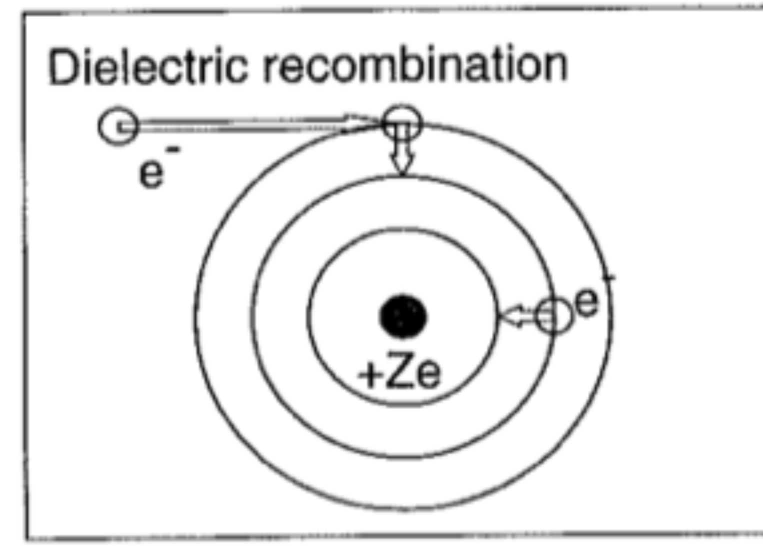


Figure 8.11

- two electrons are excited at the same time
- this system can have excited states that are above the ionization limit for singly excited system
- radiation-free transition for which one electron is released
- rare in corona

Dielectronic recombination



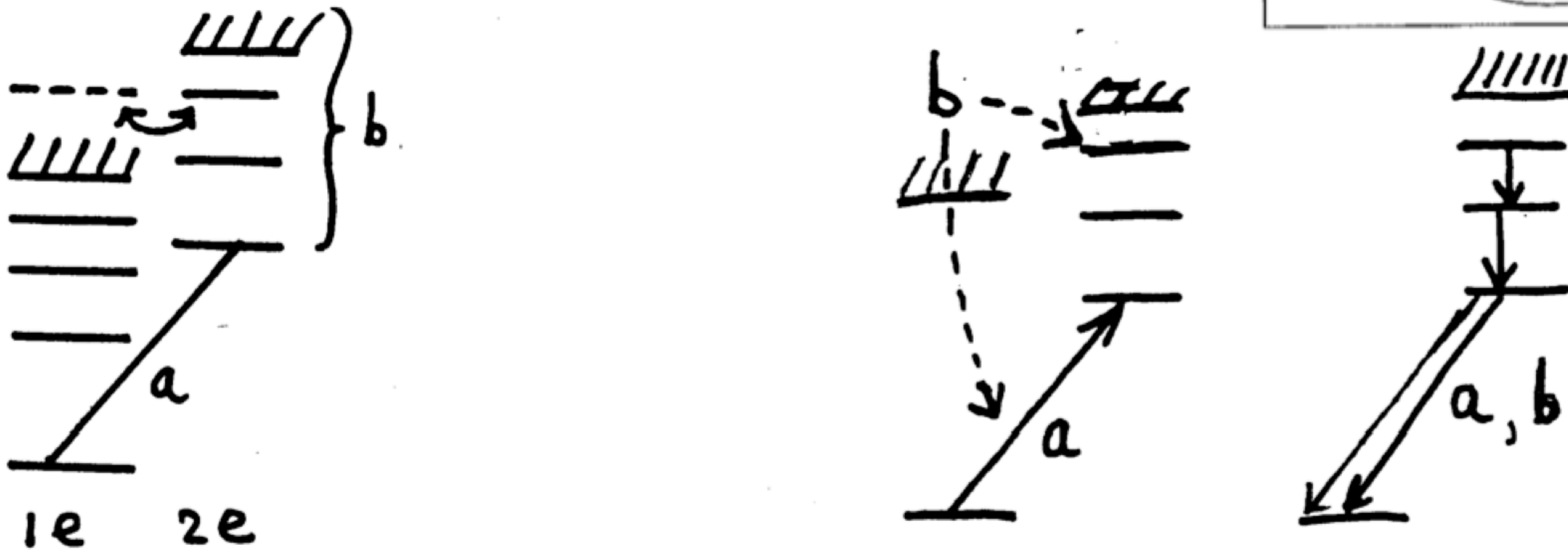


Figure 8.11: *Dielectronic recombination. The left pair of diagrams sketches how the term diagram of an atom with two excited electrons (right diagram, marked 2e) can have excited levels that are above the ionization limit of an atom with a single excited electron (1e). The right pair of diagrams sketches how first, an energetic free electron excites a bound electron in an ion as it itself is captured into another excited level (left diagram). Then, spontaneous deexcitation of both electrons, possibly in a cascade or series of transitions to progressively lower levels, provides line photons and leaves the ion in the ground state, one ionization level lower (right).*

Dielectronic recombination

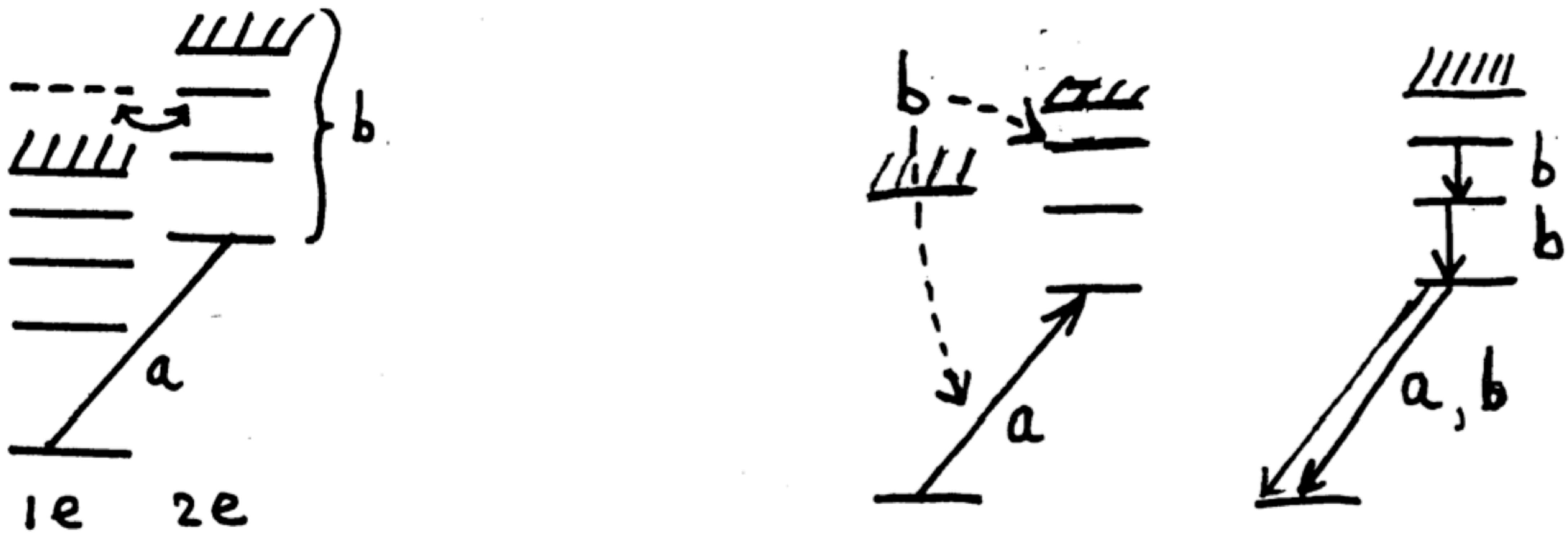
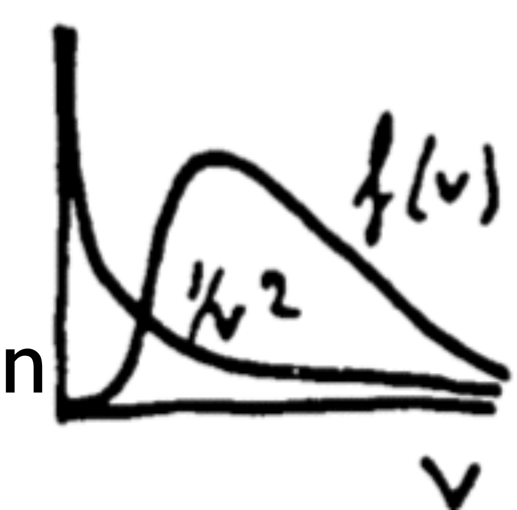


Figure 8.11: *Dielectronic recombination. The left pair of diagrams sketches how*

- efficient at high temperature:
- collisional excitation of bound electron reduces kinetic energy captured electron
- capture cross-section $\sigma_{fb} \sim 1/v^2$ (slower electrons are captured more easily)
- many spectral lines, rather than one high energy photon



Dielectronic recombination

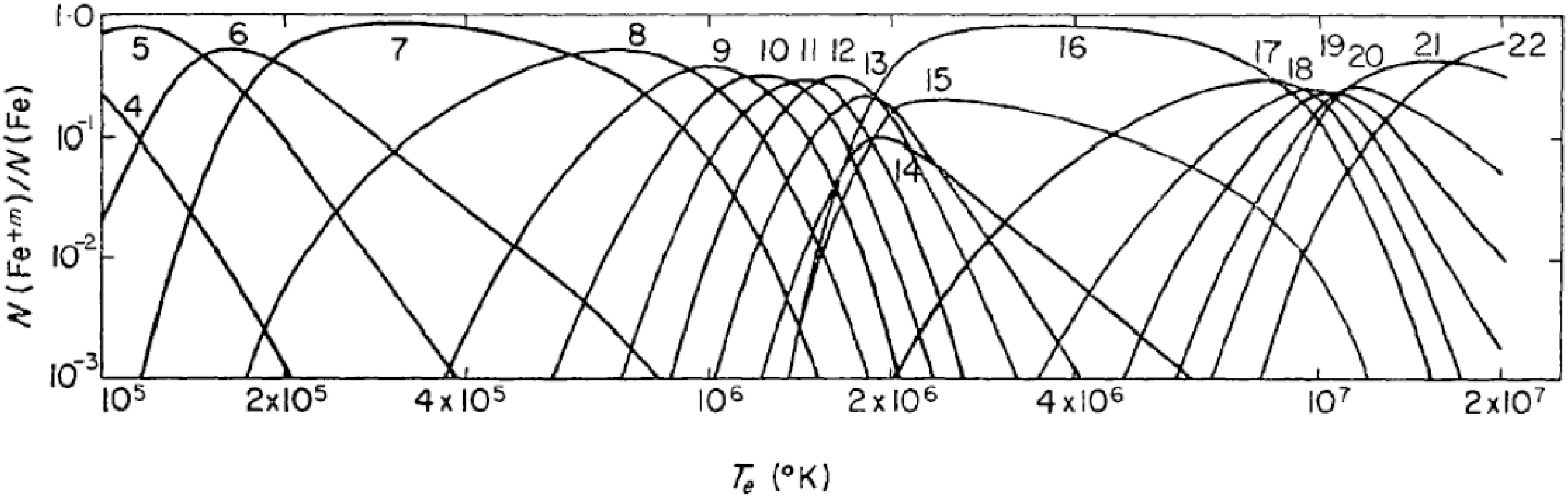
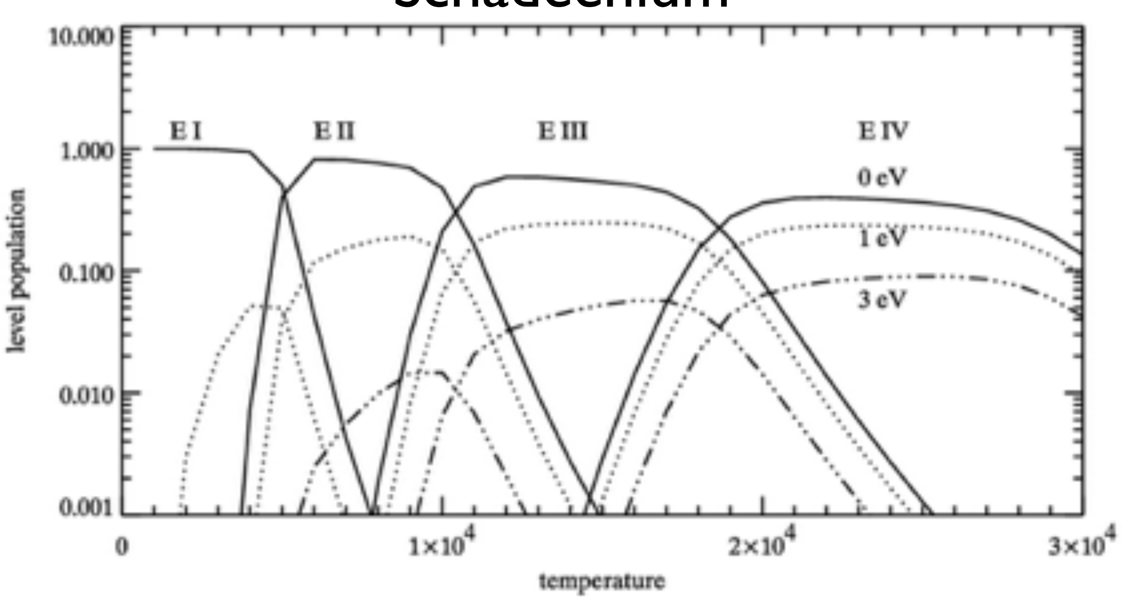


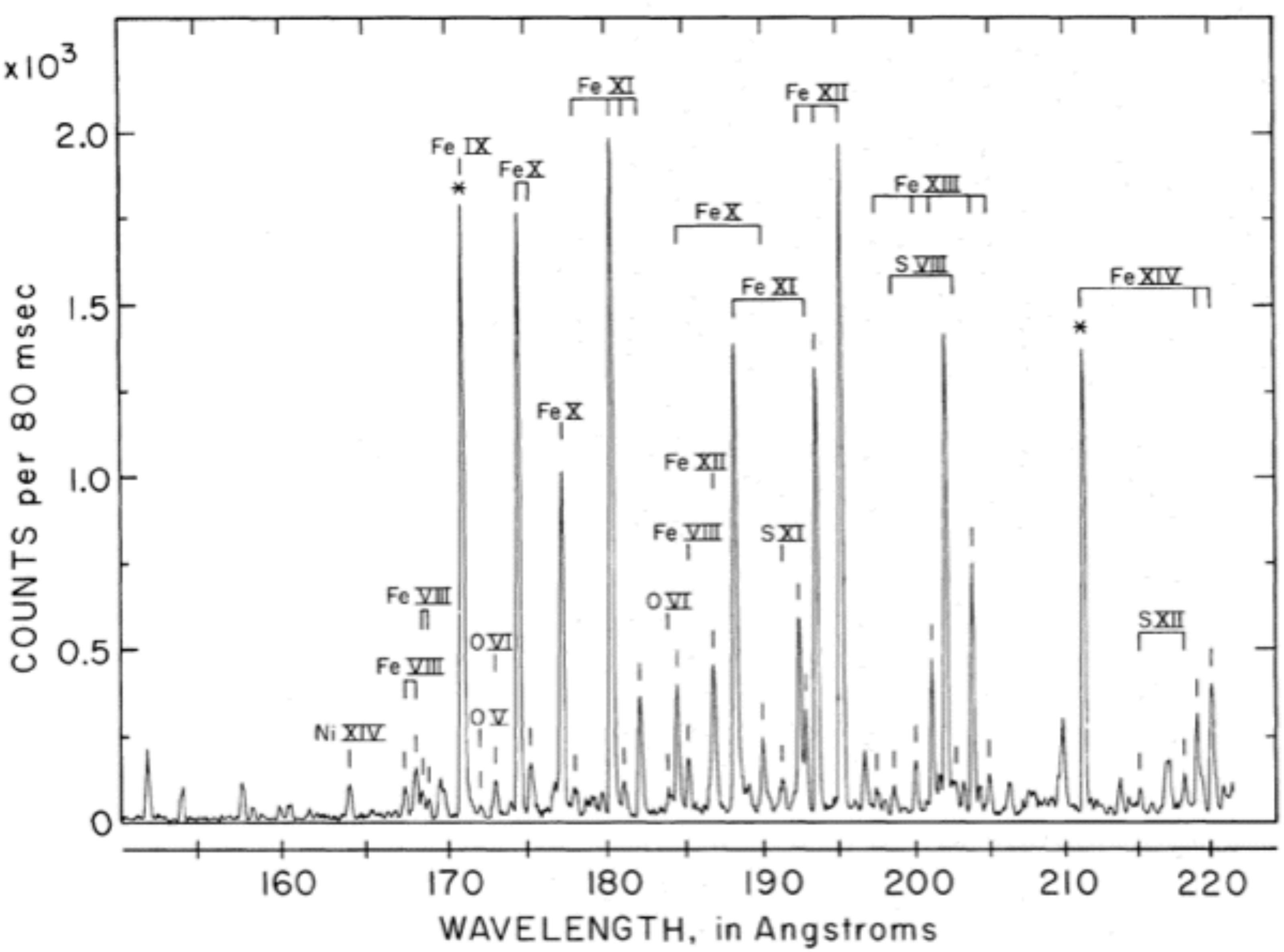
Figure 8.12: *Ionization stages of iron in the solar corona. After Jordan.*

Schadeenium



- levels with filled shells are difficult to ionize (7+, 16+)
- ions one stage below (6+, 15+) have many dielectronic recombination levels → long tail

Dielectronic recombination: de-excitation through many intermediate levels



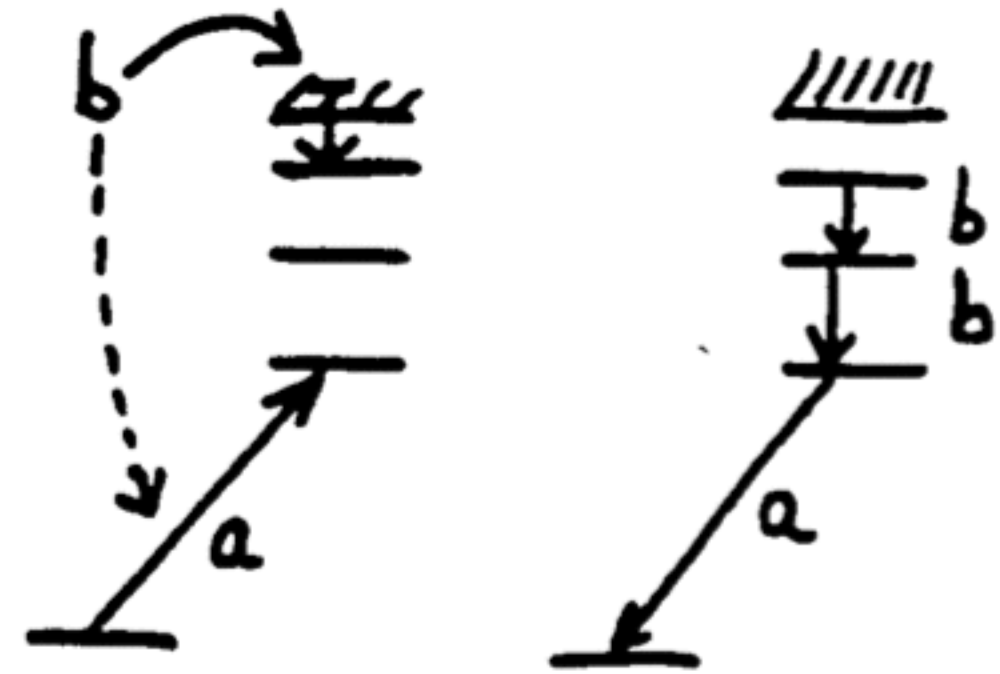
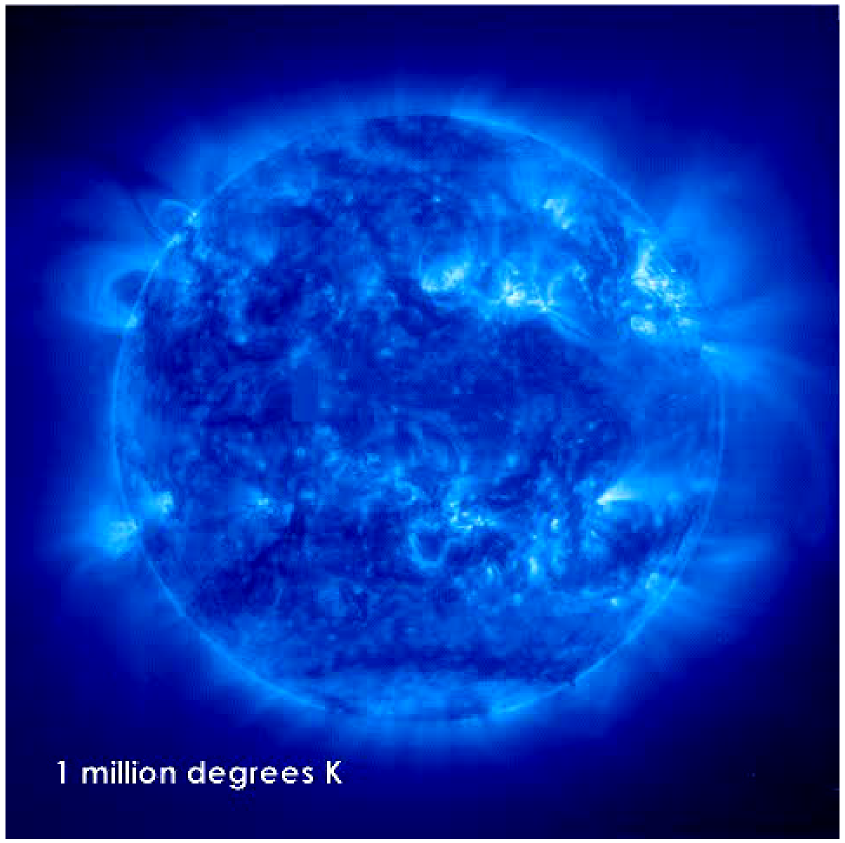
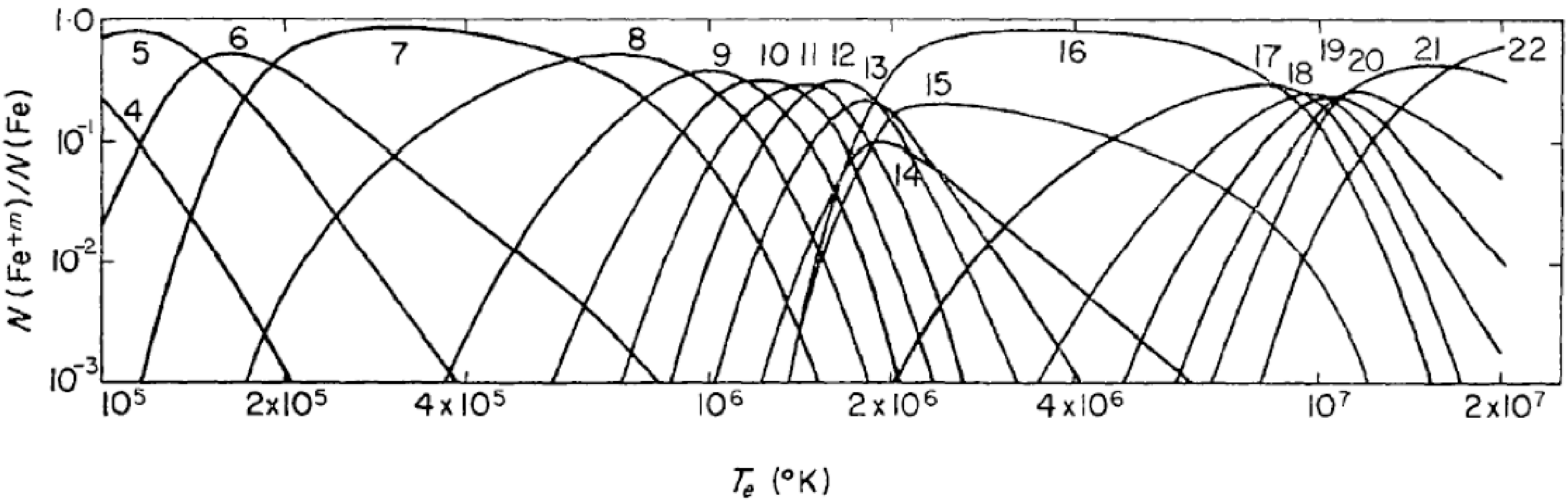


Figure 8.13 in Rutten

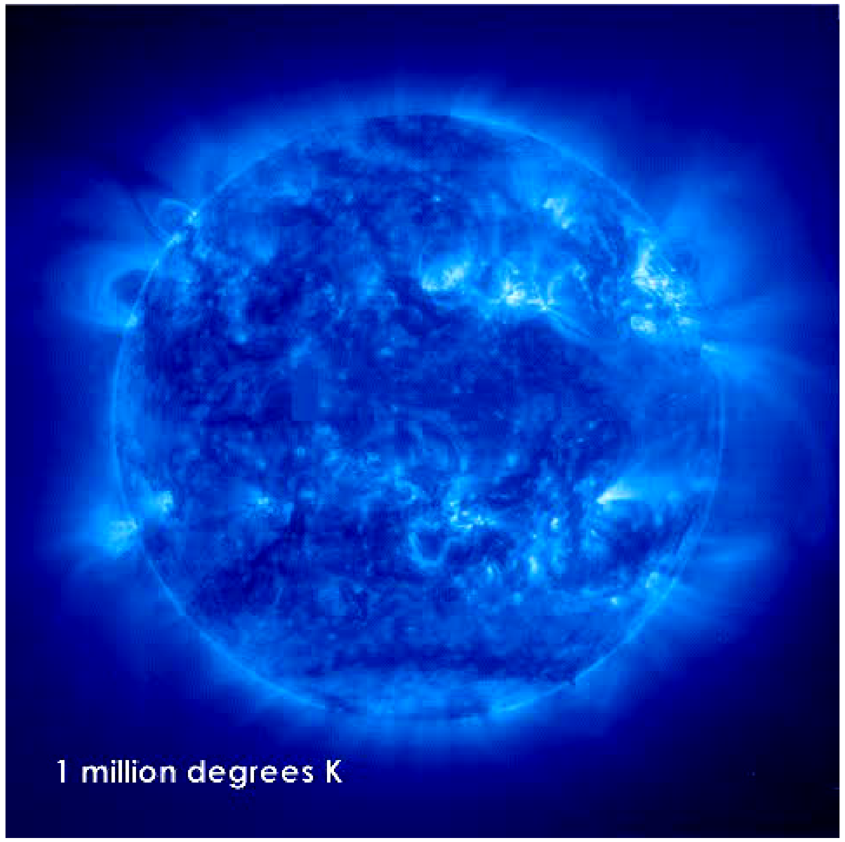
BRIGHT AND DARK IN EUV IMAGES

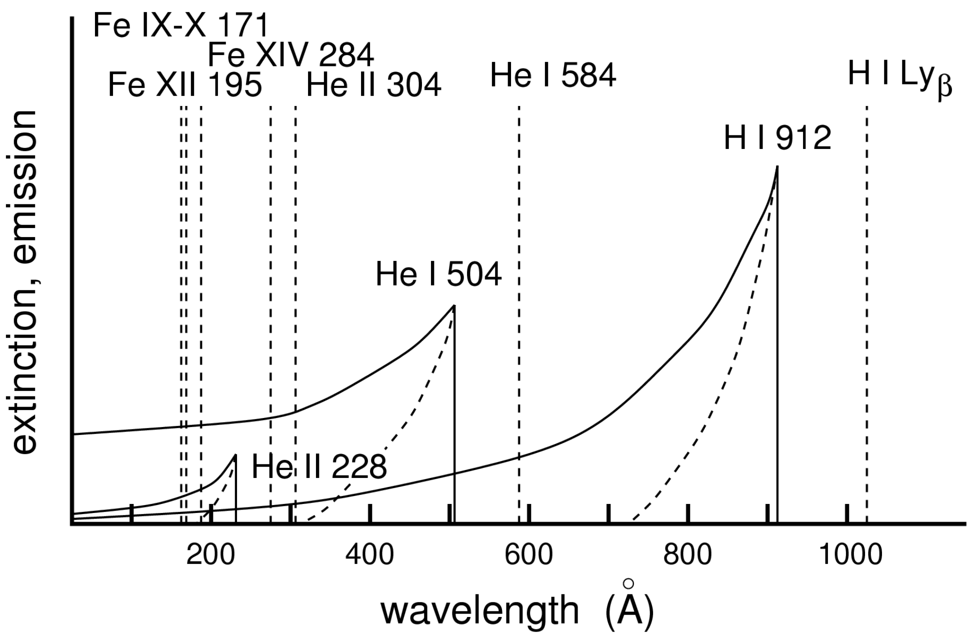


- *iron lines*
  - Fe IX/X 171 Å: about 1.0 MK
  - Fe XII 195 Å: about 1.5 MK
  - Fe XIV 284 Å: about 2 MK
- *bright*
  - collision up, radiation down
  - thermal photon creation, NLTE equilibrium
  - 171 Å: selected loops = special trees in forest



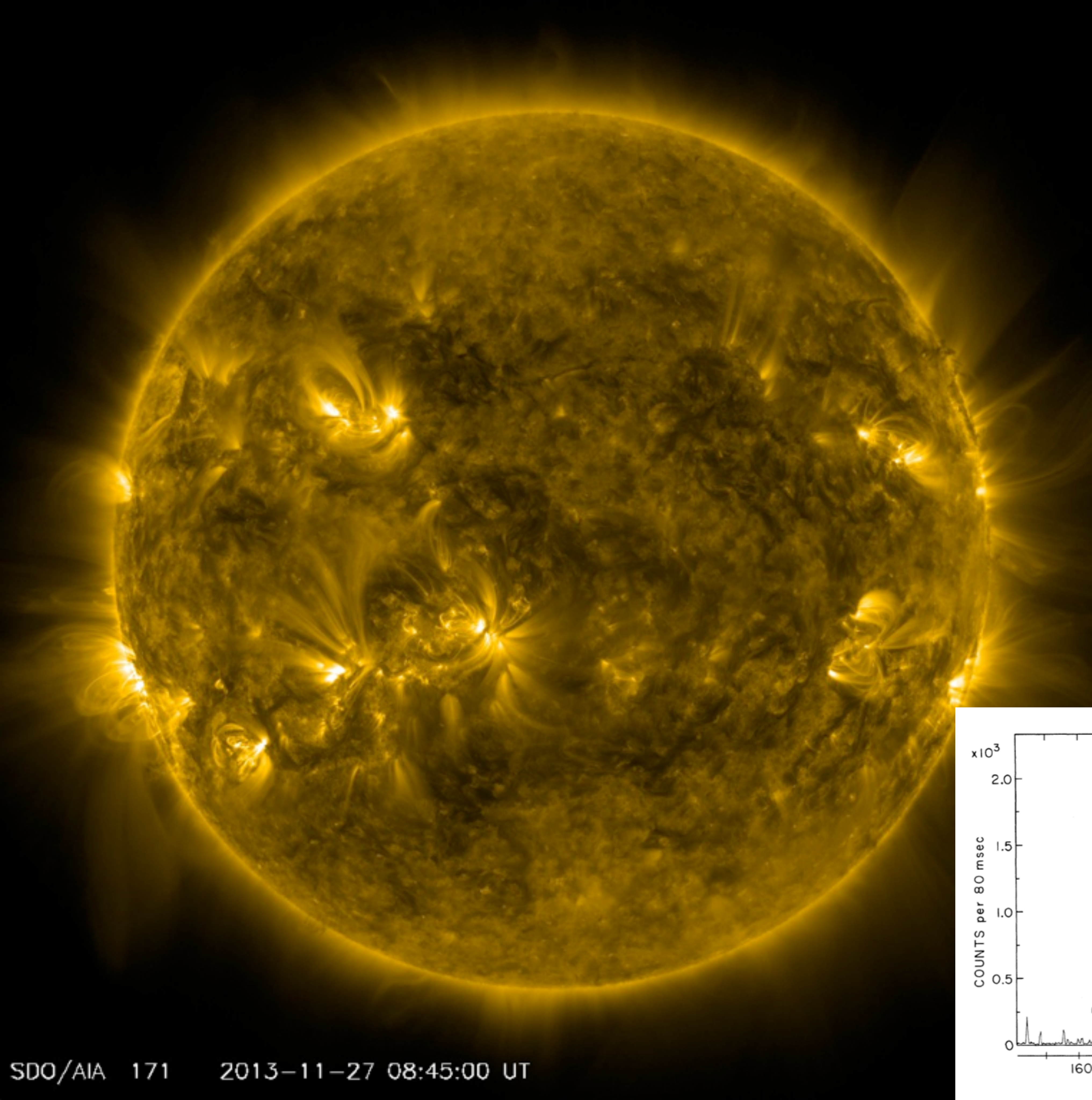
BRIGHT AND DARK IN EUV IMAGES

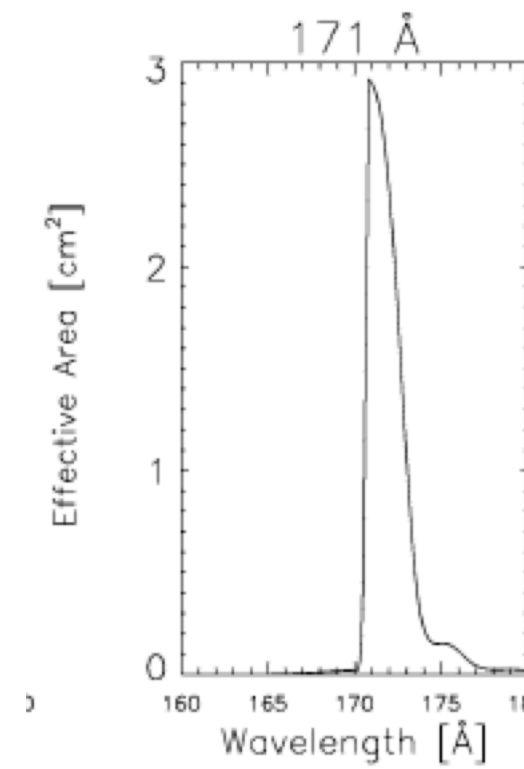




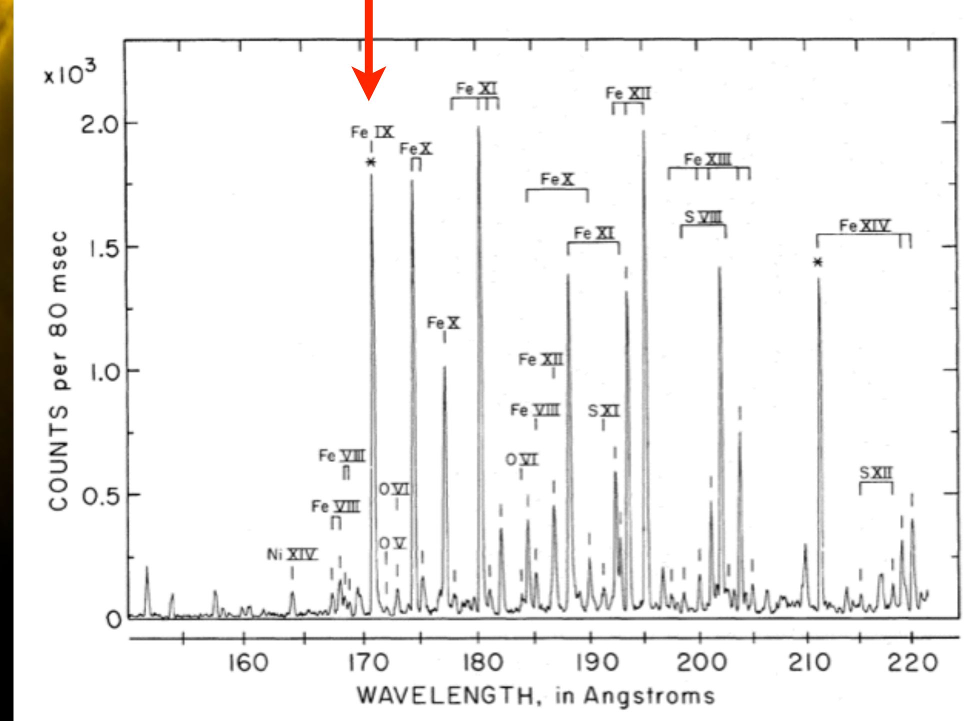
- *iron lines*
  - Fe IX/X 171 Å: about 1.0 MK
  - Fe XII 195 Å: about 1.5 MK
  - Fe XIV 284 Å: about 2 MK
- *bright*
  - collision up, radiation down
  - thermal photon creation, NLTE equilibrium
  - 171 Å: selected loops = special trees in forest
- *dark*
  - radiation up, re-radiation at bound-free edge
  - matter containing He^+, He, H: 10^4 – 10^5 K
  - large opacity

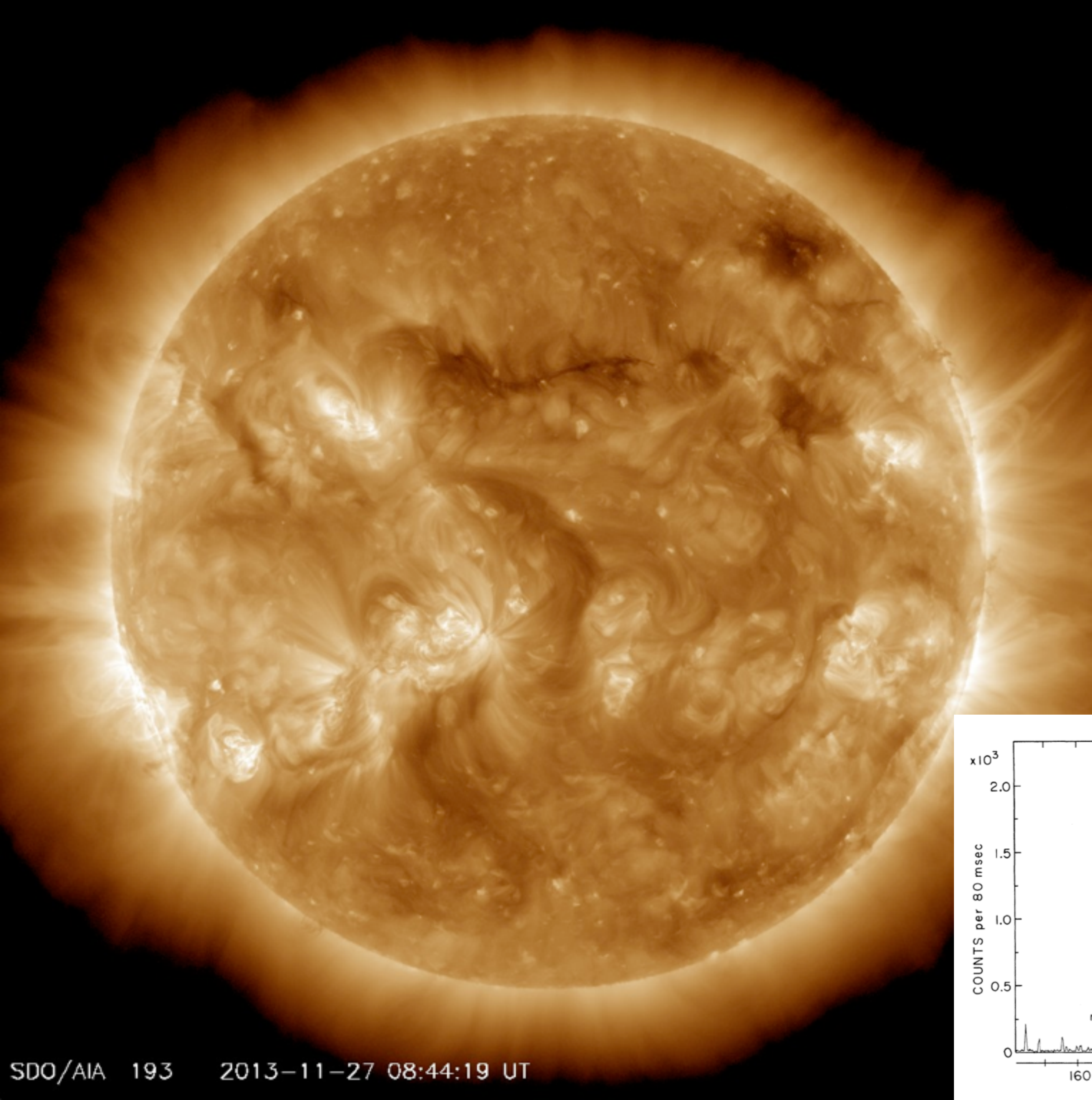
Fe IX 171 Å
0.6 MK



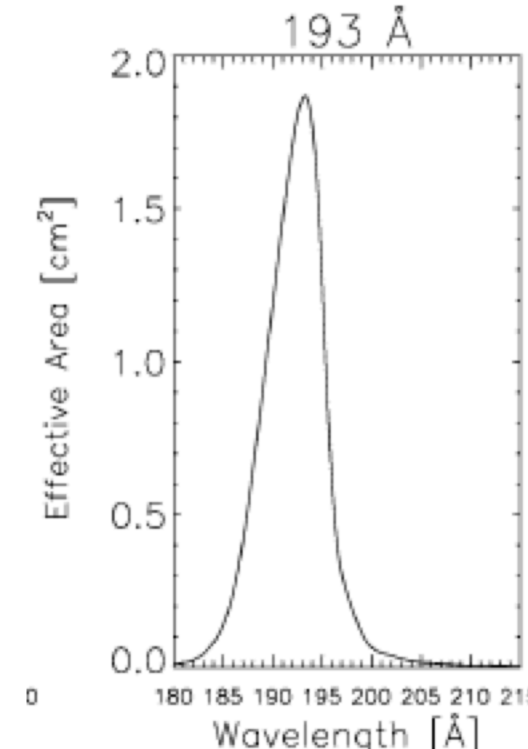


AIA filter transmission
(Boerner et al. 2012)





Fe XII 193 Å
1.5 MK



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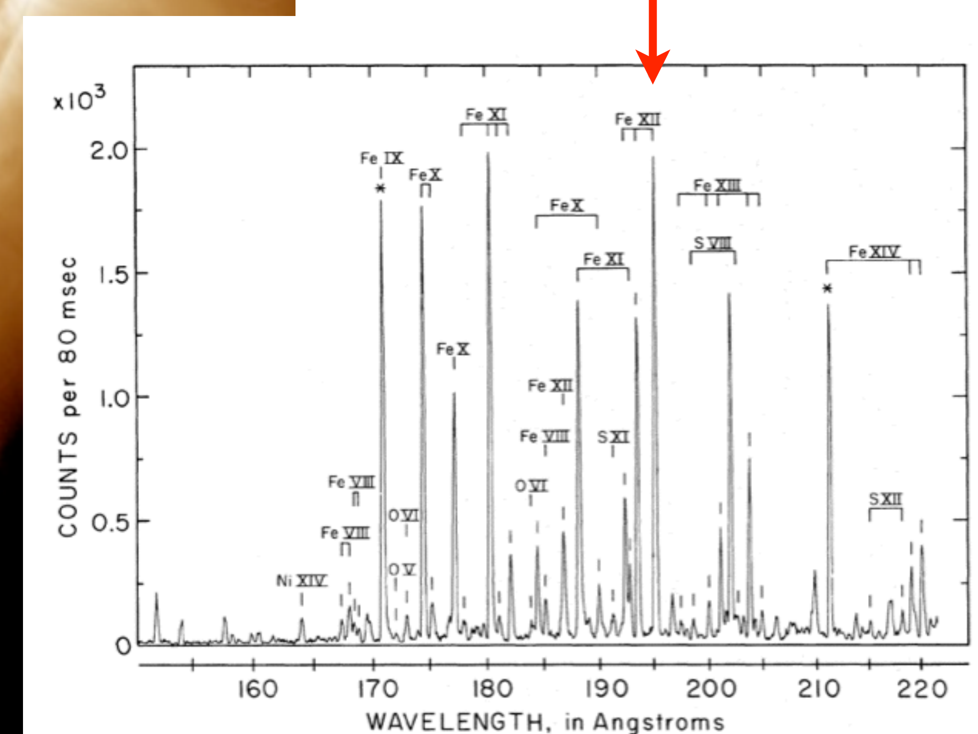
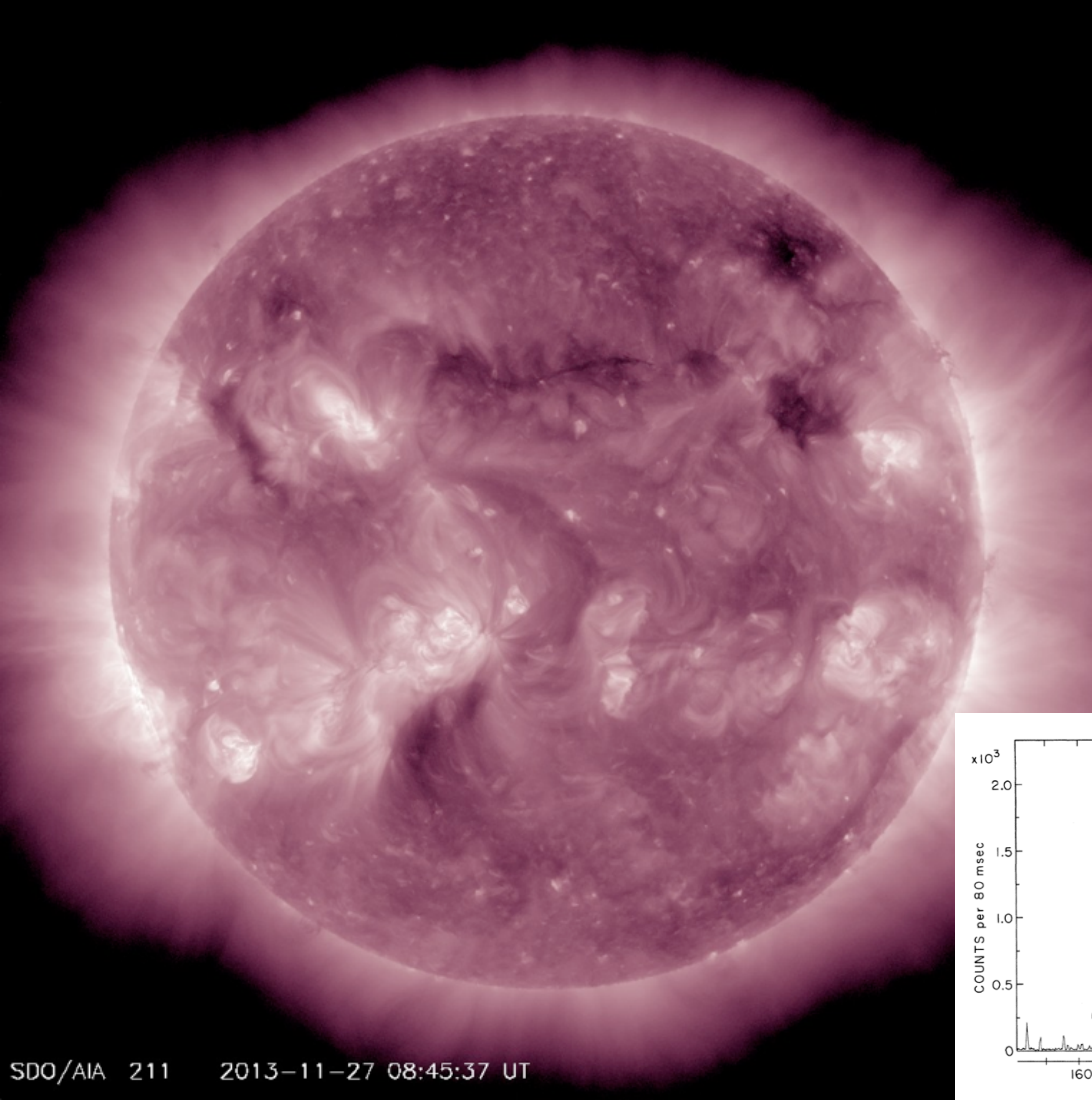
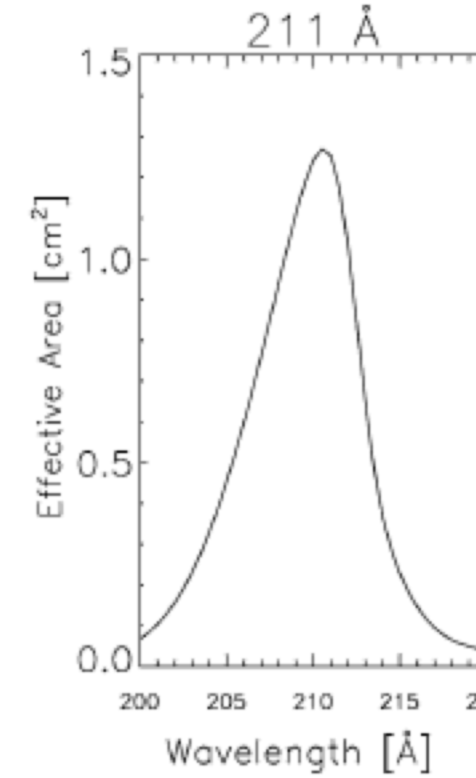
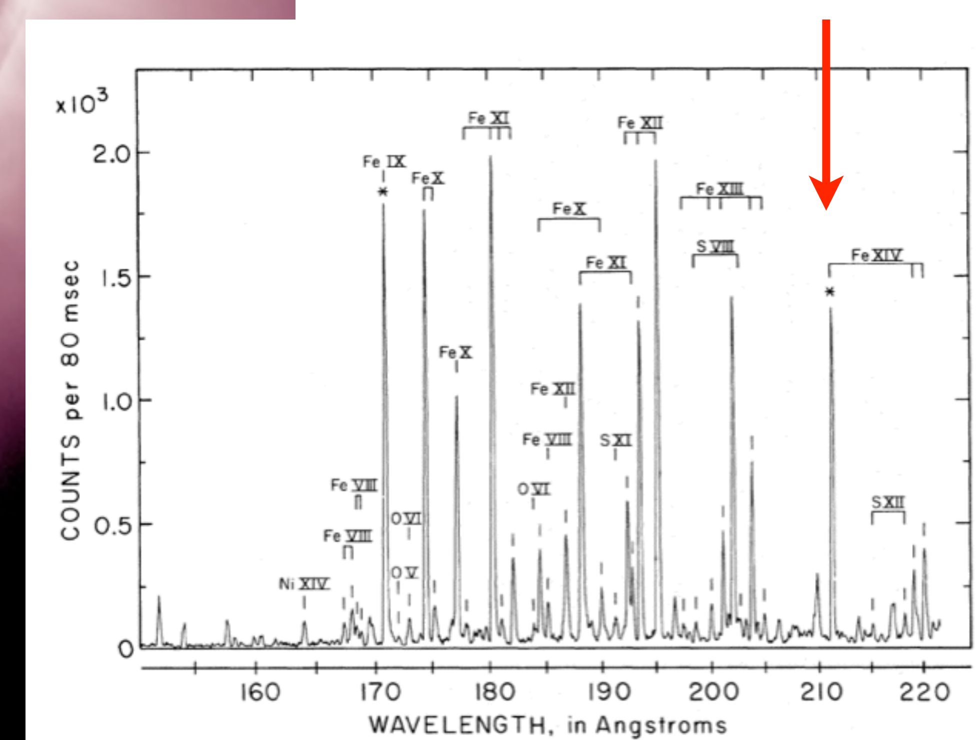


Fe XIV 211 Å
2 MK

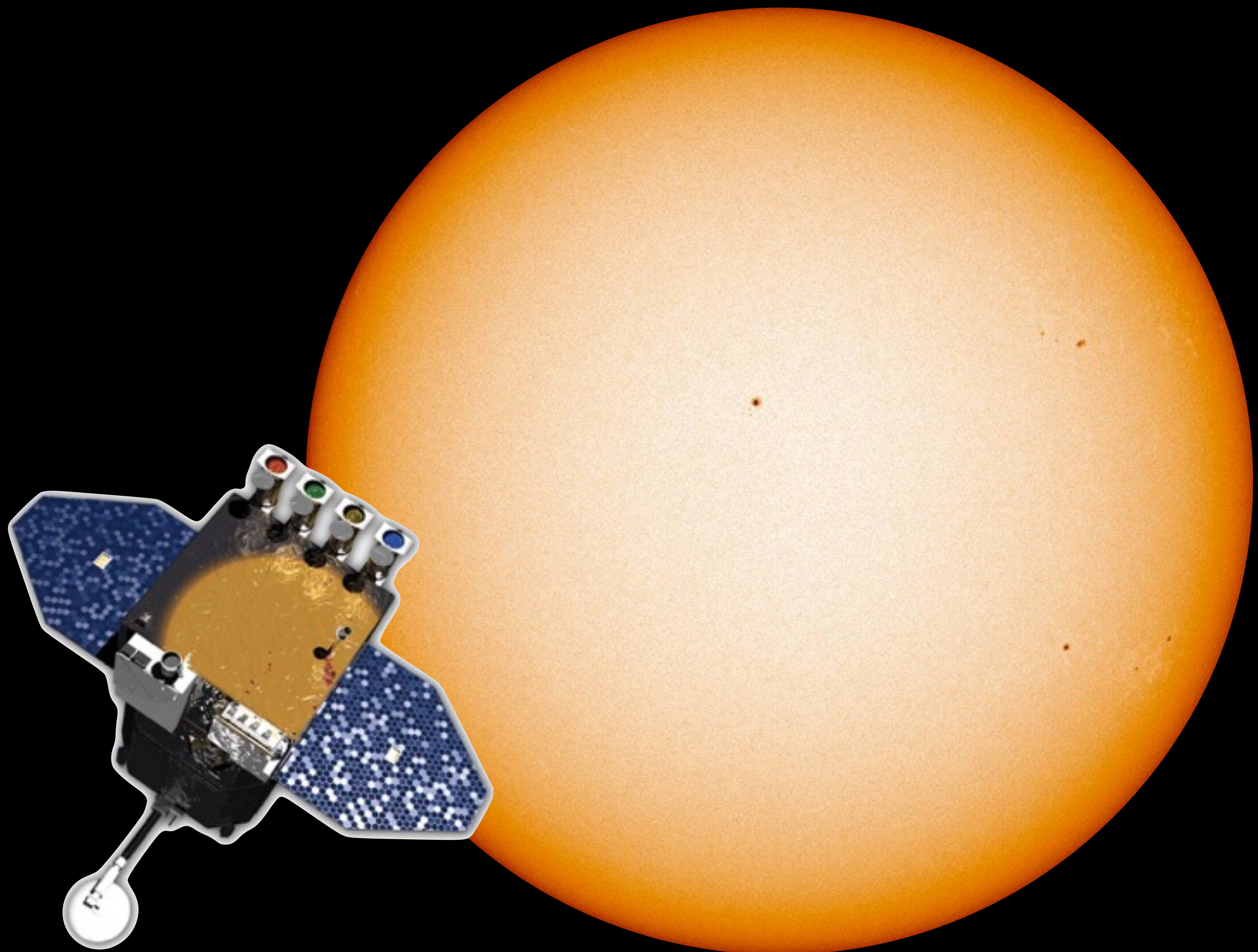




AIA filter transmission
(Boerner et al. 2012)



Solar Surface 6000 K



Solar Dynamics Observatory

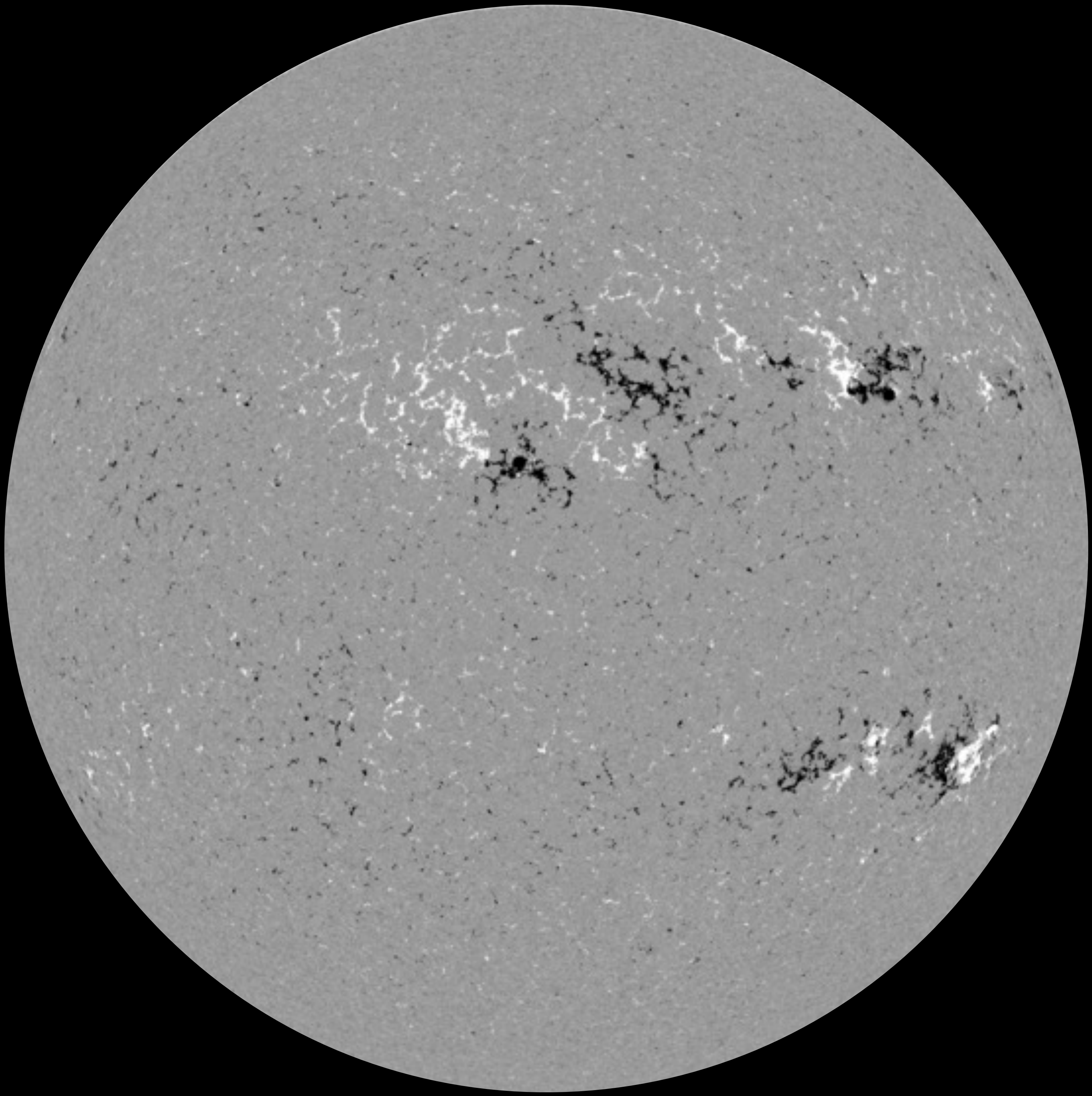
HMI/LSJU

Table 1 The primary ions observed by AIA. Many are species of iron covering more than a decade in coronal temperatures.

Channel	Primary ion(s)	Region of atmosphere	Char. log(T)
4500 Å	continuum	photosphere	3.7
1700 Å	continuum	temperature minimum, photosphere	3.7
304 Å	He II	chromosphere, transition region	4.7
1600 Å	C IV + cont.	transition region, upper photosphere	5.0
171 Å	Fe IX	quiet corona, upper transition region	5.8
193 Å	Fe XII, XXIV	corona and hot flare plasma	6.2, 7.3
211 Å	Fe XIV	active-region corona	6.3
335 Å	Fe XVI	active-region corona	6.4
94 Å	Fe XVIII	flaring corona	6.8
131 Å	Fe VIII, XXI	transition region, flaring corona	5.6, 7.0

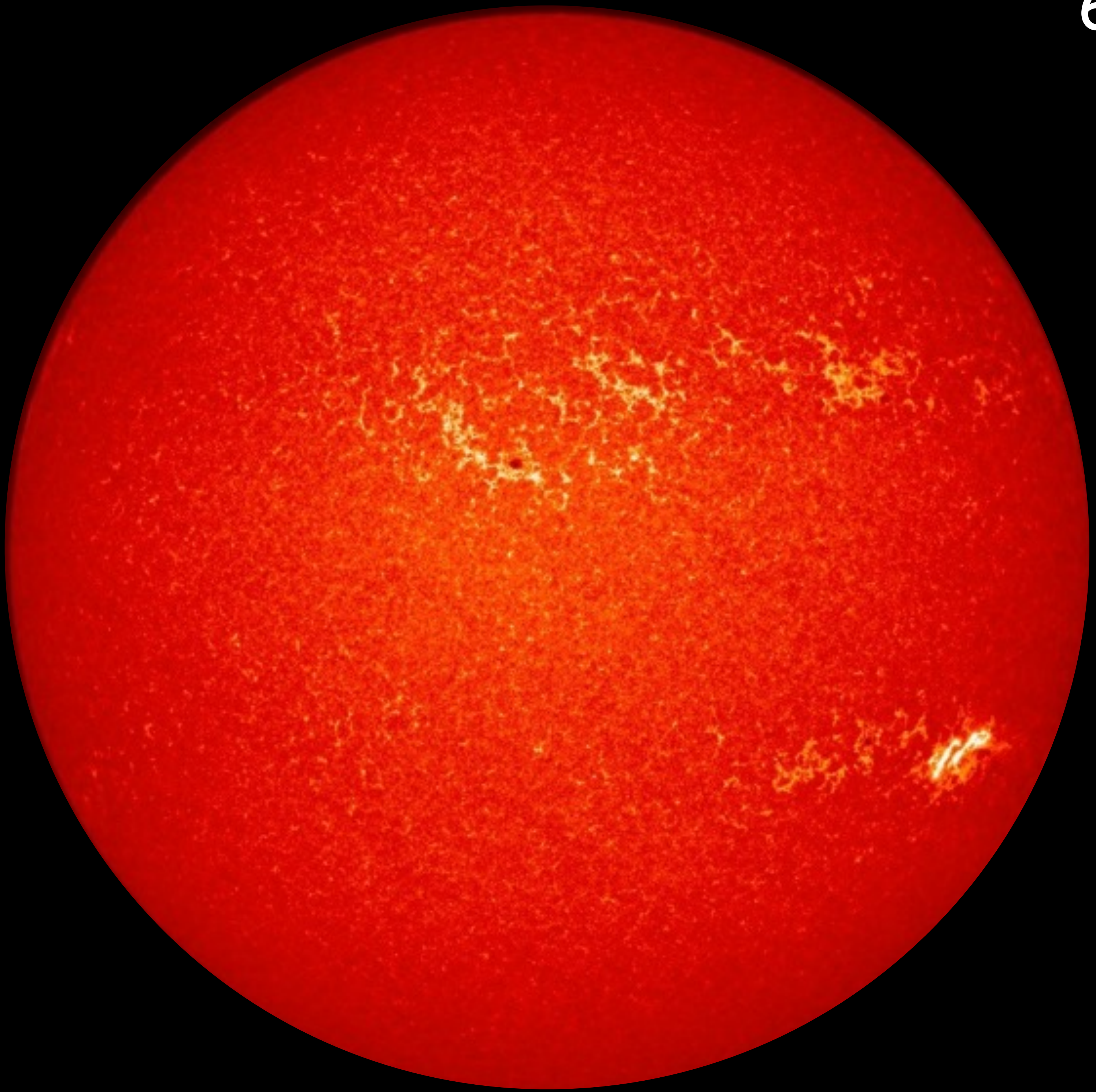
Lemen et al. 2012

Surface LOS Magnetic Field

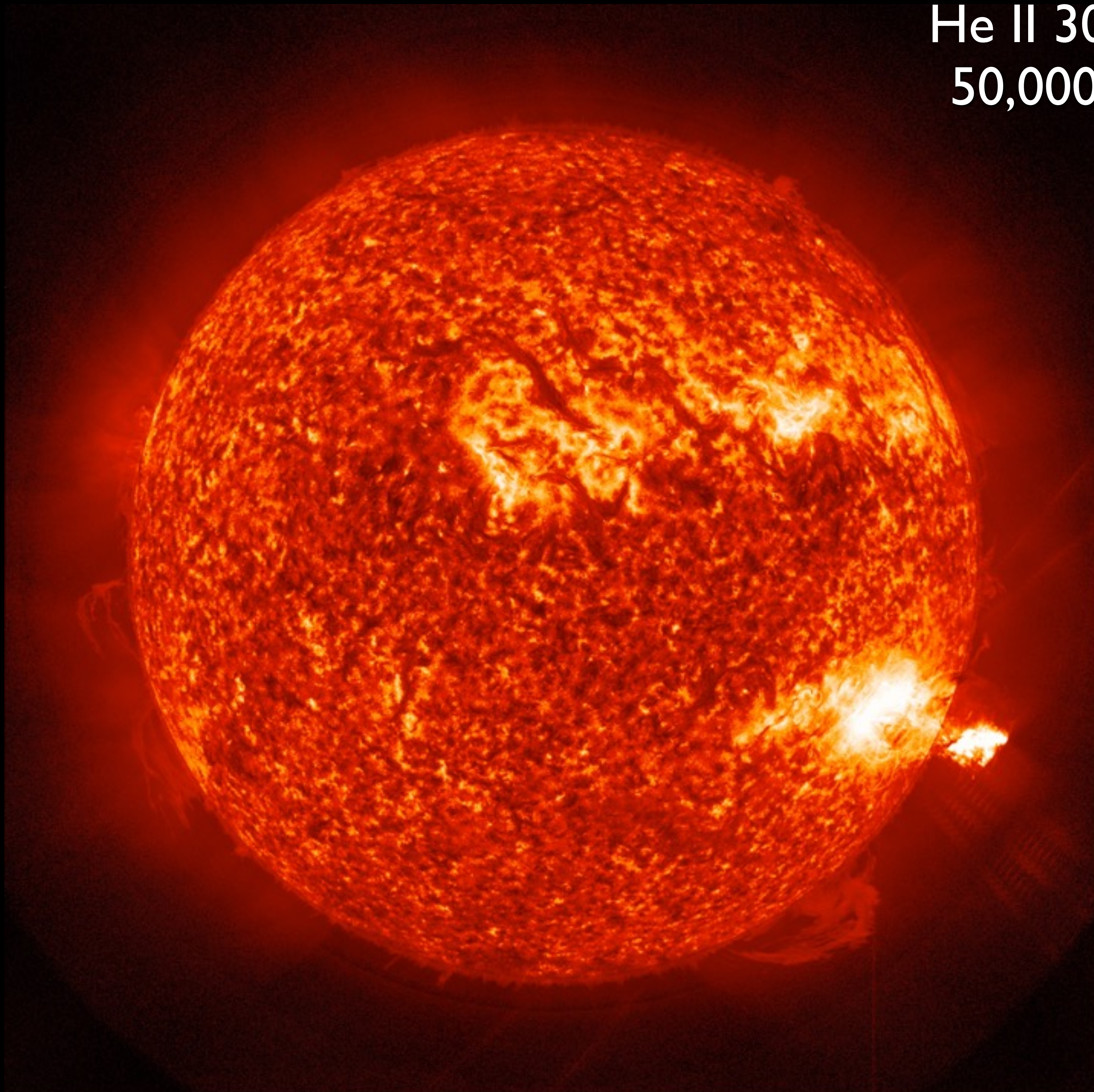


HMI/LSJU

UV Continuum
1700Å
6000 K



AIA/LMSAL



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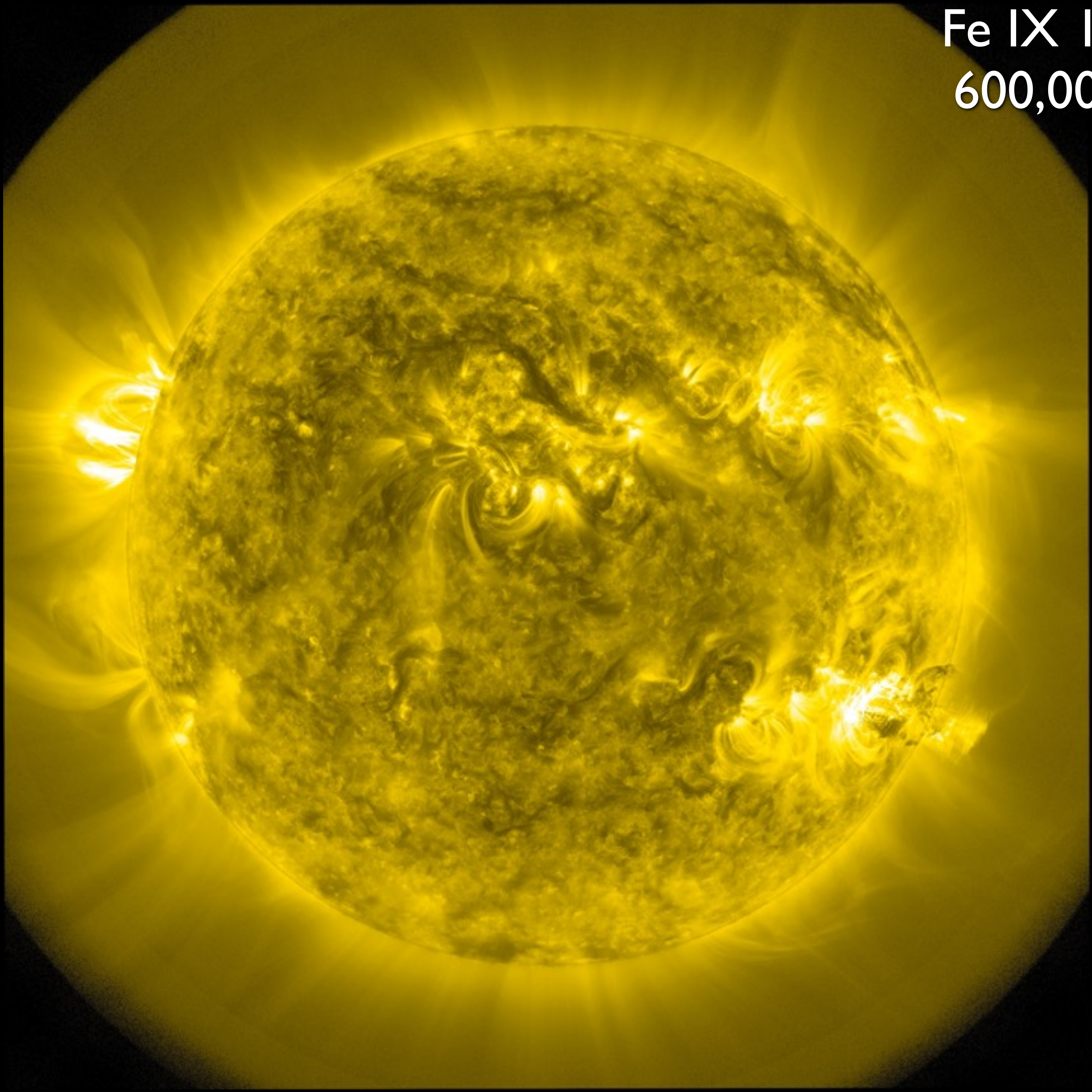
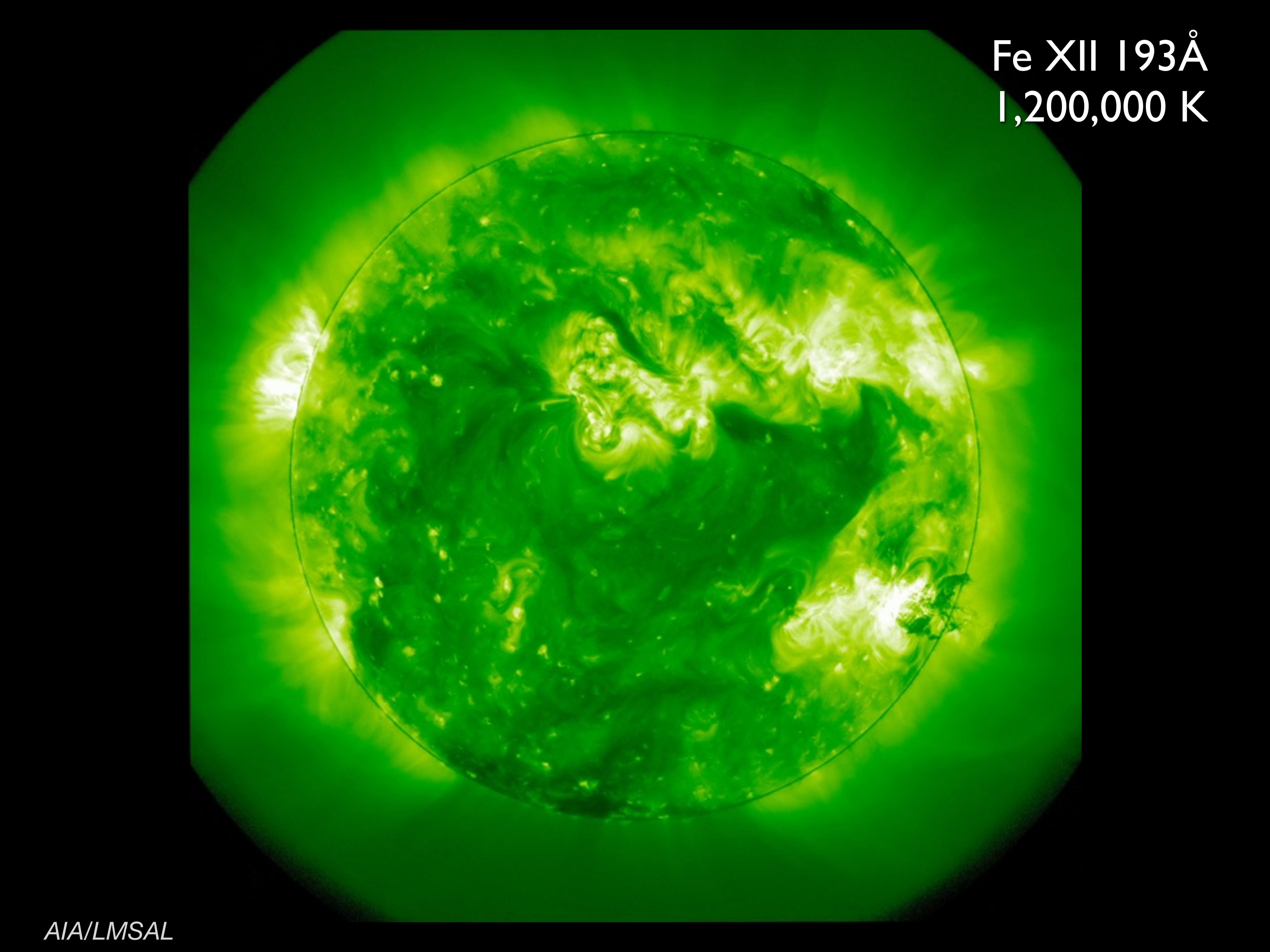
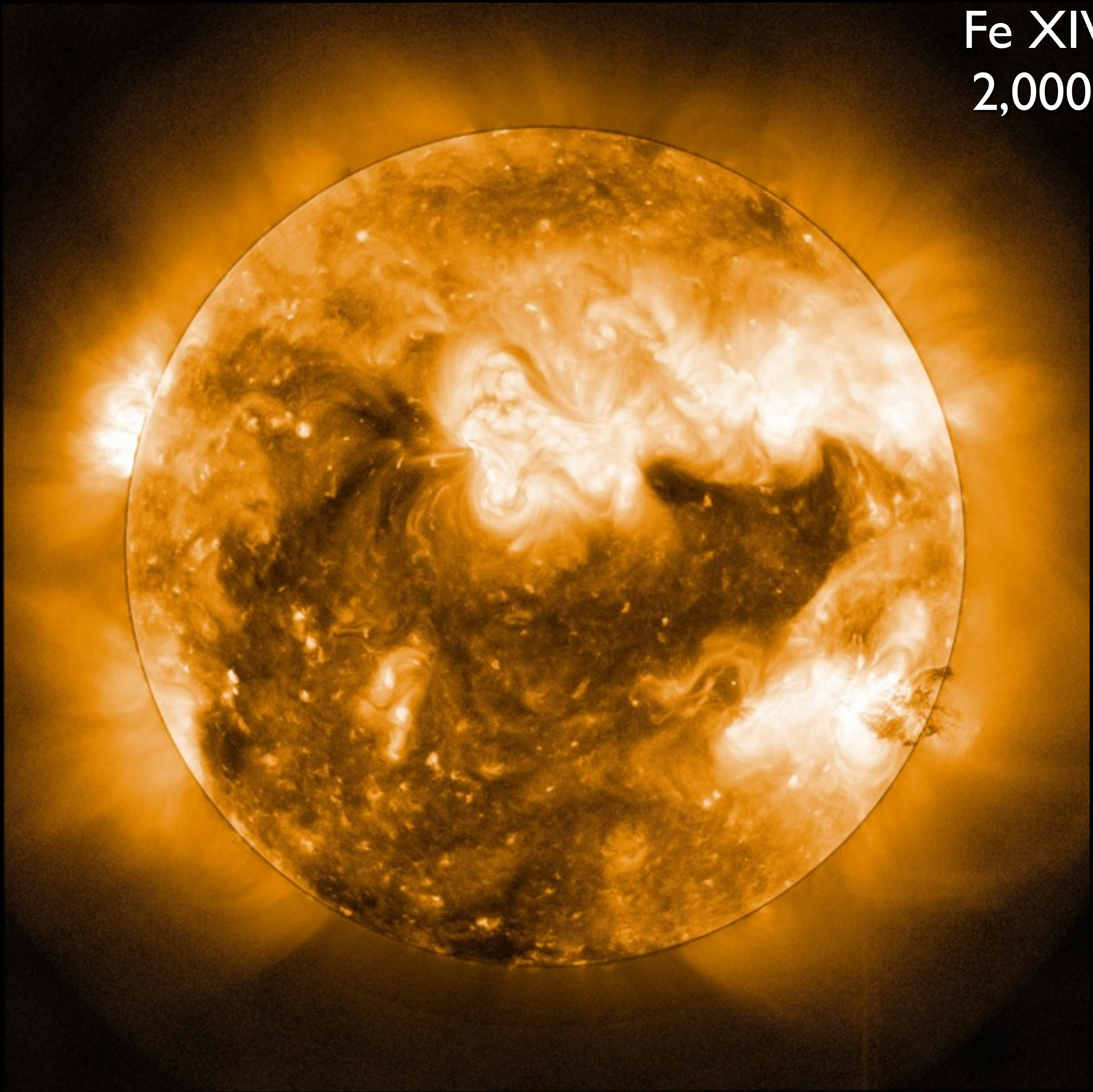
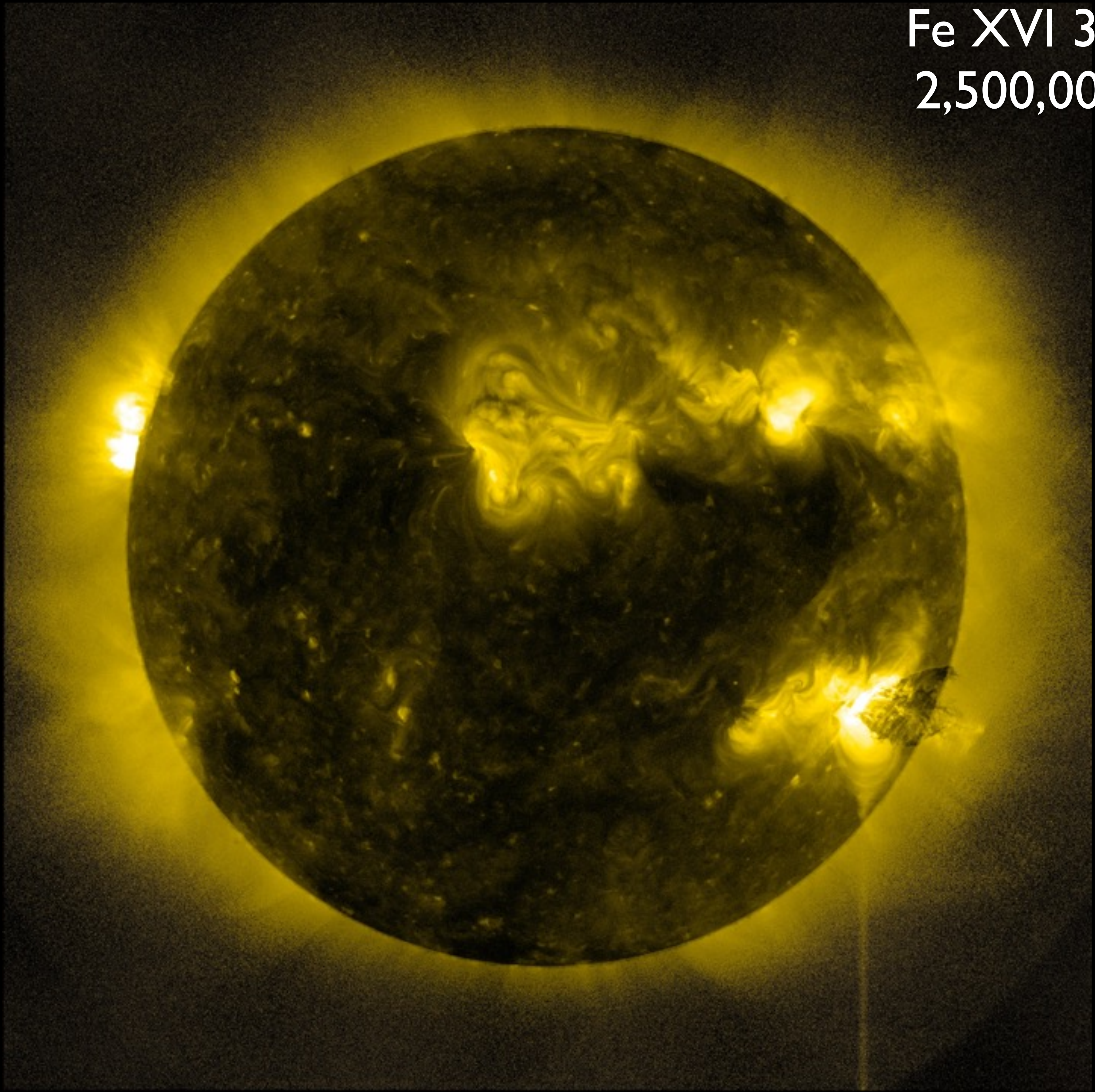


AIA/LMSAL

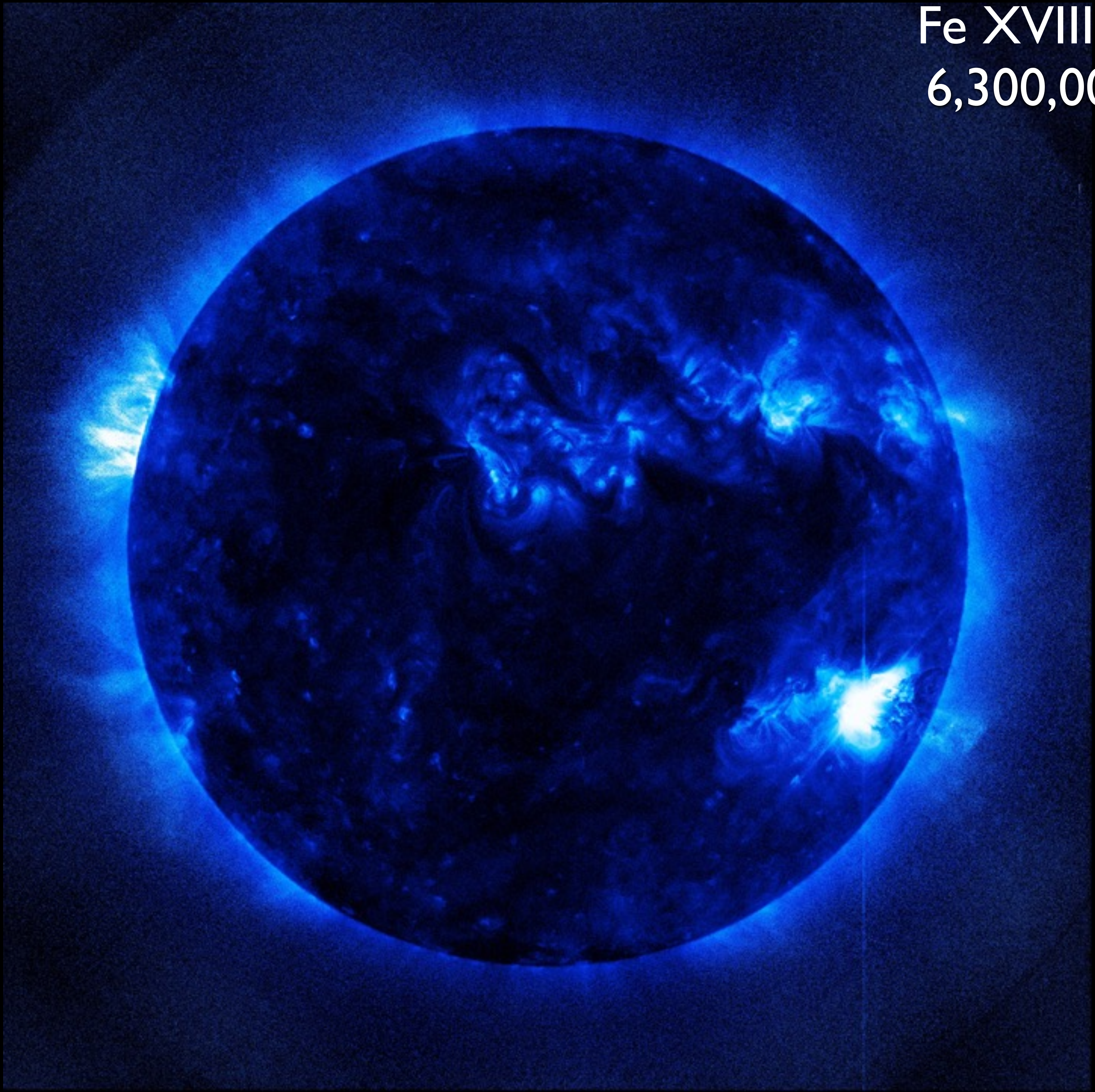

Fe XII 193Å
1,200,000 K
AIA/LMSAL



AIA/LMSAL



AIA/LMSAL



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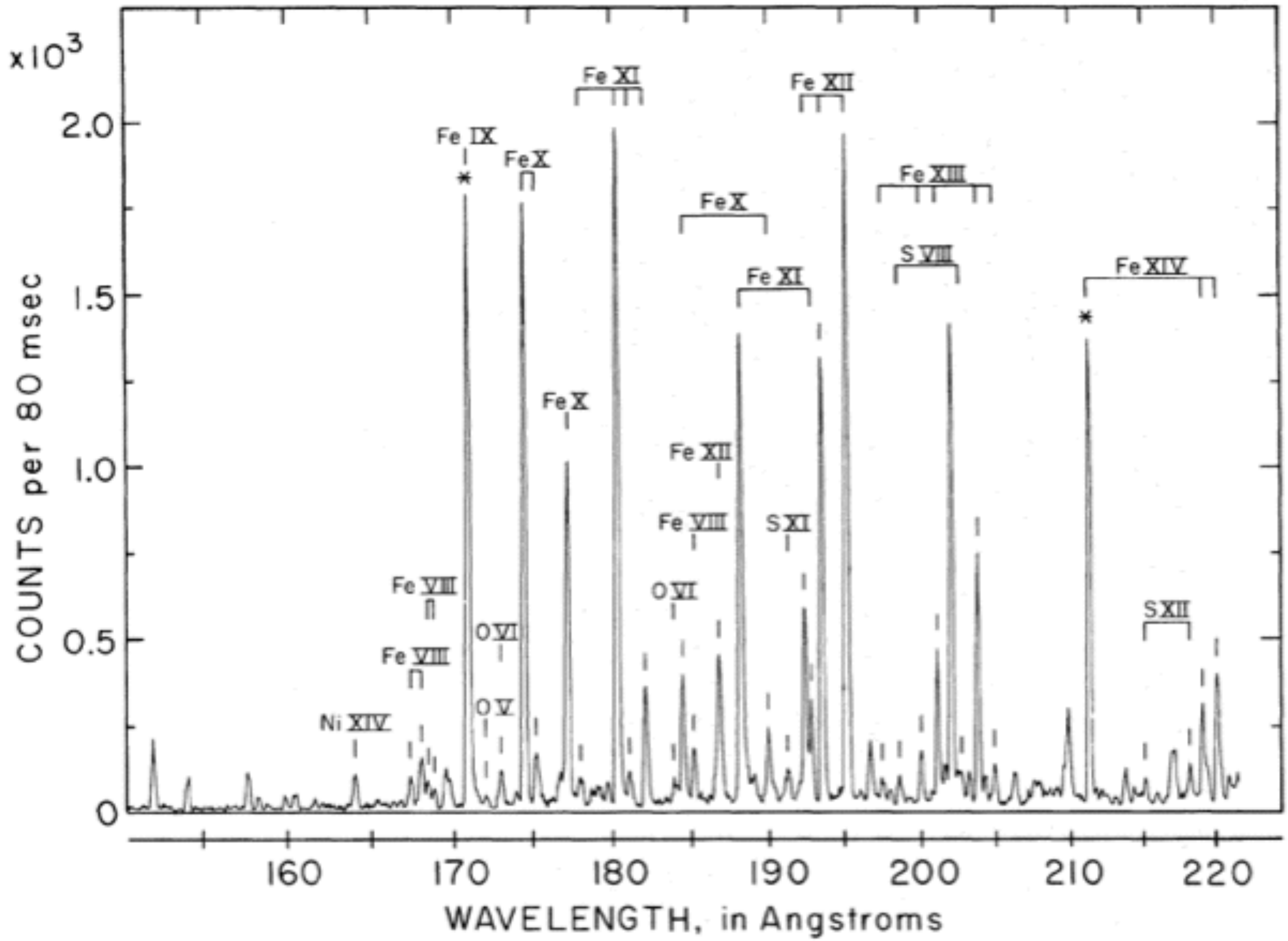
Lemen et al. 2012


x10³
2.0
1.5
1.0
0.5
0
COUNTS per 80 msec
160
170
180
190
200
210
220
WAVELENGTH, in Angstroms
Ni XIV
Fe VIII
Fe VIII
Fe IX
O VI
O V
Fe X
Fe X
Fe XI
O VI
Fe VIII
Fe XII
Fe X
Fe XI
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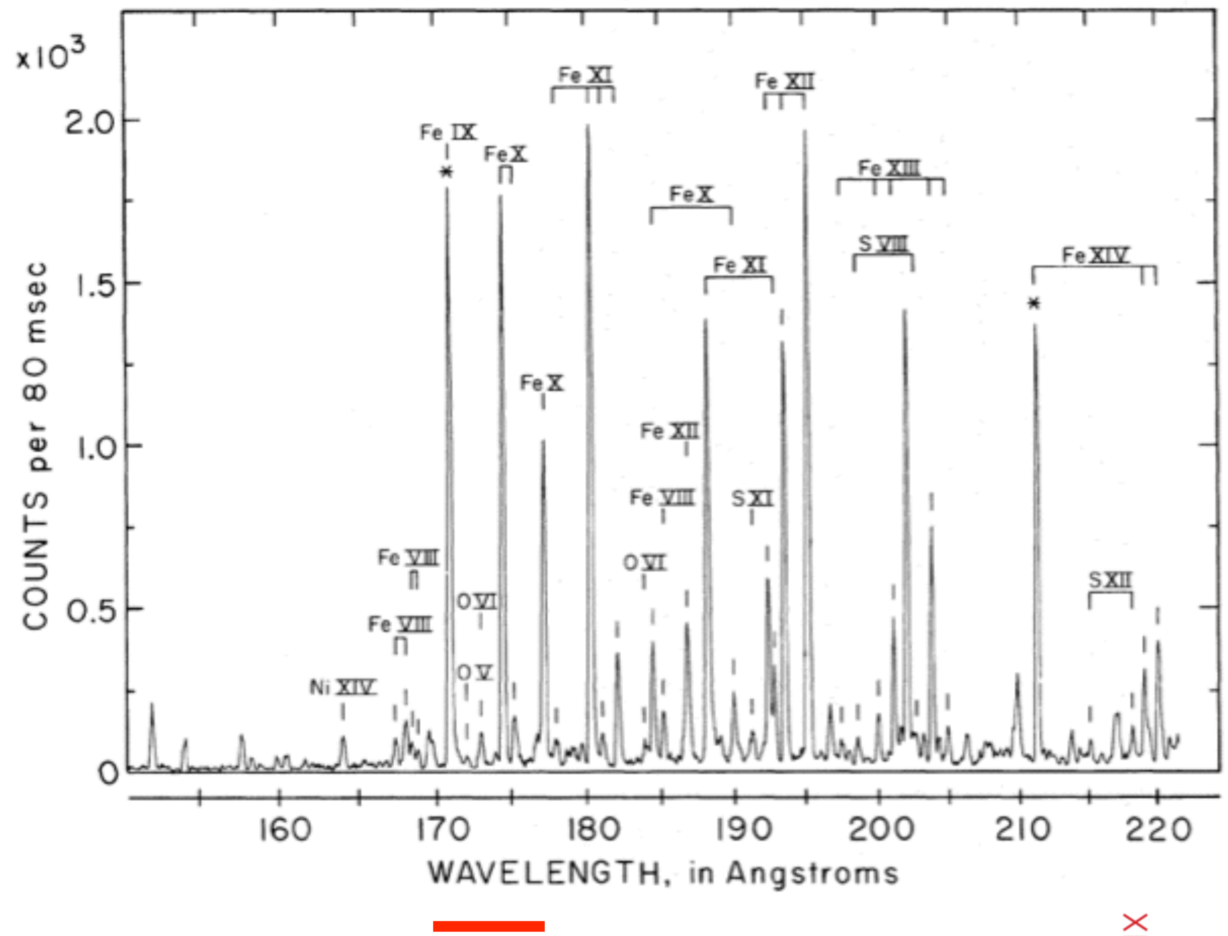
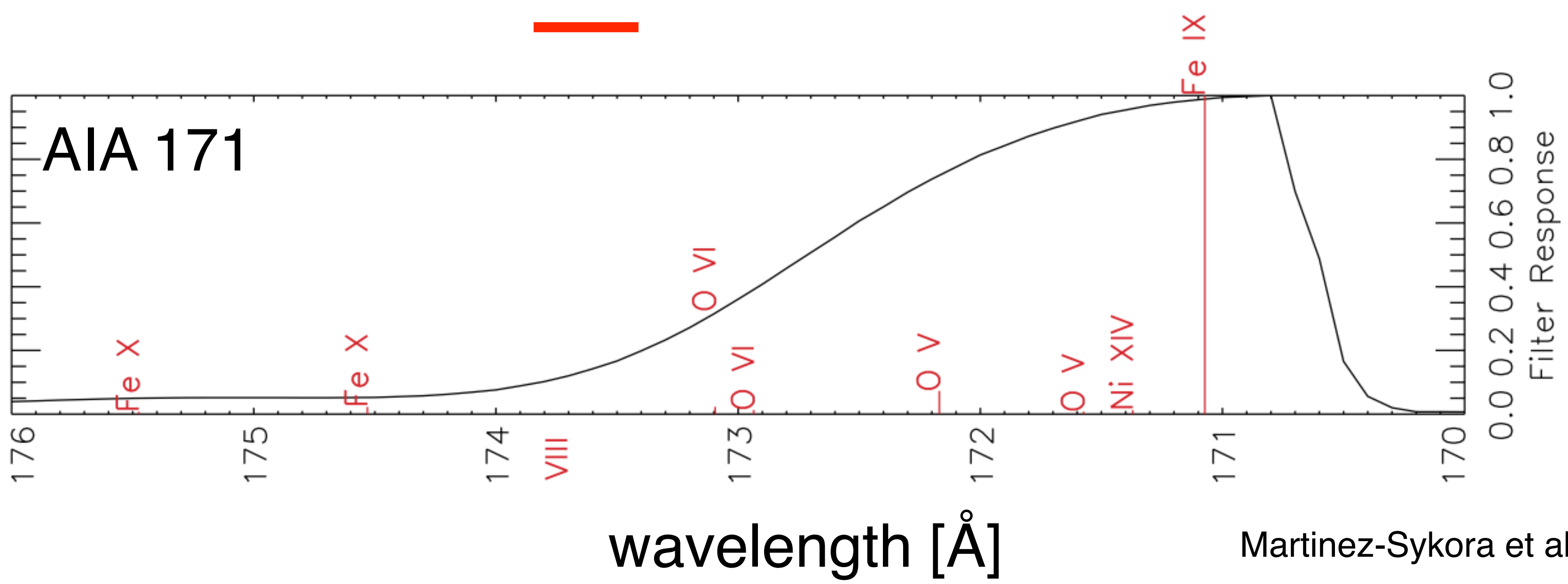
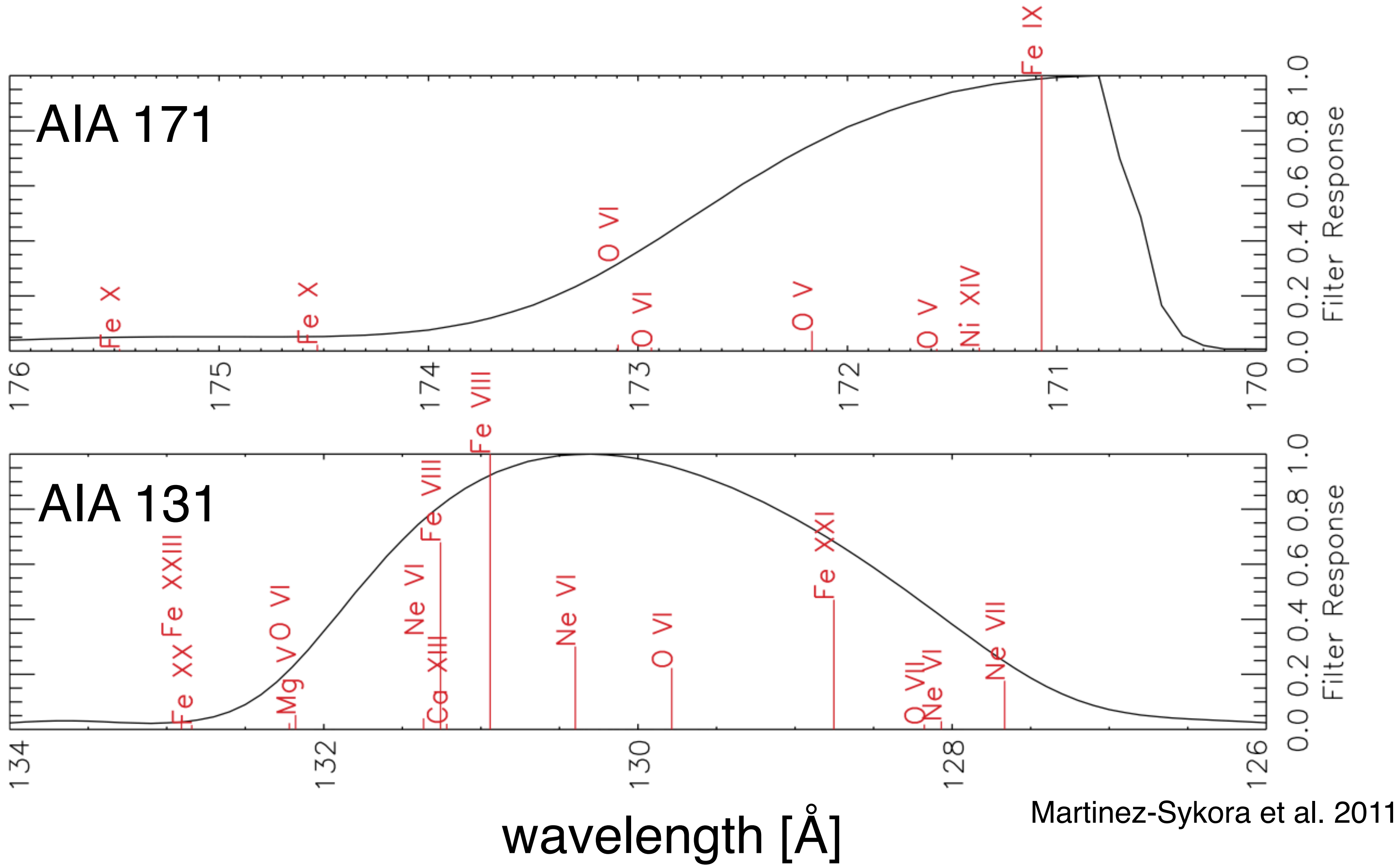
Fe XIII
S VIII
Fe XIV
S XII





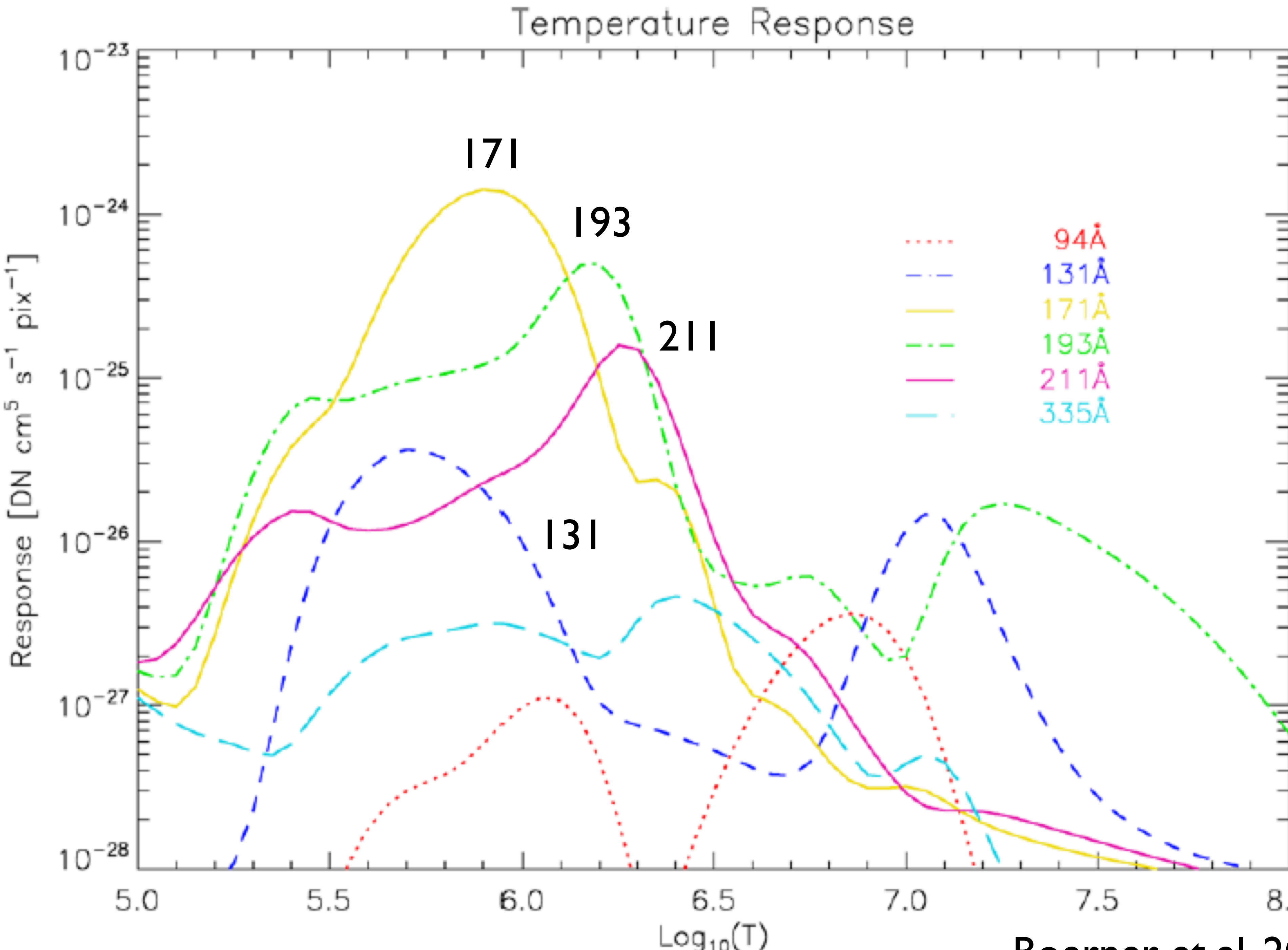
Martinez-Sykora et al. 2011

AIA 171 Å filter profile with dominating spectral lines:
Fe IX dominates (~600,000 K) but also contribution from Fe X



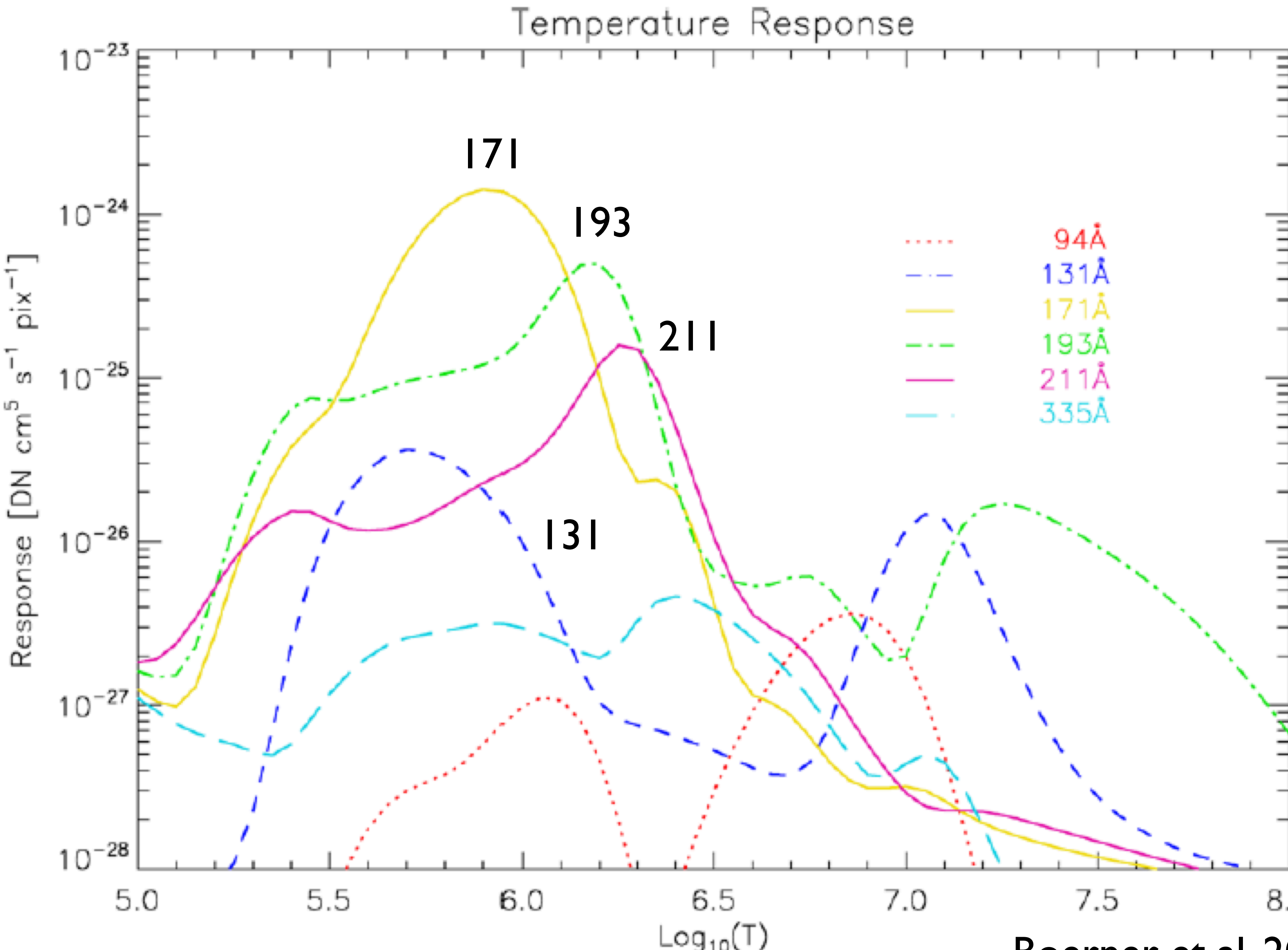
AIA 131 Å filter profile with dominating spectral lines:
Fe VIII dominates (~400,000 K) but in flares Fe XXI (10 MK) becomes strong

Temperature response for SDO/AIA filters



Boerner et al. 2012

Temperature response for SDO/AIA filters



Boerner et al. 2012

131 Å: Fe VIII Fe XXI