X-Ray Emission Processes

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http://heasarc.nasa.gov/xanadu/xspec/newmodels.html

Apec
Atable

CHIANTI

Bapec
Bbody
Bbodyrad
Bexrav
Bexriv
Bknpower
Bkn2pow
Bmc
Bremss

HULLAC
R-Matrix
FAC

NLTE Model Atmosphere
Tübingen MAP

C6mekl
Cemekl
Cflow
Compbb
CompLS
CompPS
CompST
CompTT
Cplinear
Cutoffpl

CompTB

Disk
Diskbb
Diskir
Diskline
Diskm
Disko
Diskpbb
Diskpn

Eqpair
Equil
Expdec
Ezdiskbb

Cloudy

MoCaSsIN

Gaussian
Gnei
Grad
Grbm

XSTAR

MYTorus

Laor
Laor2
Lorentz

windprof

Kdline
Kerrbb
Kerrd
Kerrdisk
Kyrline
Kyf1ll
Kyh1refl
Kyl1cr
KyB1Bphe
Kyconv

Meka
Mekal
Mkcflow

photoion

Nei
Npshock
Nsa
Nsagrav
Nsatmos
Nsmax
Nteea
Nthcomp

Pegpwrlw
Pexrav
Pexriv
Plcabs
Posm
Powerlaw
Pshock

Raymond
Redge
Refsch

Sedov
Sirf
Simpl
Smaug
Srcut
Sresc
Step

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A practical guide to understanding high-energy astrophysical sources

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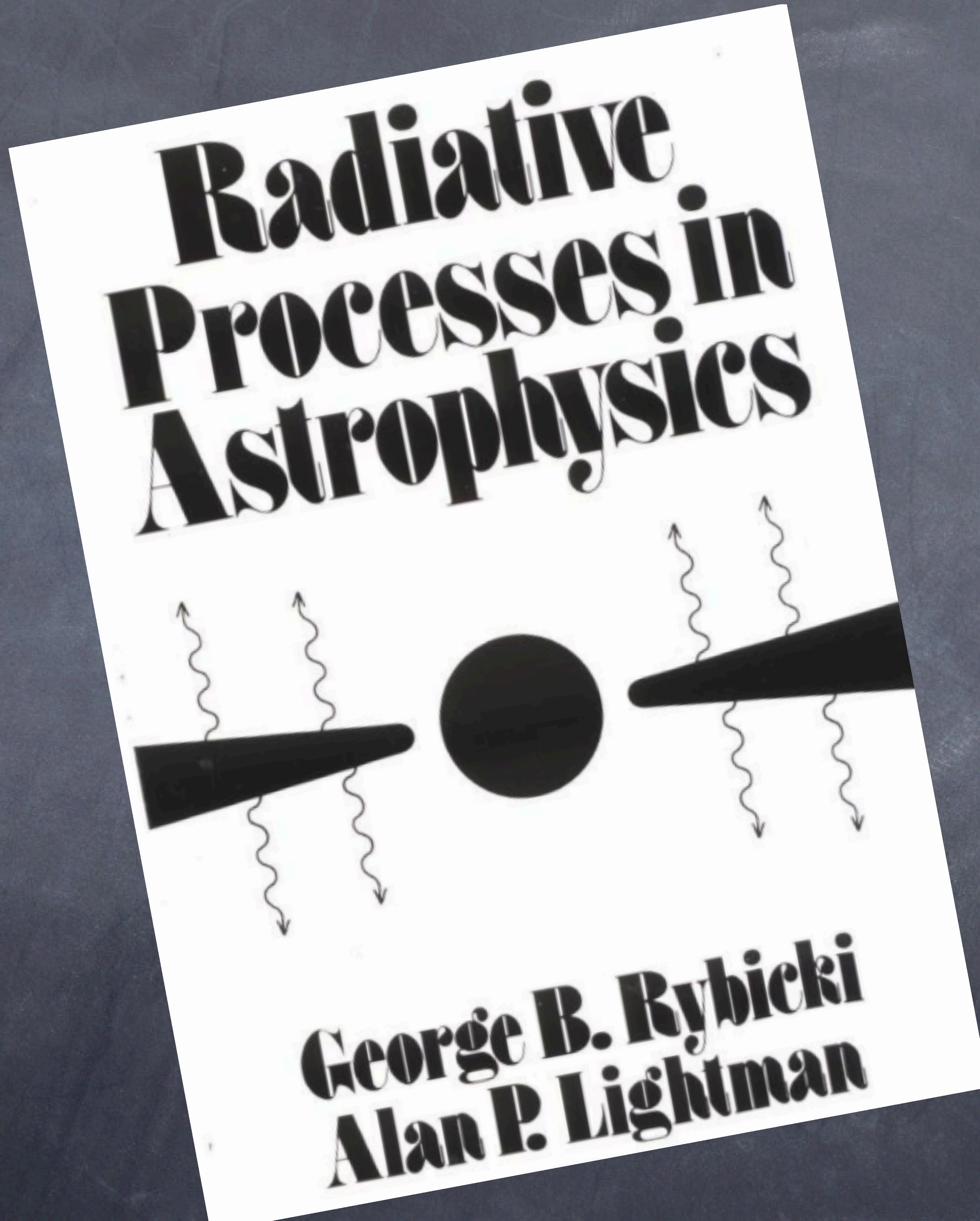
Radiative
Processes in
Astrophysics
George B. Rybicki
Alan P. Lightman

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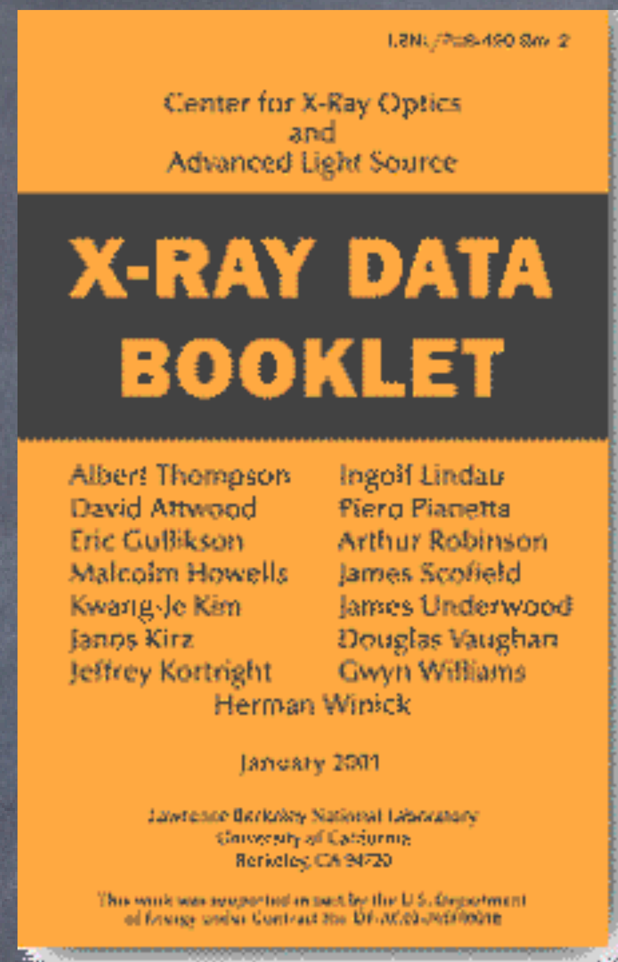

http://xdb.lbl.gov/

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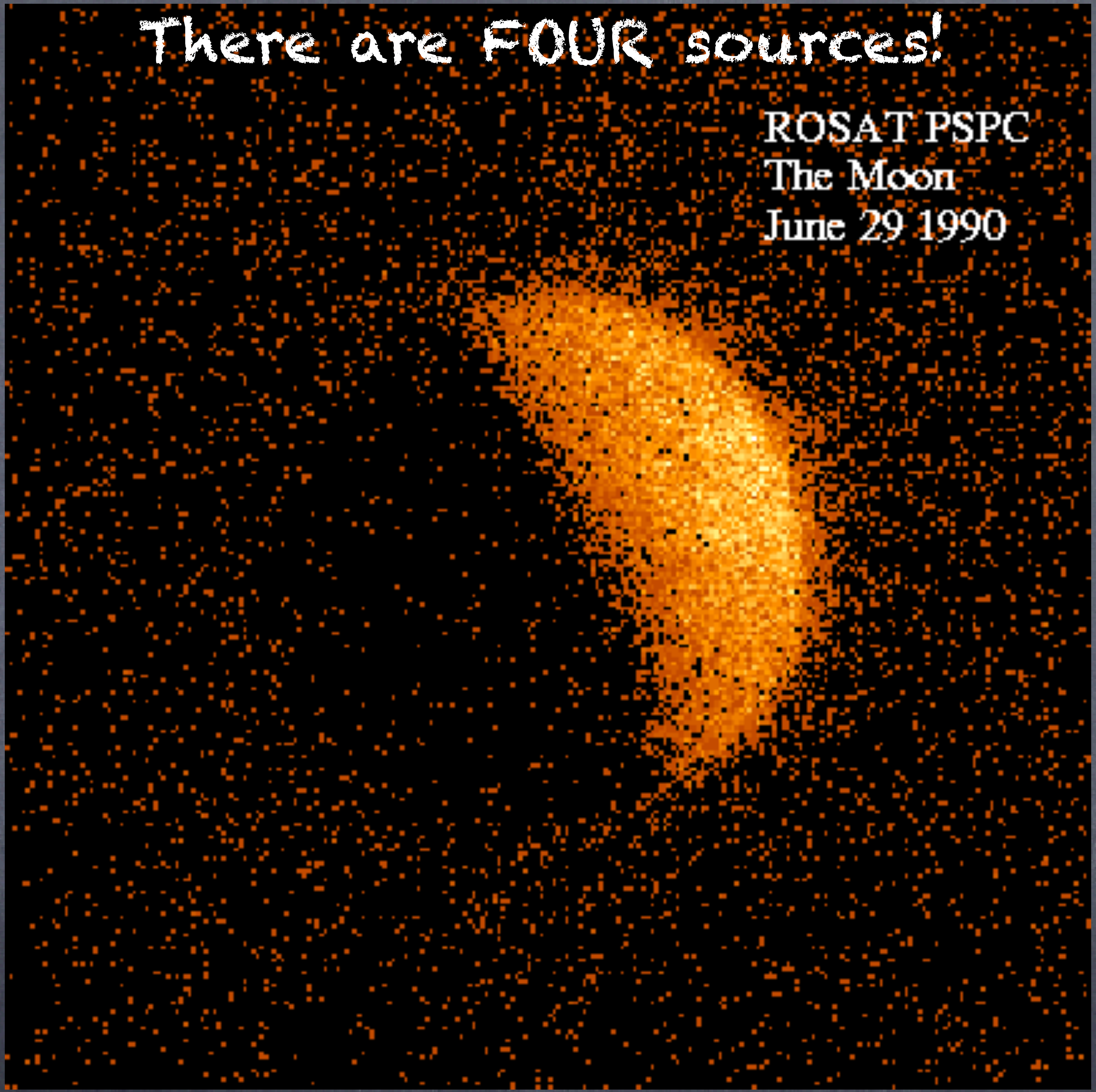
outline

- semi-representative sample survey of typical astrophysical sources
- some common emission processes and their characteristics



Typical astro question: what is the source, and what are its properties?

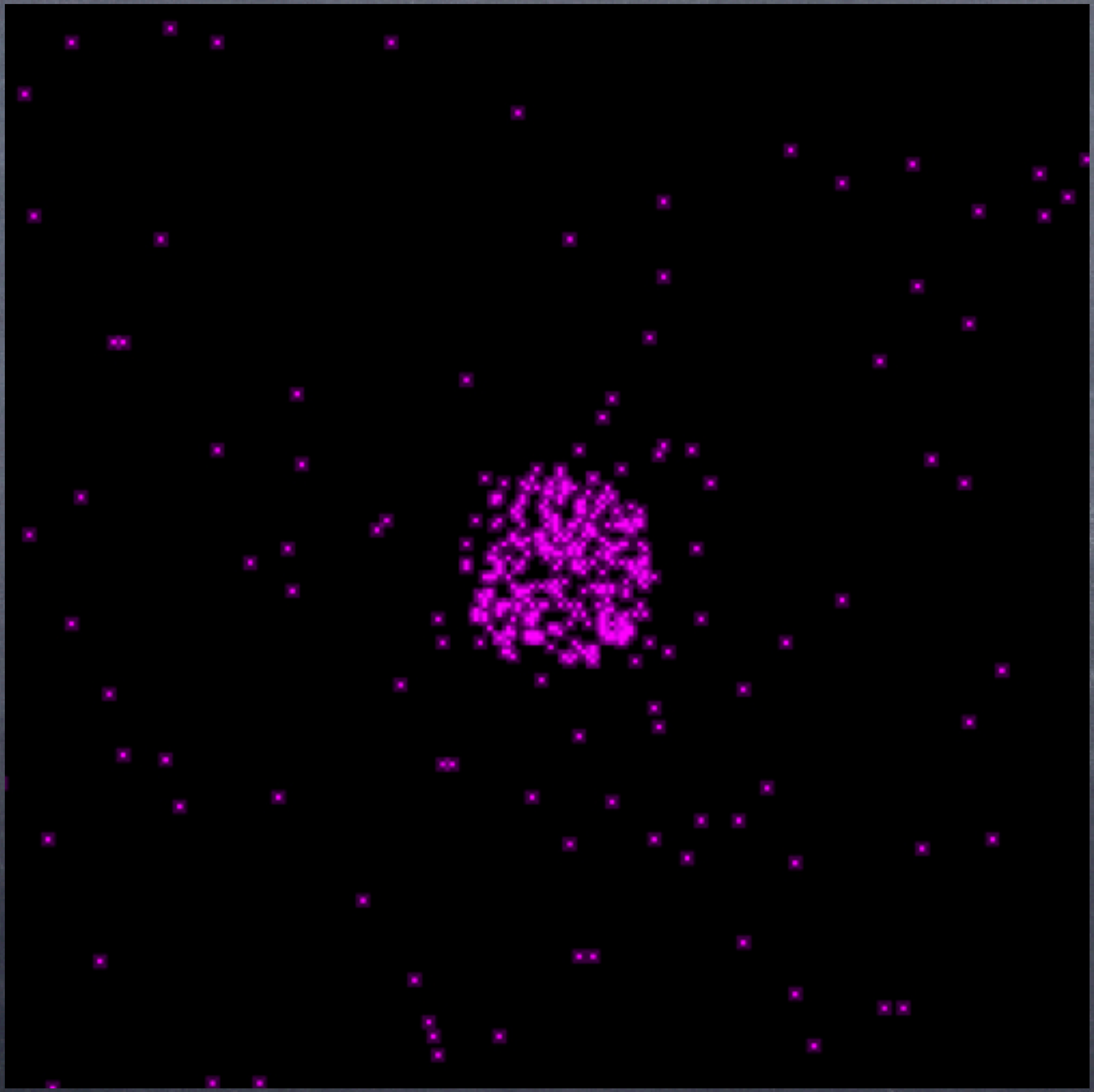
Schmitt et al. 1991, Nature

Solar wind and comets

Comet C/1999 S4 (LINEAR)

Lisse & Wolk 2000 / chandra.harvard.edu

- Solar wind and comets
- fluorescence

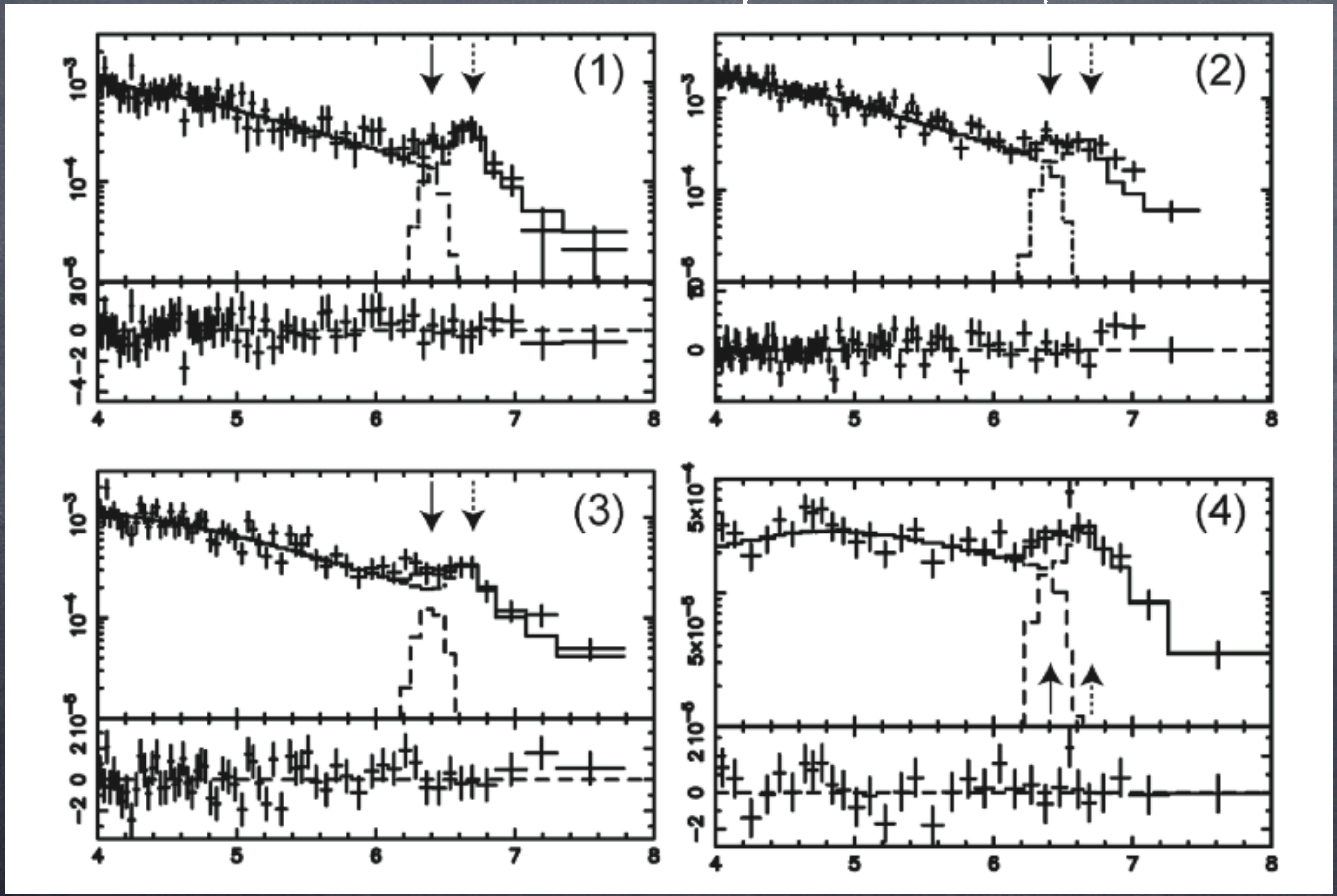


Mars

Dennerl et al. 2002 / chandra.harvard.edu

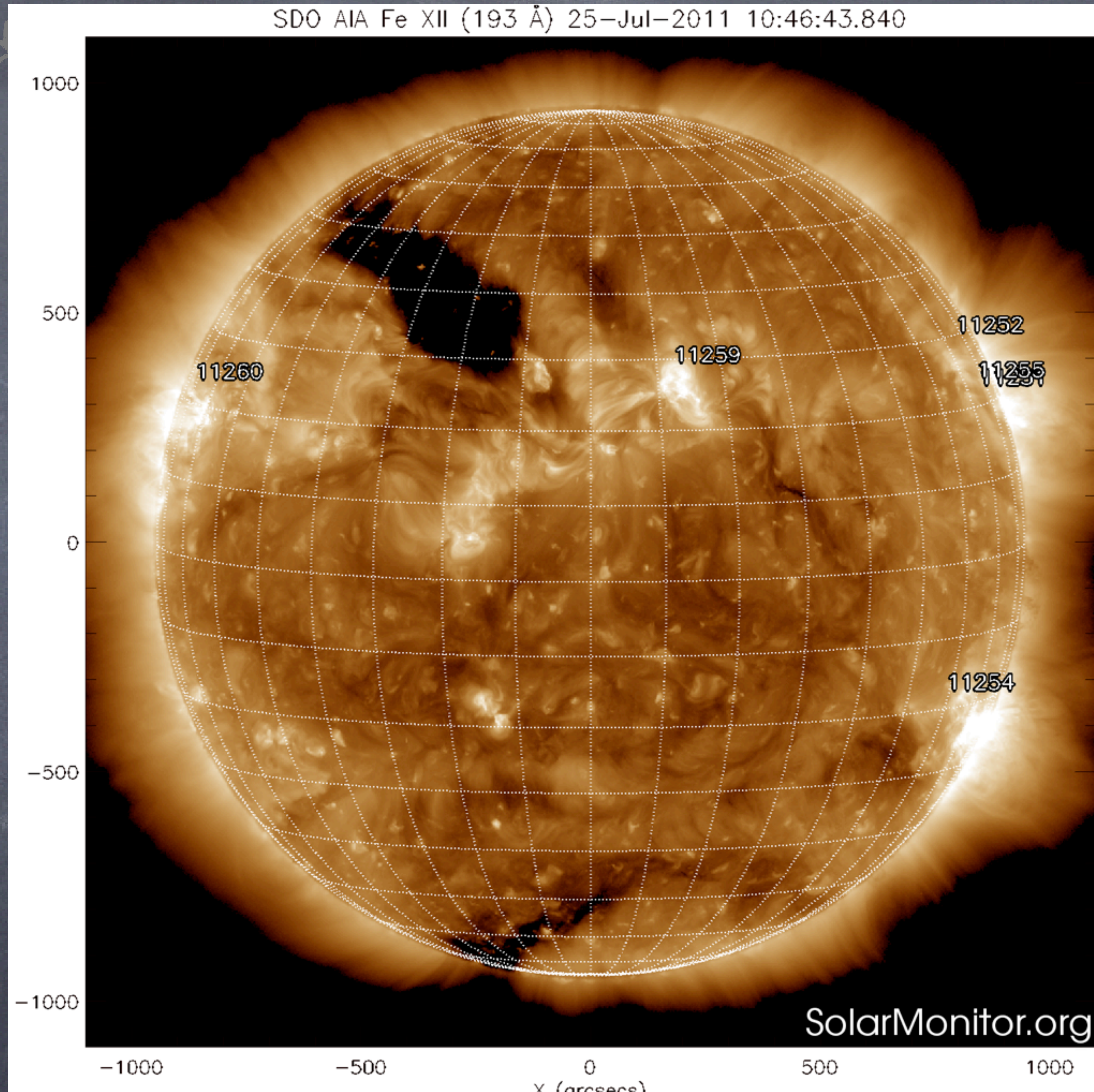
- Solar wind and comets
- fluorescence

Fe Kα fluorescence from disks around pre-Main-Sequence stars



Tsujimoto et al. 2005, ApJS, 160, 503

- Solar wind and comets
- fluorescence
- Solar (stellar) coronae



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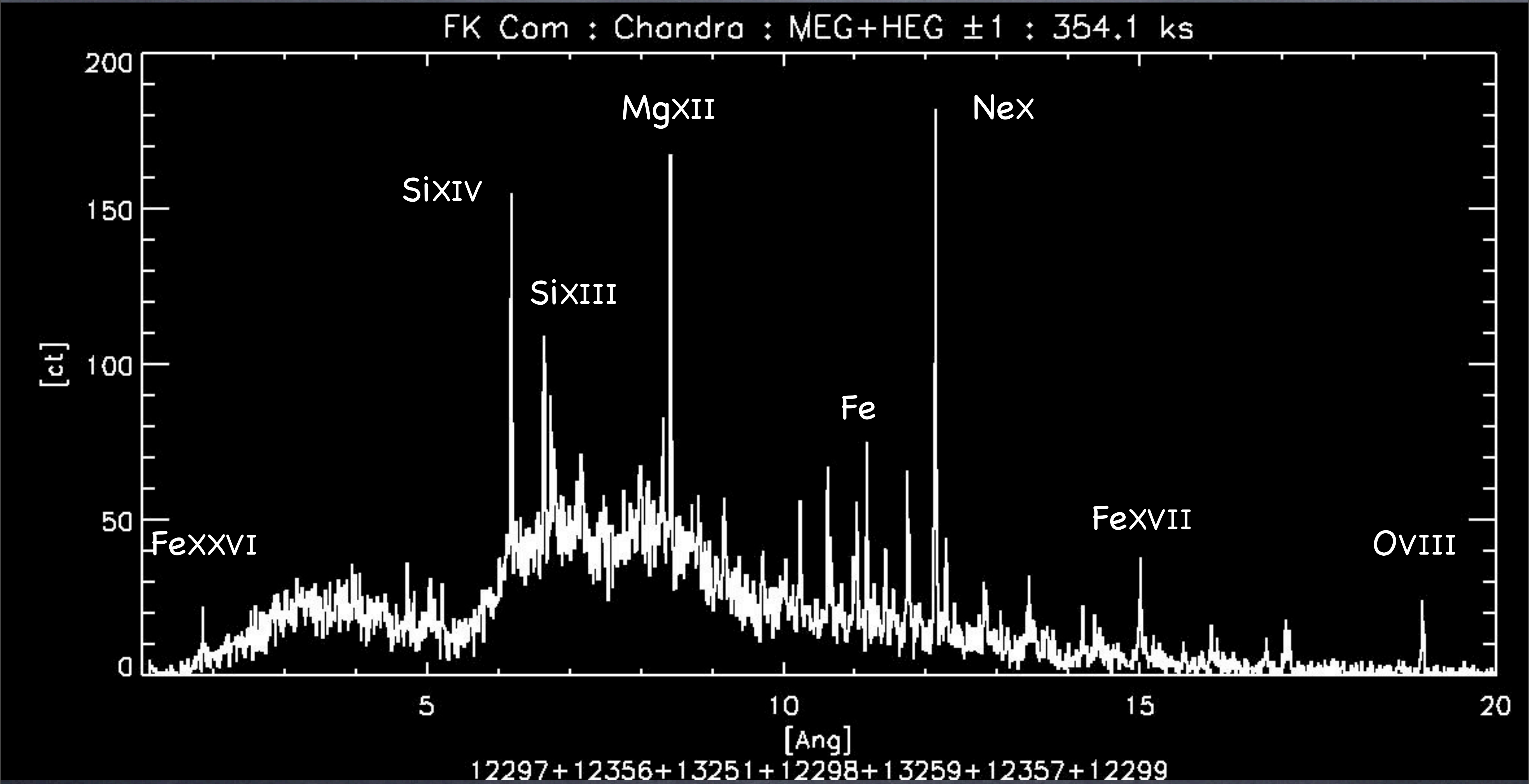
stellar coronae



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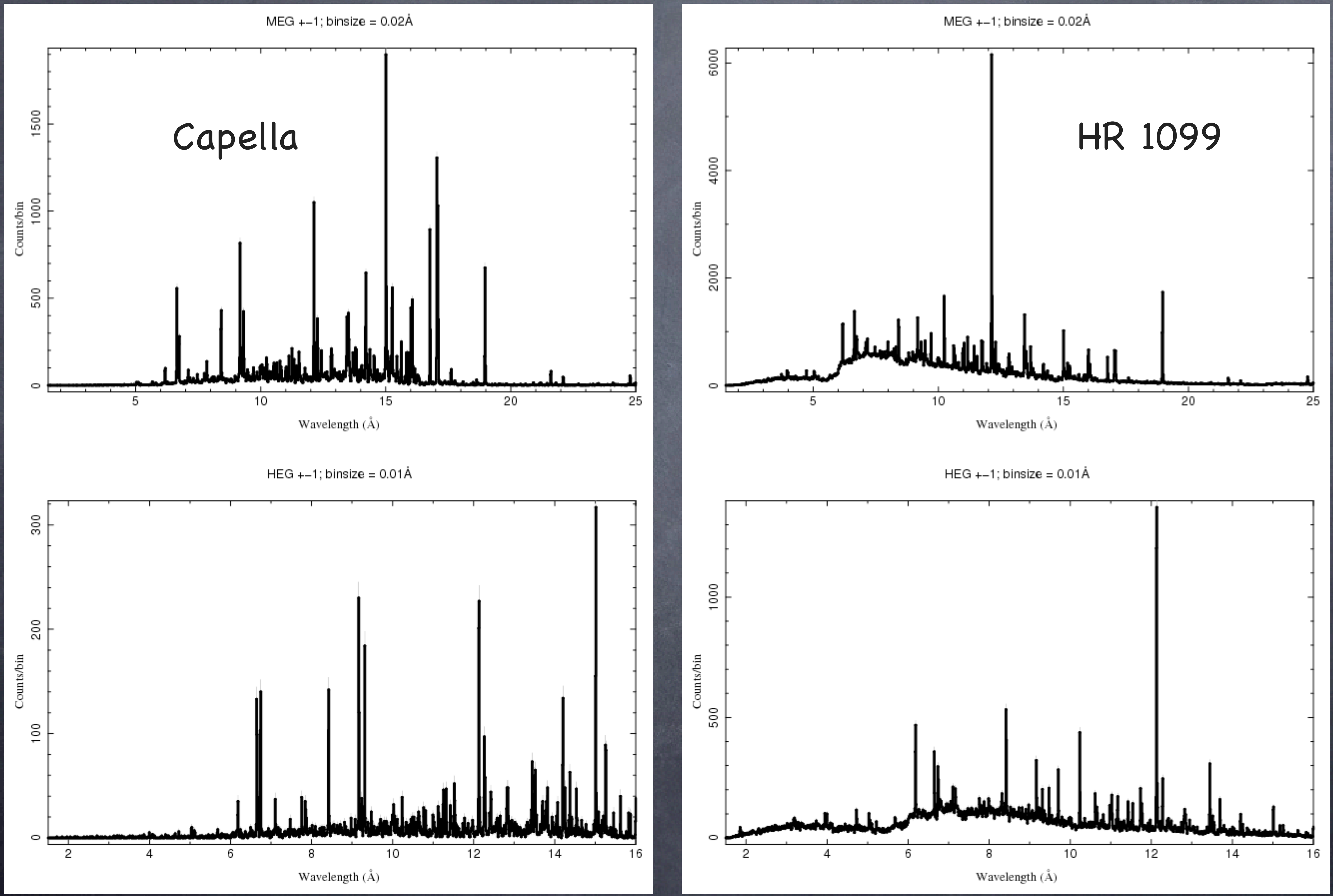
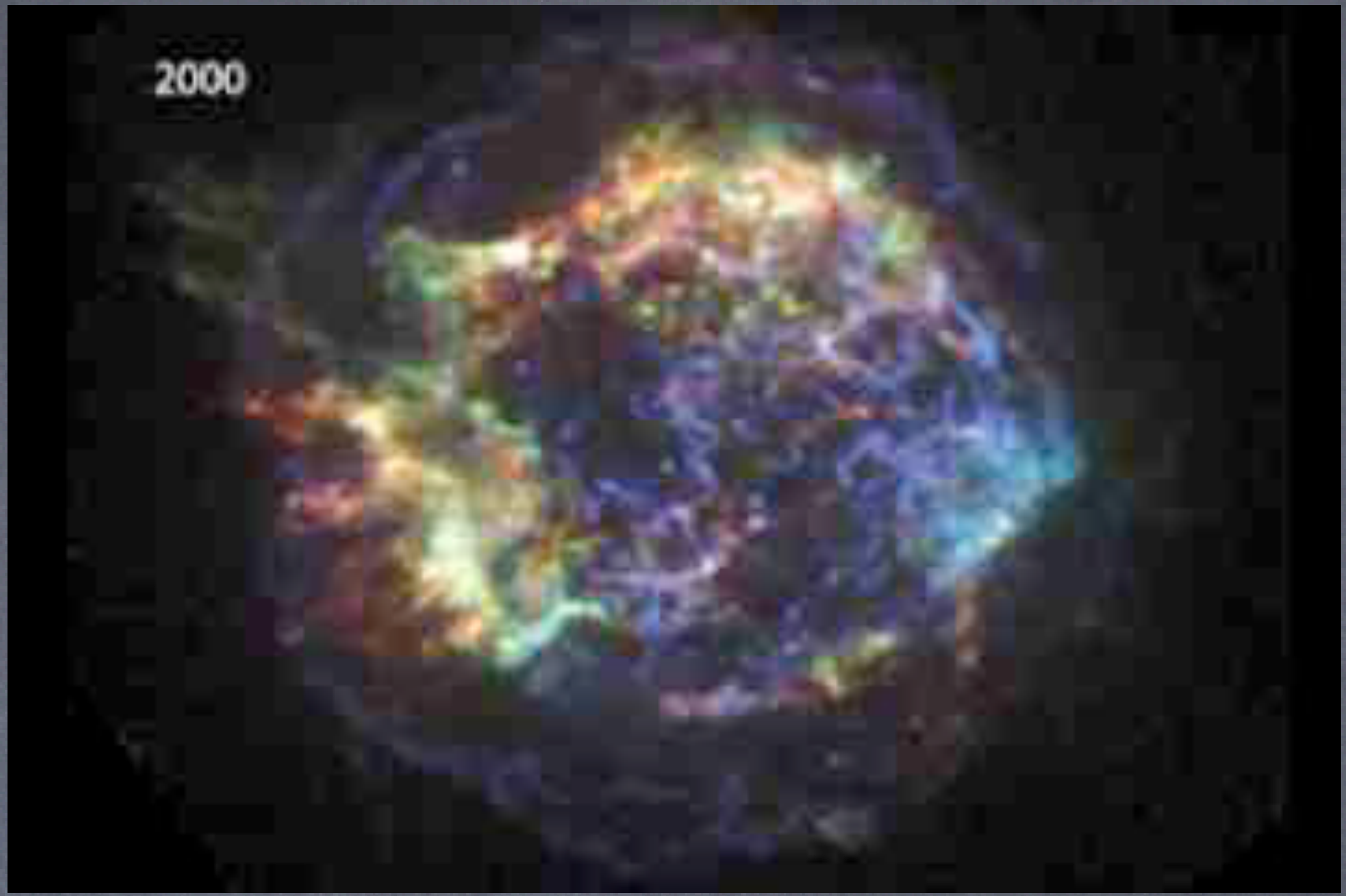
stellar coronae

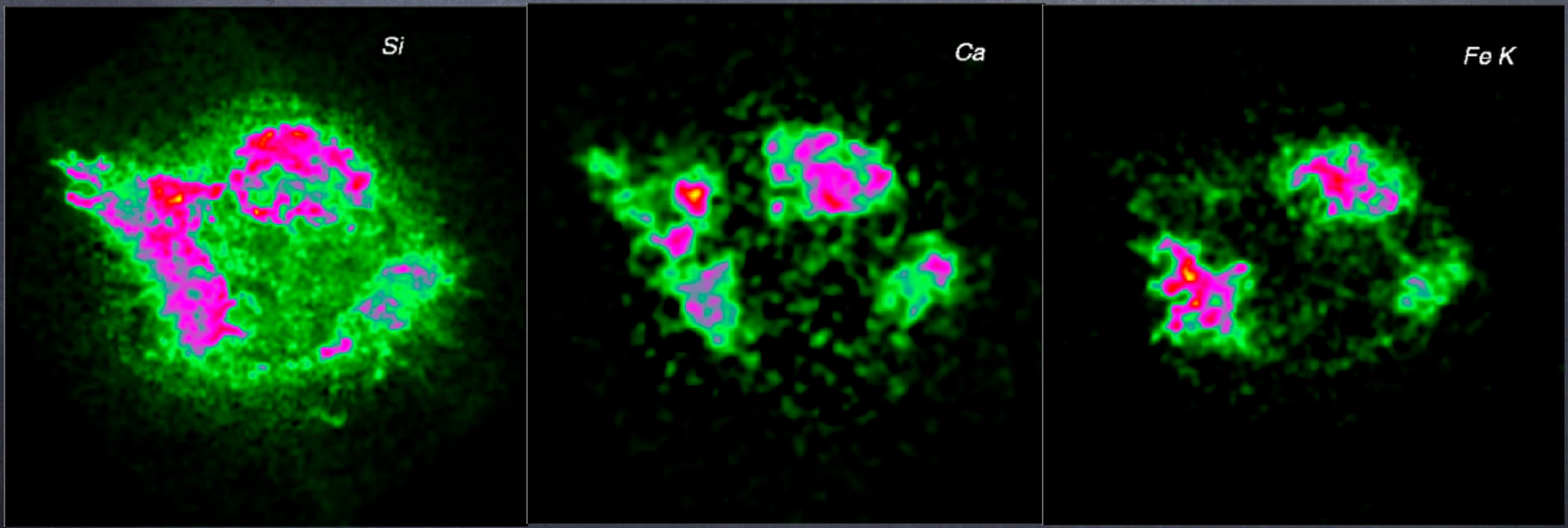
TGCAT



- Solar wind and comets
- fluorescence
- Solar (stellar) coronae
- **Shocked plasma**



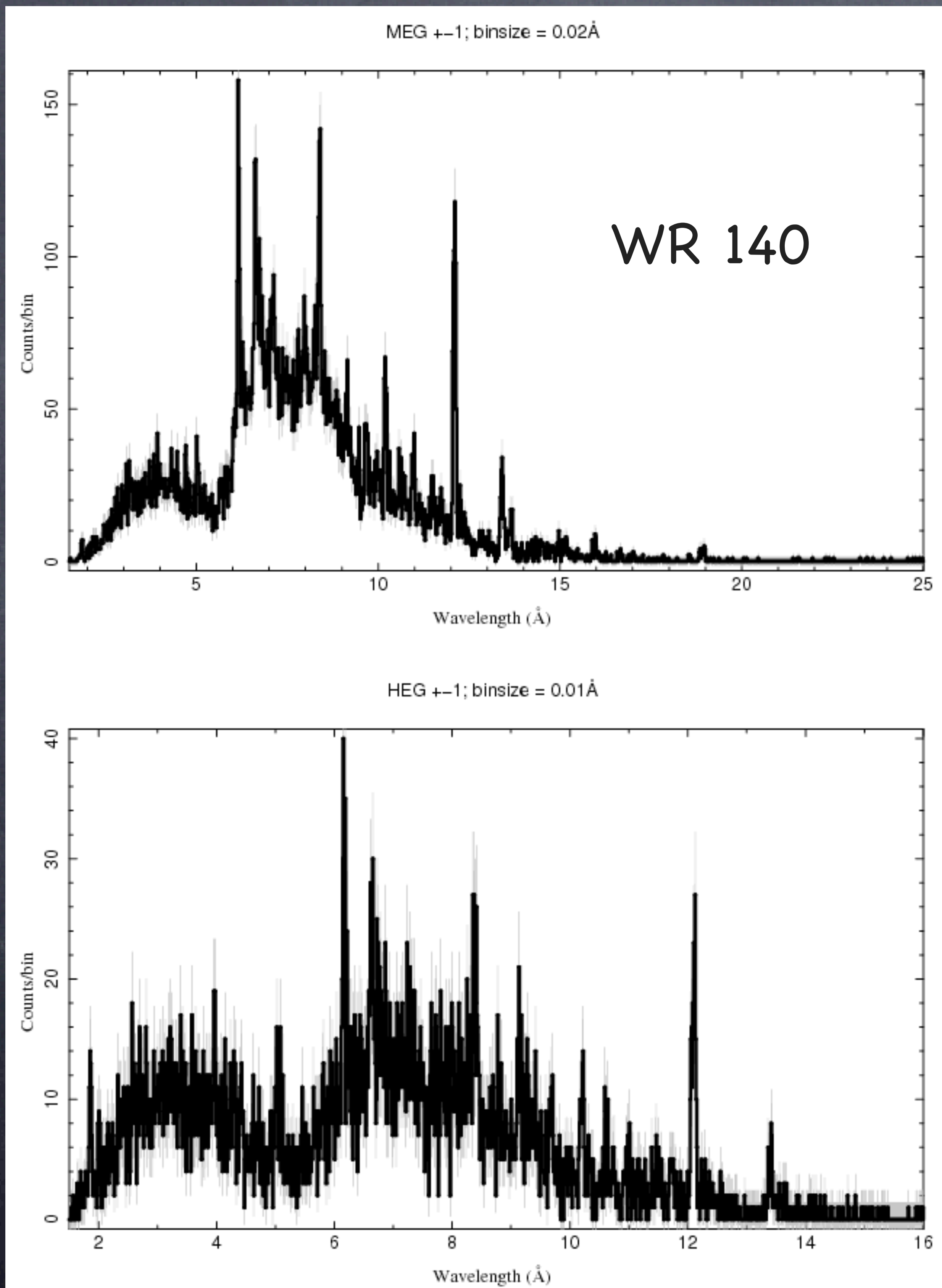
Patnaude et al. / chandra.harvard.edu

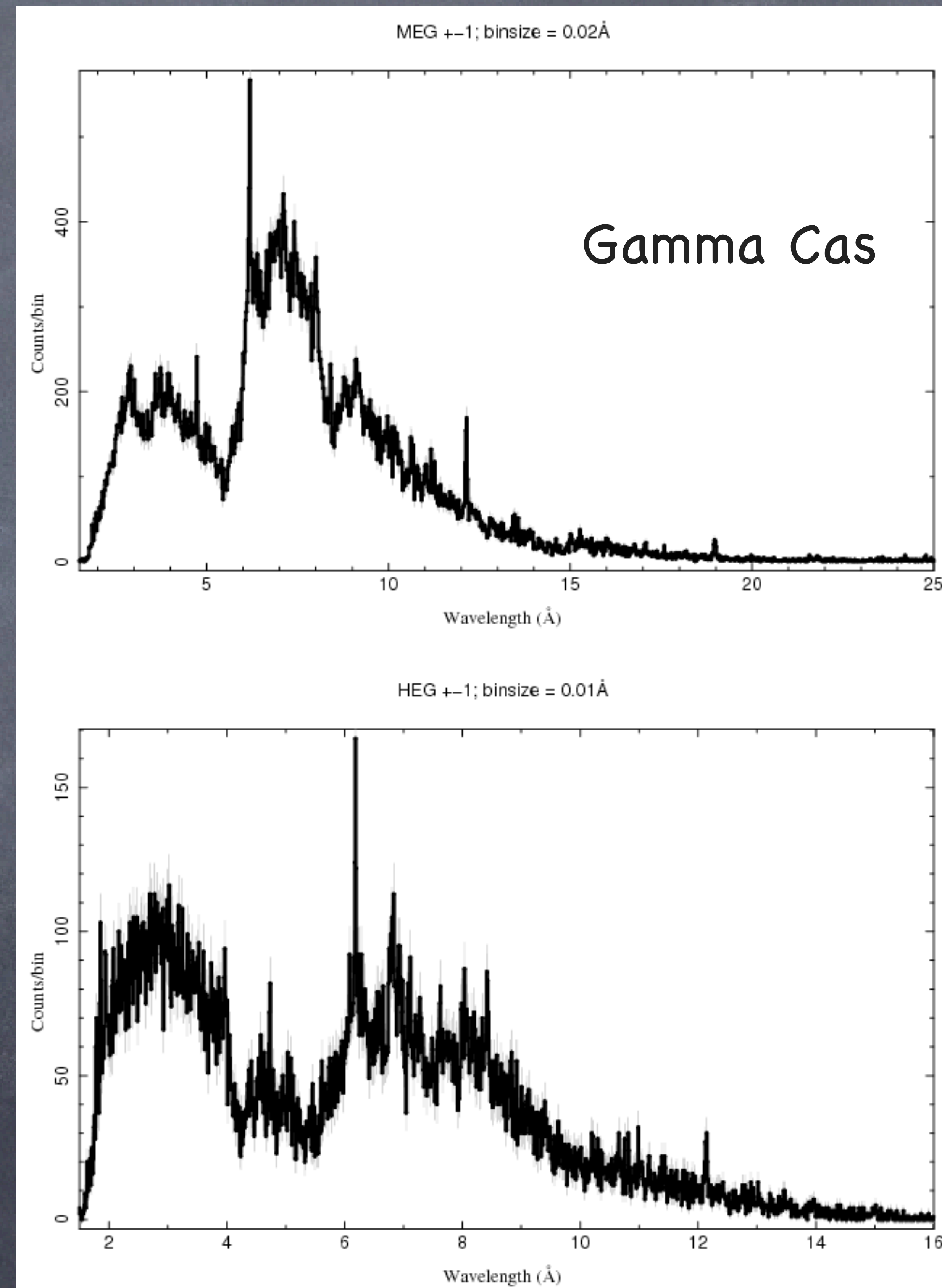


Hwang et al. 2004 / chandra.harvard.edu

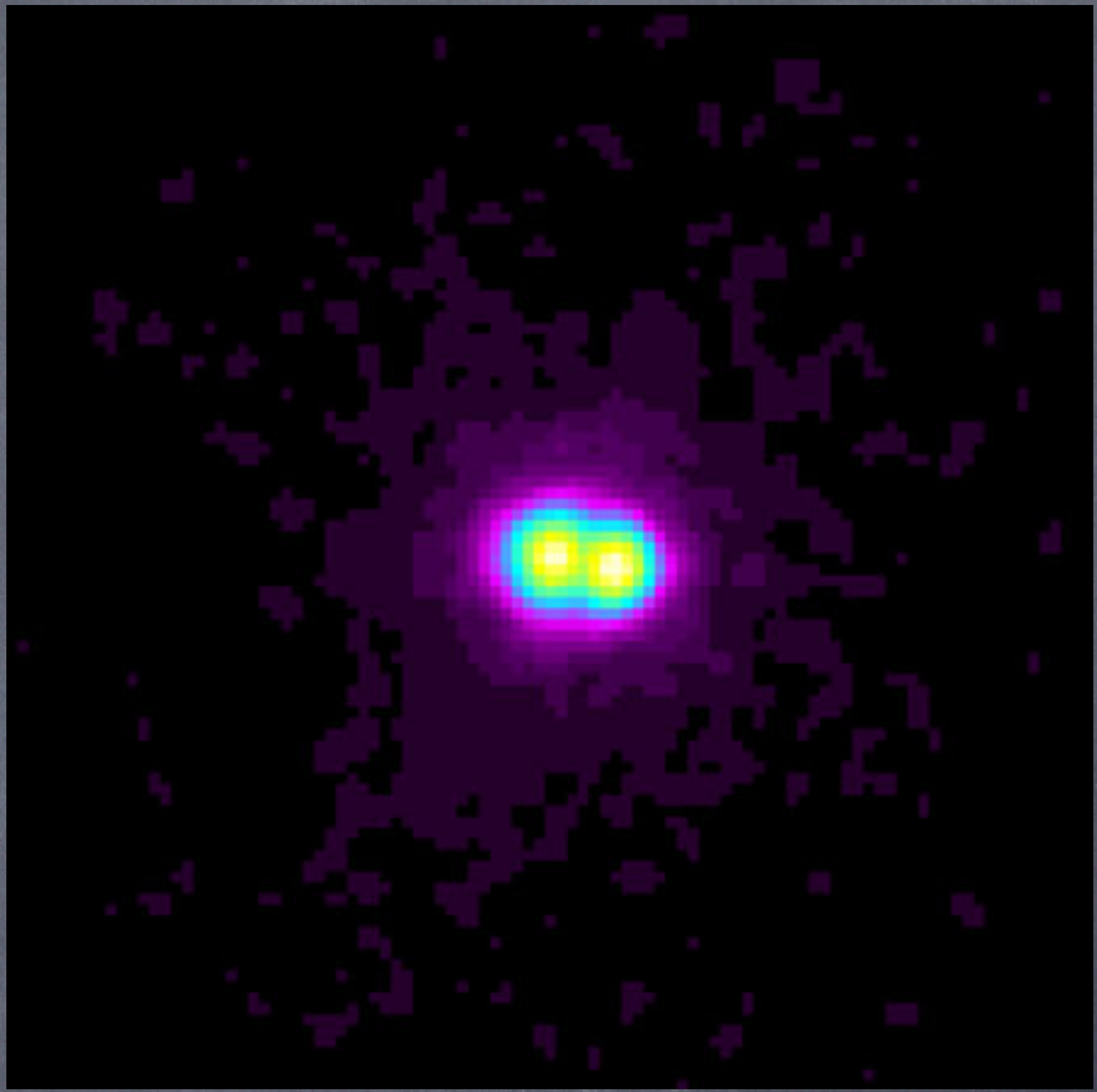
Shocked plasma

TGCAT





- Solar wind and comets
- fluorescence
- Solar (stellar) coronae
- Shocked plasma
- Accreting compact objects

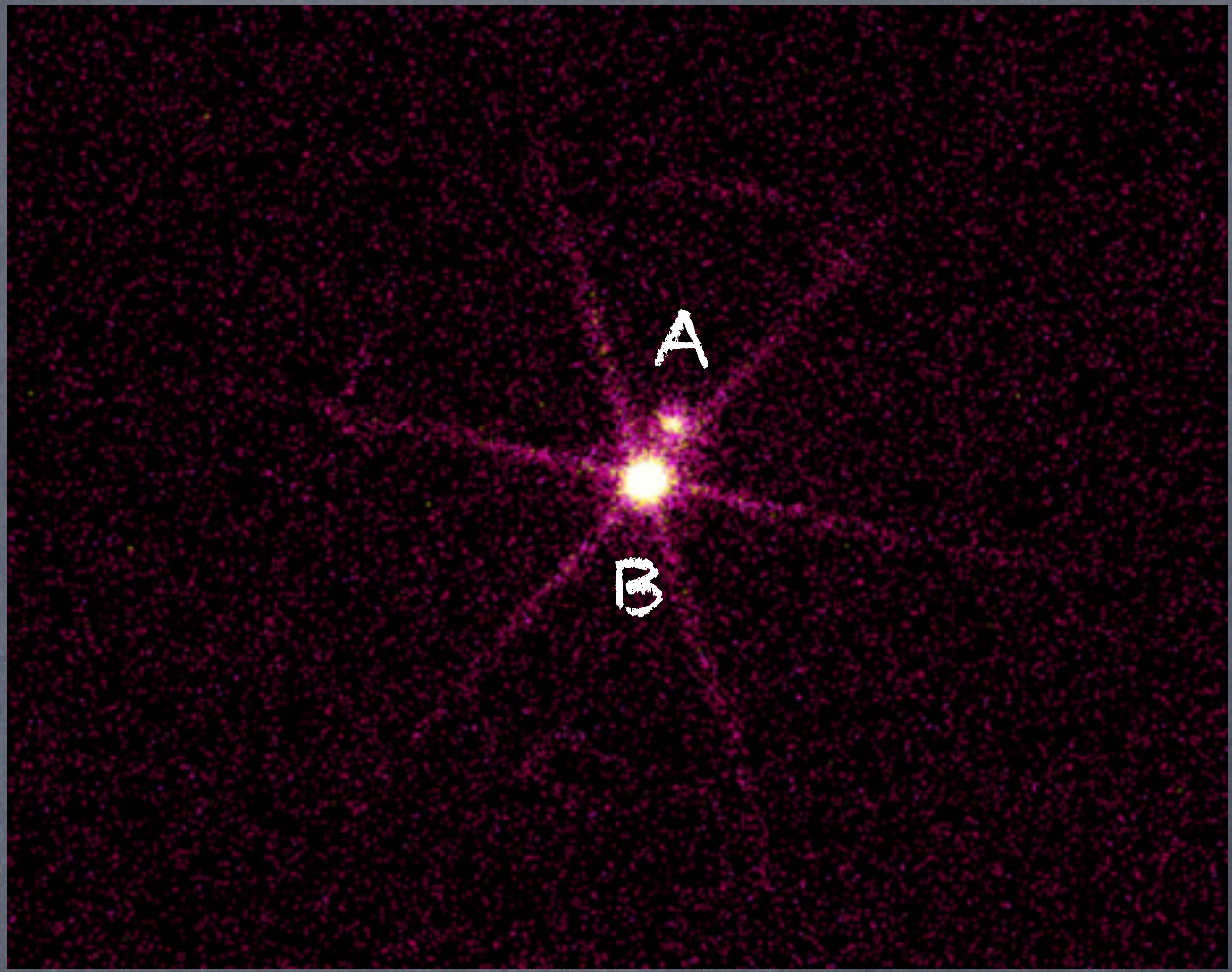


Binary neutron star binaries in M15, one with an obscuring accretion disk, and another with visible surface.

White & Angelini 2001 / chandra.harvard.edu

- Solar wind and comets
- fluorescence
- Solar (stellar) coronae
- Shocked plasma
- Accreting compact objects
- cooling compact objects

HRC-S/LETG : Sirius



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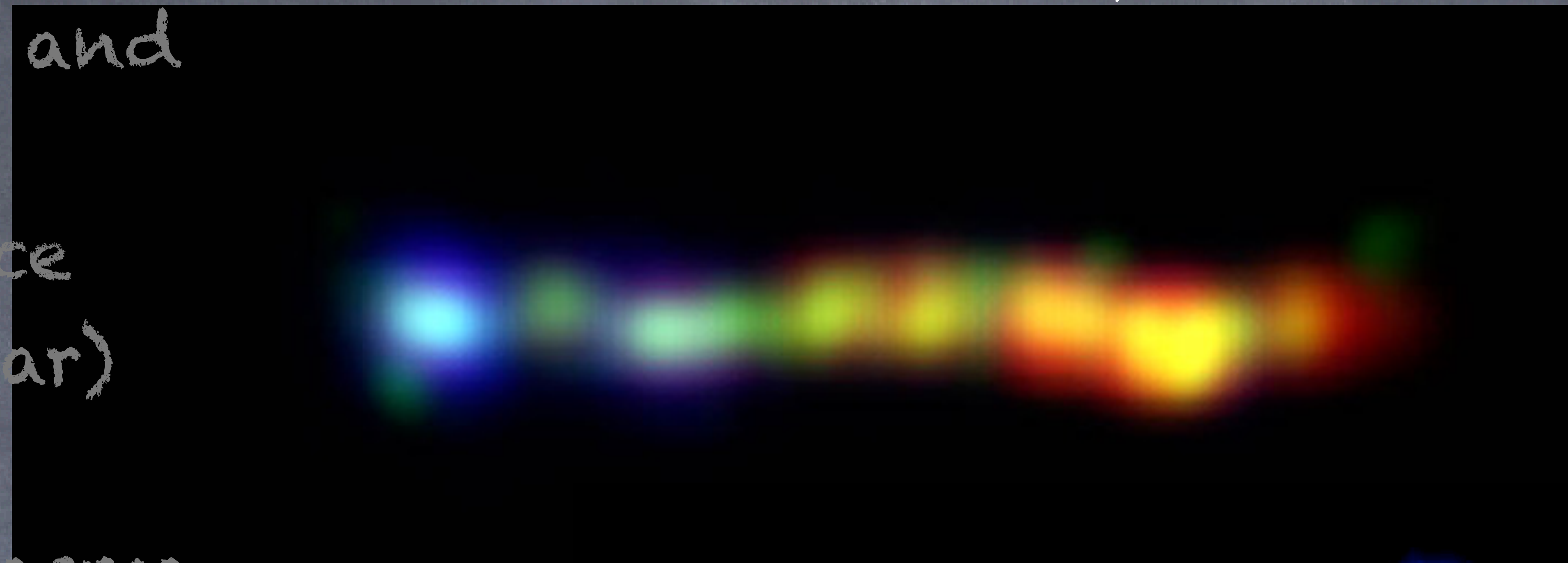
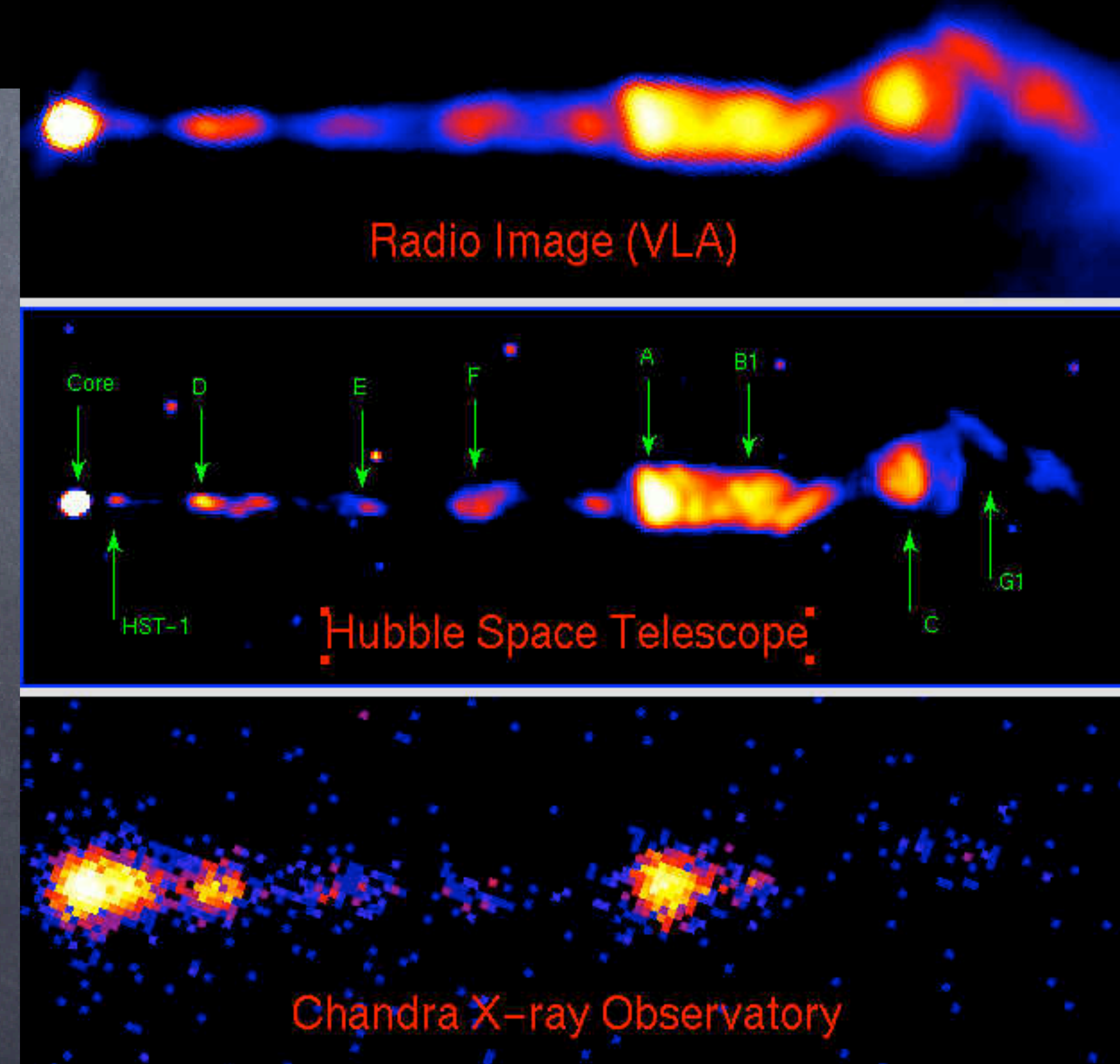
[3C 273] Jester et al. 2006, ApJ / chandra.harvard.edu



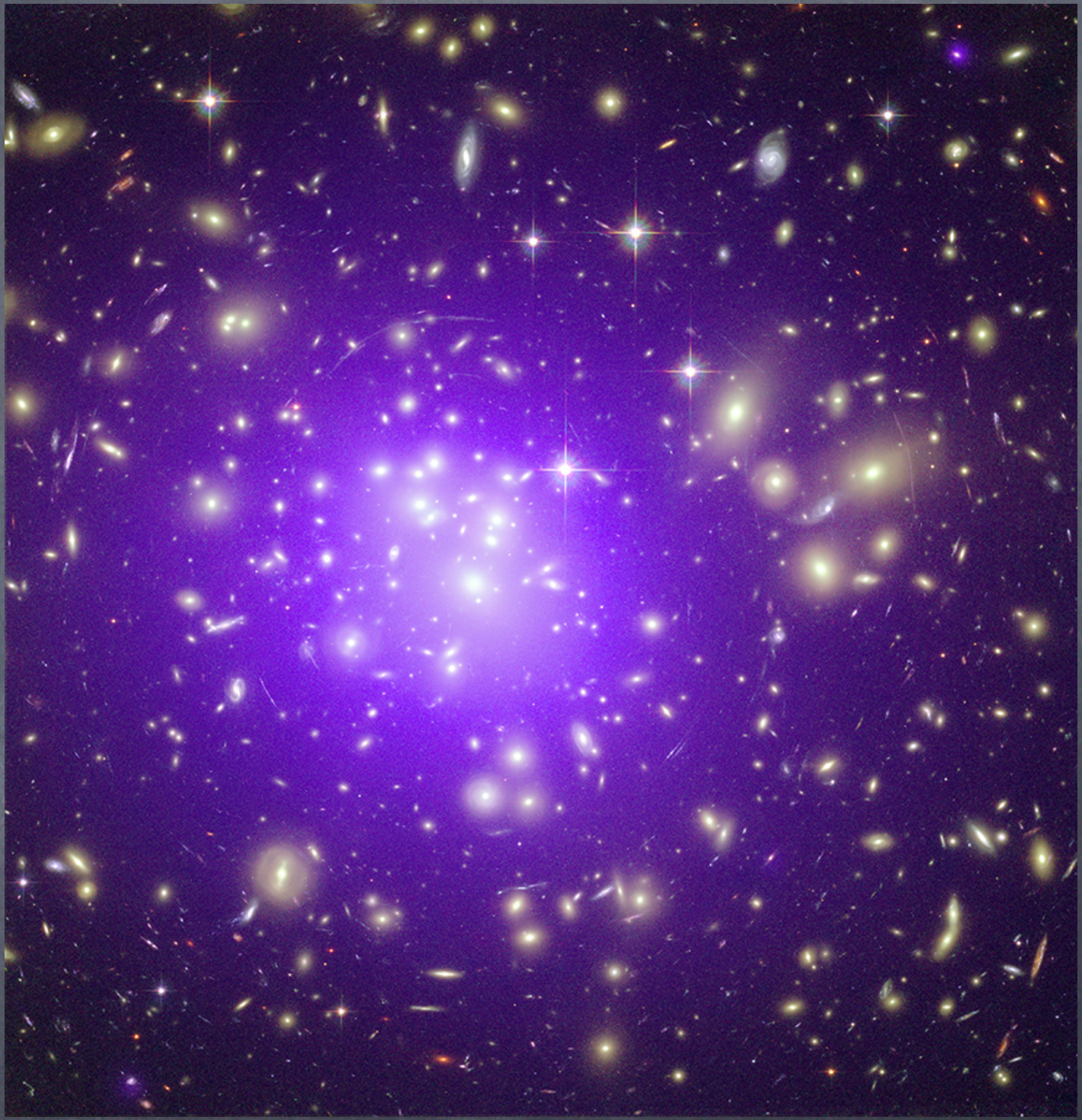
- Solar wind and comets
- fluorescence
- Solar (stellar) coronae
- Shocked plasma
- Accreting compact objects
- cooling compact objects
- **Collimated Jets**



[M87] Zhou & Owen, Biretta, Marshall et al. / chandra.harvard.edu

- Solar wind and comets
- fluorescence
- Solar (stellar) coronae
- Shocked plasma
- Accreting compact objects
- cooling compact objects
- Collimated Jets
- **Galaxy Clusters**

Abell 1689



Peng et al. 2008 / chandra.harvard.edu +STScI

- Solar wind and comets
- fluorescence
- Solar (stellar) coronae
- Shocked plasma
- Accreting compact objects
- cooling compact objects
- Collimated Jets
- Galaxy Clusters

- continuum
  - blackbody
  - synchrotron & bremsstrahlung
  - scattering
  - radiative recombination
- lines
  - charge exchange
  - fluorescence
  - thermal

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- continuum
  - blackbody

$$B_\nu(T) = 2\,h\,(\nu^3/c^2)\,[e^{h\nu/kT} - 1]^{-1} \text{ ergs s}^{-1}\text{ cm}^{-2}\text{ Hz}^{-1}\text{ sr}^{-1}$$

$$\nu_{max} = 2.82\ kT/h$$

$$\lambda_{max} = 2.9\cdot 10^7\ (T\ [\mathrm{degK}])^{-1}\ \text{Å}$$

$$\text{power radiated} = \sigma T^4$$

$$\sigma = (2\pi^5 k^4)/(15 h^3 c^2) = 5.6704\cdot 10^{-5} \text{ erg s}^{-1}\text{ cm}^{-2}\text{ K}^{-4}$$

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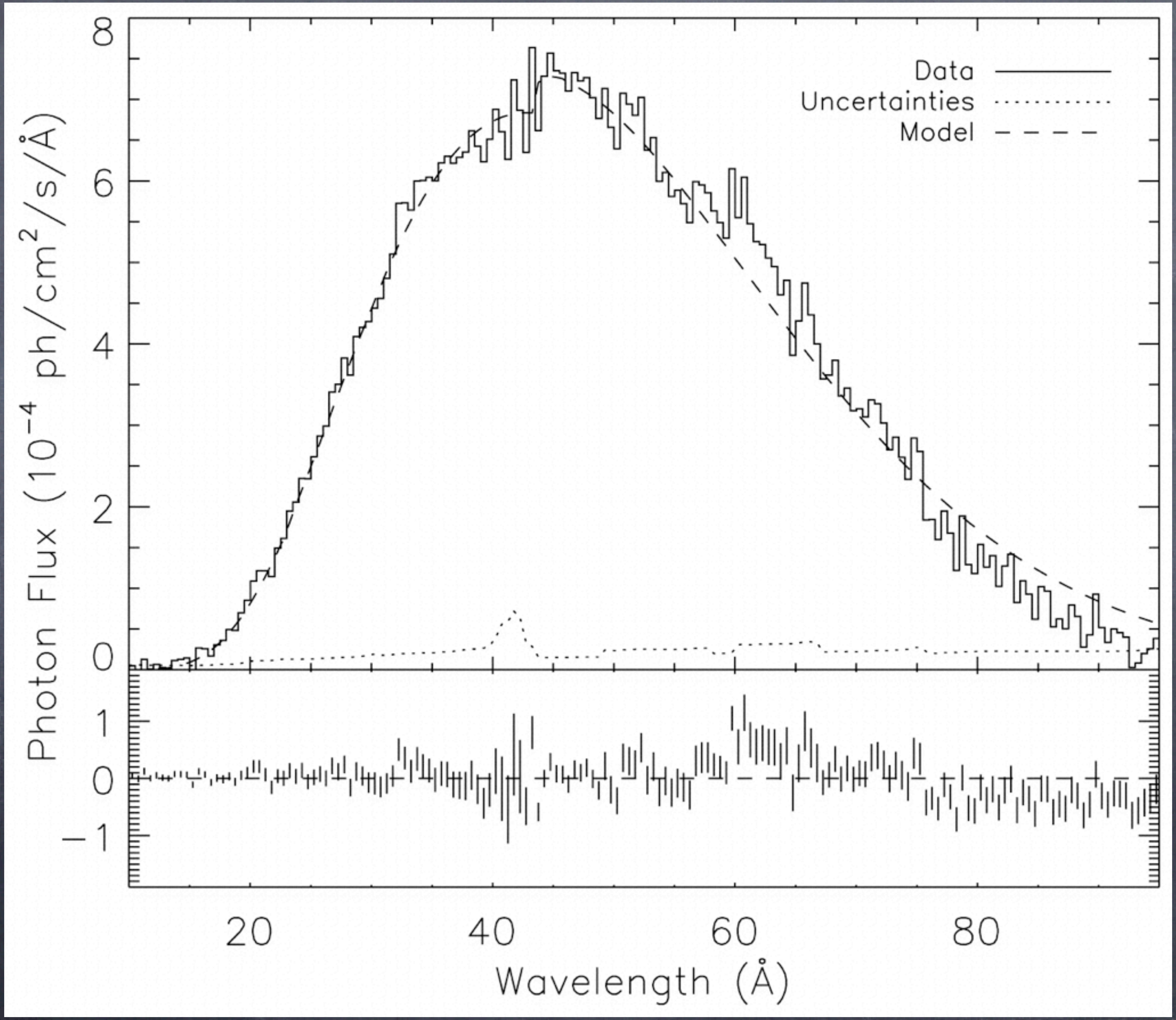
RXJ 1856.5-3754



Drake et al. 2002, ApJ, 572, 996

- continuum
  - blackbody
  - synchrotron & bremsstrahlung

accelerated charged particles emit radiation

energy emitted by single non-relativistic charged particle,

$$P = (2/3)\ (e^2/c^3)\ a^2$$

at Larmor frequency

$$\omega=(eB/mc)$$

in the presence of a magnetic field B

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synchrotron emission

characterized by power-law spectra
why?

relativistic beaming gives
$P(\omega) \sim const.*F(\omega/\omega_c)$,
with $\omega_c \sim \gamma^2$
for power-law distribution of electrons
$N(E) \sim E^{-p}$, i.e., $N(\gamma) \sim \gamma^{-p}$,
$P(\omega) \sim \omega^{-(p-1)/2}$

but not always useful to fit powerlaws -
spectra often have curvature

thermal bremsstrahlung

energy emitted per unit volume per unit time per unit frequency

$$f(\nu,T) \propto N_e N_i Z^2 T^{-1/2} e^{-h\nu/kT}$$

- flat spectrum until exponential drop at kT
- Total power ~ $\sqrt{T}$

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- continuum
  - blackbody
  - synchrotron & bremsstrahlung
  - scattering

Thomson scattering: elastic scattering of low-energy photons from low-energy electrons, with cross-section $\sigma_T = (8\pi/3)\,(e^2/mc^2) = 0.665 \cdot 10^{-24}\ \mathrm{cm}^{-2}$

Compton scattering: low-energy photon inelastically scatters off non-relativistic electron, ends up with lower energy

inverse Compton scattering: low-energy photon inelastically scatters off relativistic electron, gains energy in observer rest frame

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Compton scattering

inelastic, i.e., there is energy and momentum exchange between photon and slow-moving electron, and the photon gives up energy to the electron

$$\delta\lambda = \lambda_c\,(1 - \cos\theta)$$

Compton wavelength

$$\lambda_c = h/m_e c = 0.02426\ \text{Å}$$

cross-section is reduced as photon energy increases

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inverse Compton scattering

relativistic electrons ($\gamma^2-1 \gg h\nu/m_ec^2$) can transfer energy to photons and boost their frequencies by $\sim\gamma^2$

Radiated power,

$$P_{IC} = (4/3)\ \sigma_T c \gamma^2 \beta^2 U_{ph}$$

where $\beta=v/c$, $\gamma=1/\sqrt{(1-\beta^2)}$, U_{ph} = initial photon density

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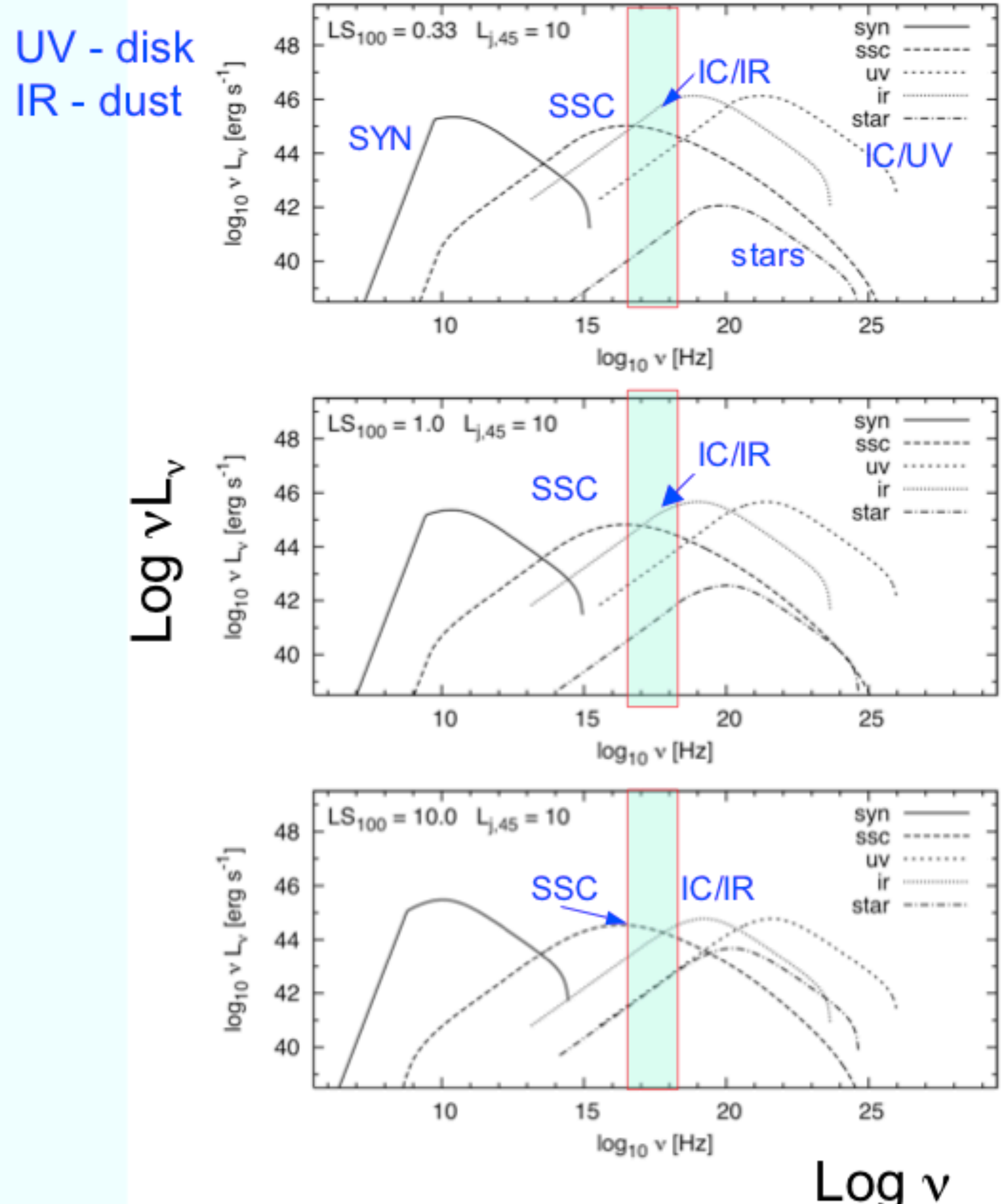
Emission in compact lobes of jets can be from Comptonized IR from dust and UV from accretion disk, or synchrotron self-Comptonization.

Jet power

$L_{jet}=10^{46}$ erg/s

X-rays



Stawarz et al 2008

Aneta Siemiginowska, CfA

- continuum
  - blackbody
  - synchrotron & bremsstrahlung
  - scattering
  - radiative recombination

capture of unbound electron into a bound level i (hence "free-bound")

radiated photon has $E > E_i$

radiated energy proportional to

$$N_e\ N(Z,I+1)\ E_i^{-3}$$

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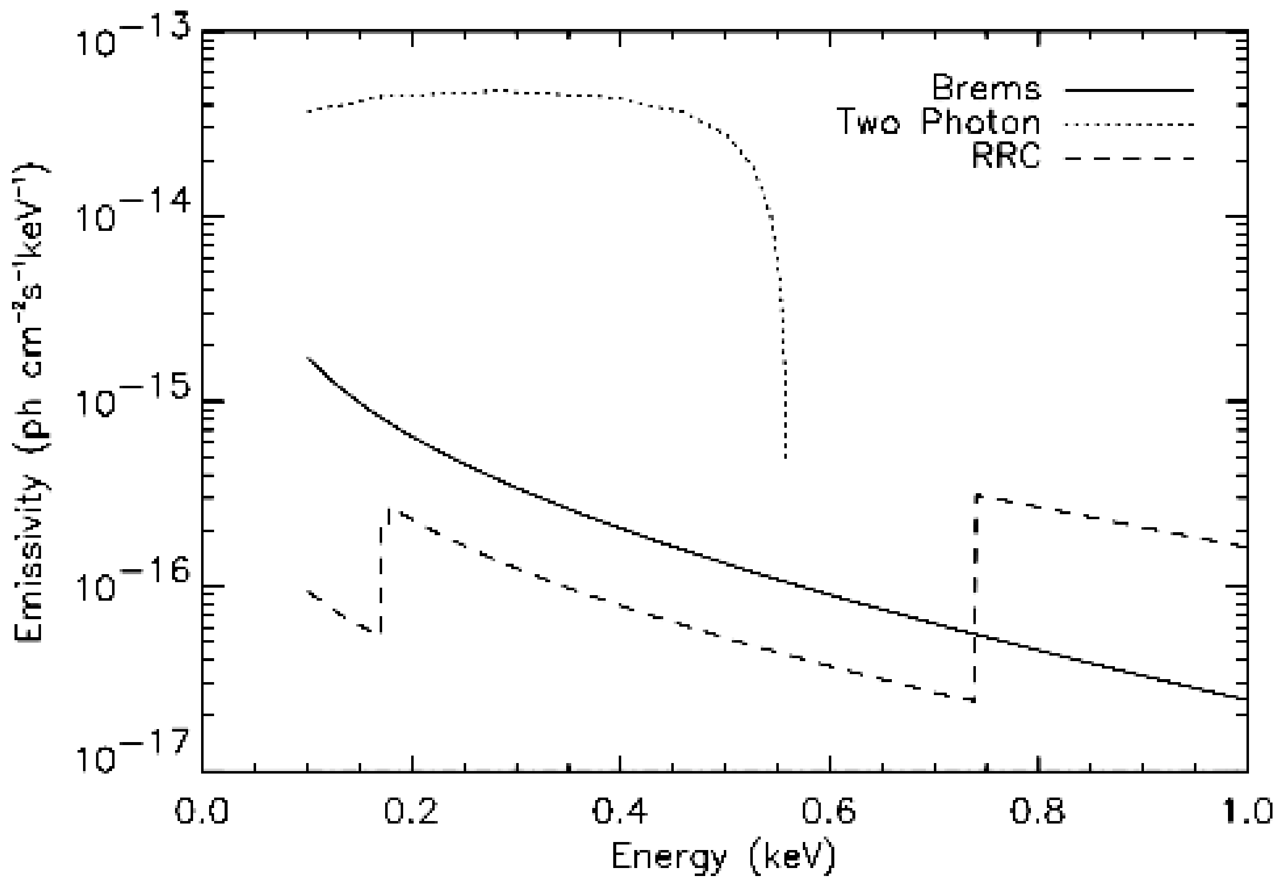
Radiative Recombination

In many cases the RRC is weak, but it is an excellent diagnostic if it can be measured. The power emitted per keV is:

$$\frac{dE}{dt dV d\omega} = \frac{dP}{dE} = n_e n_{Z,j+1} E_\gamma \sigma^{rec}(E_e) v_e \frac{f(v)dv}{dE_\gamma}$$

Tucker & Gould 1966



Sample O VII (collisional) continuum

Randall Smith's presentation from X-Ray School 2007
[http://heasarc.gsfc.nasa.gov/docs/xrayschool-2007/smith_emissionI.pdf]

ionized species in the solar wind hits cold neutral H around the planet or the comet, picks up an electron in an excited state, decays and emits radiation.

- continuum
  - blackbody
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  - scattering
  - radiative recombination
- line emission
  - charge exchange

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charge exchange

$\varepsilon_{iL} = v_c\, n_n\, n_i\, y_{iL}\, \sigma_i$ photons s^{-1} cm^{-3}

emissivity

= collision velocity ~ 400-700 km s^{-1}

* neutral species density ~ 25 r_{10}^{-3} cm^{-3}
* ionic species density ~ 10^{-4} cm^{-3}
* yield per CX excited ion ~ O(1)
* CX cross-section ~ 10^{-15} cm^2 ± 30%

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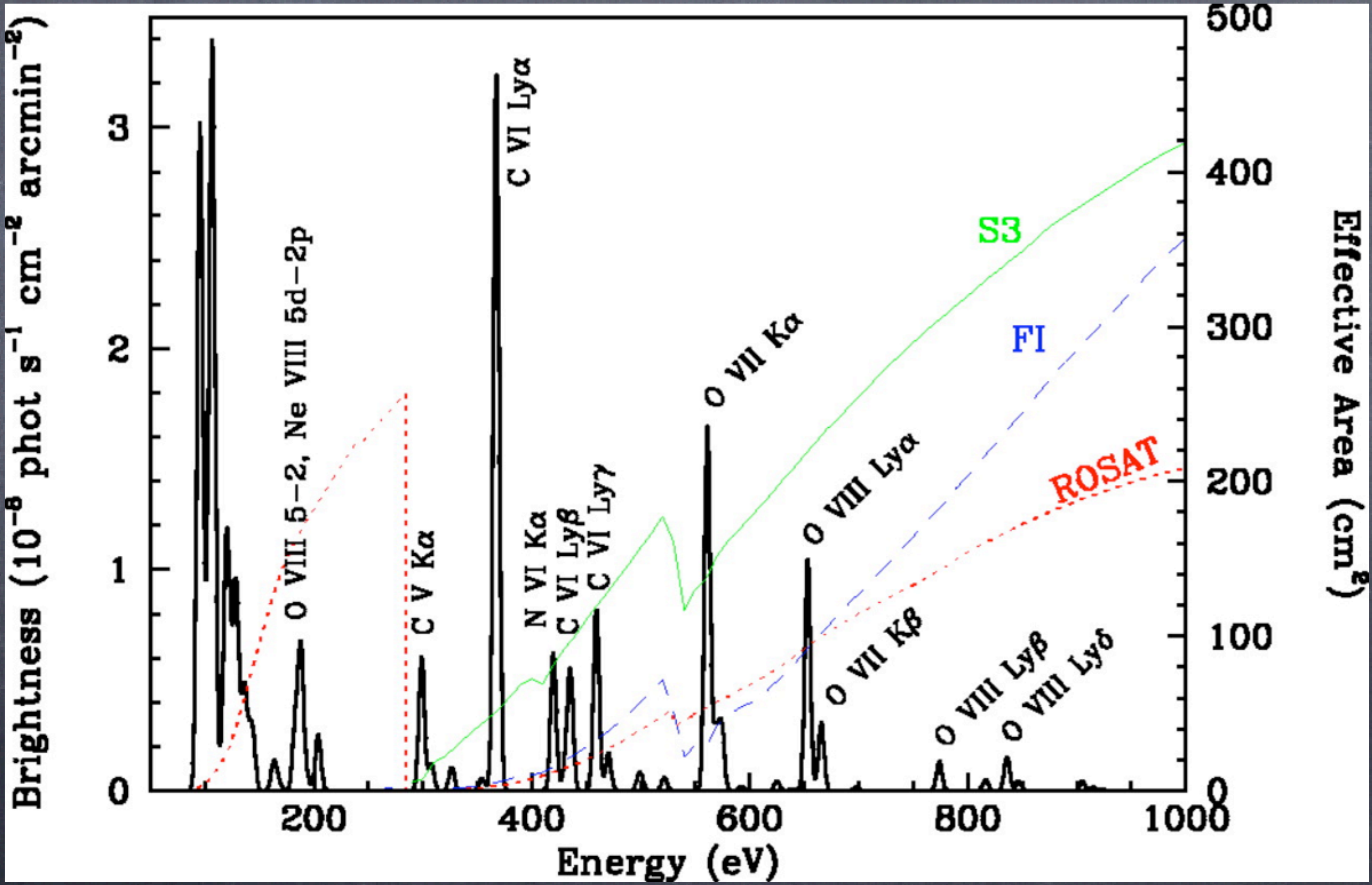
- charge exchange

what do the spectra look like?



Wargelin et al., 2004, ApJ, 607, 596

absorption of an incident photon, followed by the transfer of an outer shell electron down to the vacant level, emitting a photon of energy equal to the difference in the two levels.

- continuum
  - blackbody
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  - scattering
  - radiative recombination
- line emission
  - charge exchange
  - fluorescence

integrated over the incident energies

mass fraction of element i

absorption coefficient of element i at energy E_{in}

flourescence yield for orbital k

$$\frac{d\Omega}{4\pi}\int_{E_0}^{\infty} dE_{in}\, J(E_{in})\, w_i \frac{\mu_i(E_{in})}{\mu(E_{in}) + \mu(E_{em})\cos(\theta_{in})/\cos(\theta_{em})} R_{ik}\, Y_{ik}\, P_{ikl}$$

reemission is spherically symmetric

incident spectrum

probability of trapping incident photons at level k

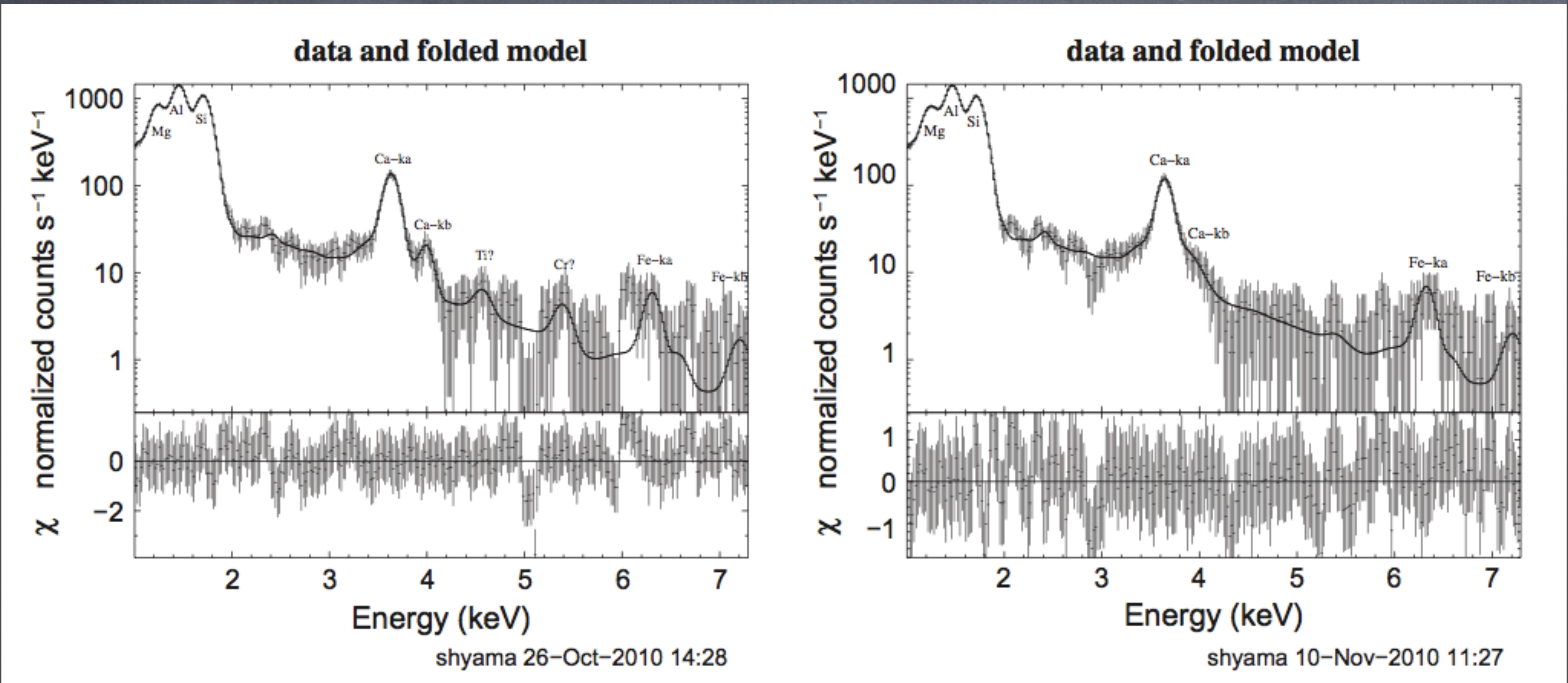
total mass attenuation coefficient

probability of electron in level l falling down to vacant level

fluorescent intensity when electron in orbital l of element i traps the incident photon of energy E_{in} and escapes, and electron in orbital k drops to the vacancy

Ogawa et al. 2008, EPS, 60, 283

lunar fluorescent spectra



Narendranath et al. 2011, Icarus, 214, 53 by far the most common mechanism of line emission is from collisionally excited radiative decay

Radiative transition rate (aka "Einstein A value") is the expected number of transitions per second

- continuum
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  - thermal

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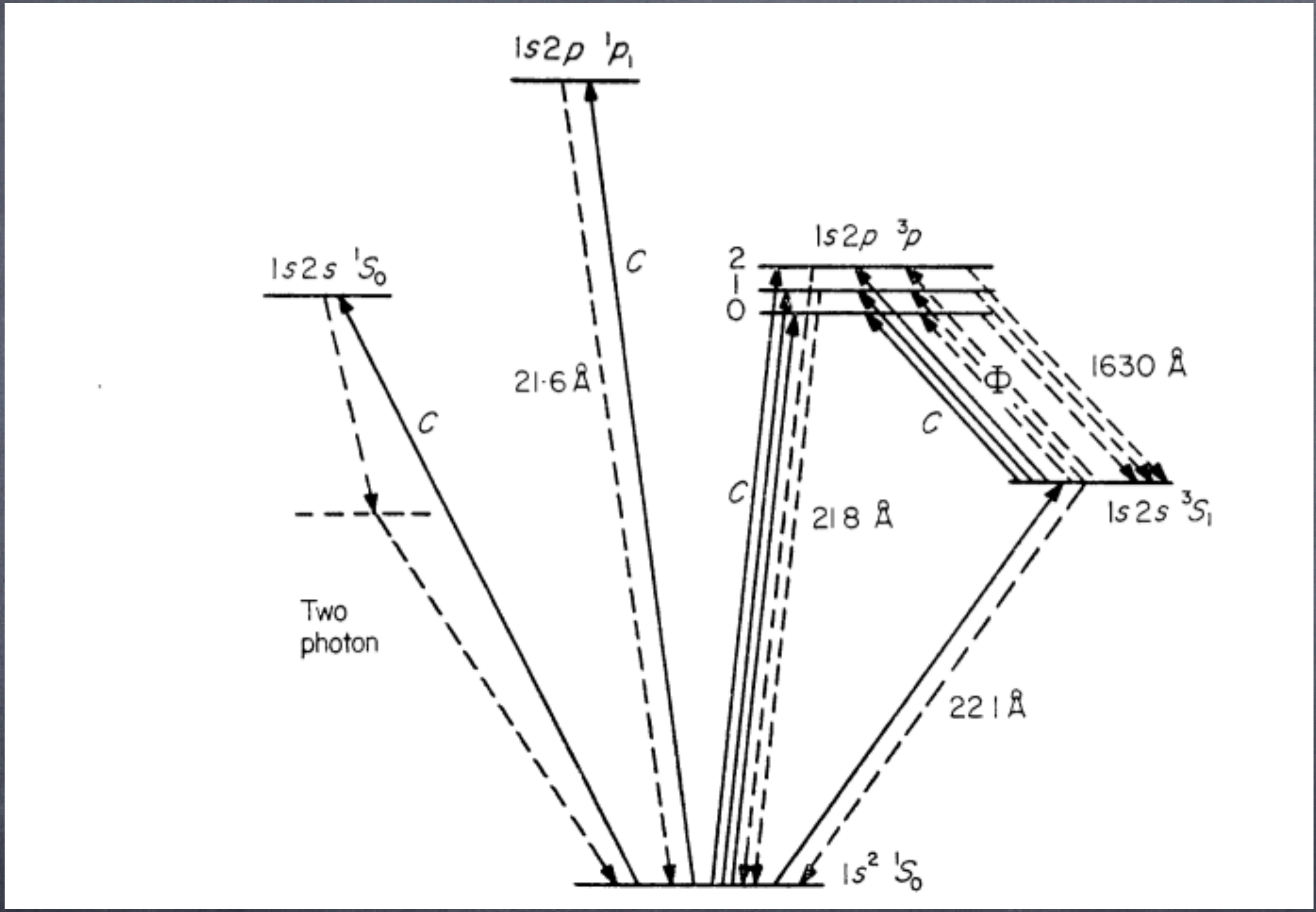
Grotrian diagram for OVII



Gabriel & Jordan 1969, MNRAS

- bound-bound

$$f_{u\to l}(\lambda;T) = (hc/\lambda)\, A_{u\to l}(Z,I;T)\, N_u(Z,I;T)\, \delta V$$

$$= (hc/\lambda)\, A_{u\to l}(Z,I;T)\, \frac{N_u(Z,I;T)}{N(Z,I;T)} \frac{N(Z,I;T)}{N(Z)} \frac{N(Z)}{N_H} \frac{N_H}{N_e(T)}\, N_e(T)\, \delta V$$

$$= (hc/\lambda)\, \frac{A_{u\to l}(Z,I;T)}{N_e(T)} \frac{N_u(Z,I;T)}{N(Z,I;T)} \frac{N(Z,I;T)}{N(Z)} \frac{N(Z)}{N_H}\, N_H\, N_e(T)\, \delta V$$

$$= \varepsilon_{u\to l}(Z,I;N_e,T) \quad i(Z,I;T) \quad A_Z \quad N_H\, N_e(T)\, \delta V$$

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Differential Emission Measure

consider photons emitted from elemental volume at $\vec{r}$

$$f_{u\to l}(\lambda,\vec{r};T) = A_Z\, \varepsilon_{u\to l}(Z,I;N_eT)\, i(Z,I;T)\, N_H(\vec{r})\, N_e(T,\vec{r})\, \delta V(\vec{r})$$

group together all volume which has the same temperature

$$f_{u\to l}(\lambda;T) = A_Z\, \varepsilon_{u\to l}(Z,I;N_eT)\, i(Z,I;T) \sum_{\vec{r}|_T} N_H(\vec{r}|_T)\, N_e(T,\vec{r}|_T)\, \delta V(\vec{r}|_T)$$

rewrite as a function of Temperature, assuming N_e, A_Z, etc. are not changing by a lot spatially

$$f_{u\to l}(\lambda;T) = A_Z\, \varepsilon_{u\to l}(Z,I;N_eT)\, i(Z,I;T)\, \boxed{N_H\, N_e(T)\, \frac{\delta V(T)}{\delta \log T}}\, \delta \log T$$

$$f_{u\to l}(\lambda;T) = A_Z\, G_{u\to l}(Z,I;N_e,T)\, DEM(N_e,T)\, \delta \log T$$

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Things ignored, but not ignorable

- absorption (and opacity)
- dynamical evolution
- ionization balance
  - non-equilibrium ionization
  - ionization mechanism (collisional vs photoionization)
- composition
- model errors and misspecification

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summary of emission mechanisms

blackbody : everything hits everything, many times
synchrotron : electrons bend in magnetic fields
free-free : electrons bend in electric fields
Compton scattering : photons hit electrons
inverse Compton : photons hit energetic electrons
free-bound : electrons hit atoms, get captured
photoionization : photons hit atoms, electrons escape
charge exchange : ions hit neutrals, swap electrons
bound-bound : electrons jump down quantum levels

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