X-Ray Emission Processes

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<th>Model Name</th>
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For more details, visit: [http://heasarc.nasa.gov/xanadu/xspec/newmodels.html](http://heasarc.nasa.gov/xanadu/xspec/newmodels.html)
A practical guide to understanding high-energy astrophysical sources
Radiative Processes in Astrophysics

George B. Rybicki
Alan P. Lightman
http://xdb.lbl.gov/
outline

semi-representative sample survey of typical astrophysical sources

some common emission processes and their characteristics
There are FOUR sources!

ROSAT PSPC
The Moon
June 29 1990

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)

Direction of Motion

North

East

To Sun

Nucleus

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

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

FK Com: Chandra: MEG+HEG ±1: 354.1 ks

Fe XXVI
Si XIV
Si XIII
Mg XII
Fe XXVII
O VIII

12297 + 12356 + 13251 + 12298 + 13259 + 12357 + 12299
stellar coronae

Capella

HR 1099

MEG $\pm 1$; binsize = 0.02Å

MEG $\pm 1$; binsize = 0.02Å
Solar wind and comets
fluorescence
Solar (stellar) coronae
Shock plasma

Patnaude et al. / chandra.harvard.edu

Hwang et al. 2004 / chandra.harvard.edu
Shocked plasma

WR 140

Gamma Cas
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.
Solar wind and comets

Fluorescence

Solar (stellar) coronae

Shocked plasma

Accreting compact objects

Cooling compact objects

HRC-S/LETG : Sirius
Solar wind and comets
fluorescence
Solar (stellar) coronae
Shockered plasma
Accreting compact objects
cooling compact objects
Collimated Jets

Radio Image (VLA)

Hubble Space Telescope

Chandra X-ray Observatory
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
- Solar (stellar) coronae
- Shocked plasma
- Accreting compact objects
- Collimated Jets
- Galaxy Clusters

- Continuum
- Blackbody
- Synchrotron & bremsstrahlung
- Scattering
- Radiative recombination
- Lines
- Charge exchange
- Fluorescence
- Thermal
\[ B_\nu(T) = 2 \hbar \left( \frac{\nu^3}{c^2} \right) \left[ e^{\frac{\hbar \nu}{kT}} - 1 \right]^{-1} \text{ergs s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1} \]

\[ \nu_{\text{max}} = 2.82 \frac{kT}{h} \]

\[ \lambda_{\text{max}} = 2.9 \times 10^7 \left( T \text{ [degK]} \right)^{-1} \text{Å} \]

\[ \text{power radiated} = \sigma T^4 \]

\[ \sigma = \frac{2\pi^5 k^4}{15\hbar^3 c^2} = 5.6704 \times 10^{-5} \text{erg s}^{-1} \text{cm}^{-2} \text{K}^{-4} \]
accelerated charged particles emit radiation

energy emitted by single non-relativistic charged particle,
\[ P = \left(\frac{2}{3}\right) \left(\frac{e^2}{c^3}\right) a^2 \]
at Larmor frequency
\[ \omega = \left(\frac{eB}{mc}\right) \]
in the presence of a magnetic field \( B \)
synchrotron emission

characterized by power-law spectra

why?

relativistic beaming gives

\[ P(\omega) \sim \text{const.} \times F(\omega/\omega_c), \]

with \( \omega_c \sim \gamma^2 \)

for power-law distribution of electrons

\[ N(E) \sim E^{-p}, \text{ i.e., } N(\gamma) \sim \gamma^{-p}, \]

\[ P(\omega) \sim \omega^{-(p-1)/2} \]

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

energy emitted per unit volume per unit time per unit frequency

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

- flat spectrum until exponential drop at \( kT \)
- Total power \( \sim \sqrt{T} \)
Thomson scattering: elastic scattering of low-energy photons from low-energy electrons, with cross-section

\[ \sigma_T = \left( \frac{8 \pi}{3} \right) \left( \frac{e^2}{mc^2} \right) = 0.665 \cdot 10^{-24} \text{ cm}^2 \]

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
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

\[ \lambda_c = \frac{h}{me_c} = 0.02426 \, \text{Å} \]

cross-section is reduced as photon energy increases
inverse Compton scattering

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

Radiated power,

$$P_{\text{IC}} = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{\text{ph}}$$

where $\beta = v/c$, $\gamma = 1/\sqrt{1-\beta^2}$, $U_{\text{ph}} = \text{initial photon density}$
Emission in compact lobes of jets can be from Comptonized IR from dust and UV from accretion disk, or synchrotron self-Comptonization.
capture of unbound electron into a bound level $i$ (hence "free-bound")

radiated photon has $E > E_i$

radiated energy proportional to $N_e N(Z,I+1) E_i^{-3}$
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:

$$\frac{dE}{dtdV d\omega} = \frac{dP}{dE} = n_\text{e} n_{Z,j+1} E_\gamma \sigma_\text{rec}(E_\text{e}) v_\text{e} \frac{f(v)dv}{dE_\gamma}$$

Tucker & Gould 1966

Sample O VII (collisional) continuum

Randall Smith's presentation from X-Ray School 2007

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.
Charge Exchange

\[ \epsilon_{iL} = V_c \, n_n \, n_i \, \gamma_{iL} \, \sigma_i \quad \text{photons s}^{-1} \text{cm}^{-3} \]

**Emissivity**
- collision velocity
- neutral species density
- ionic species density
- yield per CX excited ion
- CX cross-section

\[ \sim 400-700 \text{ km s}^{-1} \]
\[ \sim 25 \times 10^{-3} \text{ cm}^{-3} \]
\[ \sim 10^{-4} \text{ cm}^{-3} \]
\[ \sim 0(1) \]
\[ \sim 10^{-15} \text{ cm}^2 \pm 30\% \]
charge exchange

what do the spectra look like?

[Graph showing brightness vs. energy and different spectral lines labeled with energy levels and ions.]
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.
fluorescent intensity when electron in orbital \( l \) of element \( i \) traps the incident photon of energy \( E_{\text{in}} \) and escapes, and electron in orbital \( k \) drops to the vacancy.

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

\( R_{ik} \) probability of trapping incident photons at level \( k \)

\( Y_{ik} \) fluorescence yield for orbital \( k \)

\( P_{ikl} \) probability of electron in level \( l \) falling down to vacant level

\( \mu_i(E_{\text{in}}) \) absorption coefficient of element \( i \) at energy \( E_{\text{in}} \)

\( \omega_i \) mass fraction of element \( i \)

\( J(E_{\text{in}}) \) incident spectrum

\( \int_{E_0}^{\infty} dE_{\text{in}} \) integrated over the incident energies

\( R_{ik} Y_{ik} P_{ikl} \) total mass attenuation coefficient

\( \frac{d\Omega}{4\pi} \) reemission is spherically symmetric

\( dE_{\text{in}} \) incident spectrum

Ogawa et al. 2008, EPS, 60, 283
lunar fluorescent spectra
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.
Grotrian diagram for O VII

\[ f_{u \rightarrow l}(\lambda; T) = \left(\frac{hc}{\lambda}\right) A_{u \rightarrow l}(Z,I;T) \frac{N_u(Z,I;T)}{N(Z,I;T)} \frac{N(Z)}{N(Z,I;T)} \frac{N_H}{N(Z)} \frac{N_e(T)}{N_H} \delta V \]

\[ = \left(\frac{hc}{\lambda}\right) A_{u \rightarrow l}(Z,I;T) \frac{N_u(Z,I;T)}{N_e(T)} \frac{N(Z,I;T)}{N(Z)} \frac{N(Z)}{N_H} \frac{N_H}{N_e(T)} \delta V \]

\[ = \epsilon_{u \rightarrow l}(Z,I;N_e,T) \quad i(Z,I;T) \quad A_Z \quad N_H \quad N_e(T) \delta V \]
Differential Emission Measure

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

$$f_{u\rightarrow l}(\lambda, \vec{r}; T) = A_Z \epsilon_{u\rightarrow l}(Z, I; N_{e T}) i(Z, I; T) N_H(\vec{r}) N_{e}(T, \vec{r}) \delta V(\vec{r})$$

group together all volume which has the same temperature

$$f_{u\rightarrow l}(\lambda; T) = A_Z \epsilon_{u\rightarrow l}(Z, I; N_{e T}) i(Z, I; T) \sum_{\vec{r} | T} N_H(\vec{r}| T) N_{e}(T, \vec{r}| T) \delta V(\vec{r}| T)$$

rewrite as a function of Temperature, assuming $N_{e}$, $A_Z$, etc. are not changing by a lot spatially

$$f_{u\rightarrow l}(\lambda; T) = A_Z \epsilon_{u\rightarrow l}(Z, I; N_{e T}) i(Z, I; T) N_H N_{e}(T) \frac{\delta V(T) \delta \log T}{\delta \log T}$$

$$f_{u\rightarrow l}(\lambda; T) = A_Z G_{u\rightarrow l}(Z, I; N_{e T}) \text{DEM}(N_{e T}) \delta \log T$$
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
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