Violent Universe Explored by Japanese X-ray Satellites

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Asia Academic Seminar
CPS 8th International School of Planetary Science
September 30, 2011 at Awaji

Lecture Plan

September 30, 9:00-10:15

I. Basic processes in High energy astronomy

- **I-1: Why X-ray astronomy?**
- **I-2: Emission mechanisms**
- **I-3: Energy sources**

II. High energy phenomena

- **II-1: Stellar X-ray emission**

September 30, 10:45-12:00

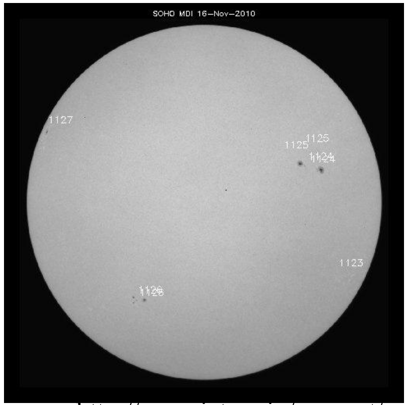
- **II-2: Supernova remnants (SNR)**
- **II-3: Neutron stars and blackholes**
- **II-4: Active Galactic Nuclei**
- **II-5: Cluster of galaxies and Cosmology**

I-1. Why X-ray astronomy?

1. Sun

http://swc.nict.go.jp/sunspot/

Optical Image



http://swc.nict.go.jp/sunspot/

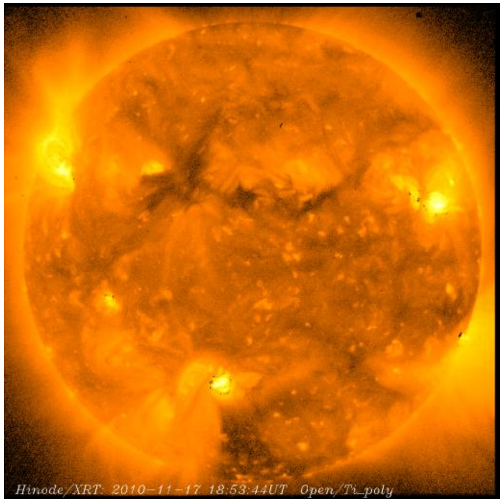
Photosphere : Black body radiation

$T = 6430^\circ$ K → $\lambda_{peak} \sim 4500$ A

Wien's law $\lambda T = 2800$ micron K

Density $\sim 10^{14}$ atom/cc (10^{-6} g/cc)

X-ray Image by



http://hinode.nao.ac.jp/latest/

Corona : Thin thermal emission + lines

$T = 10^6\,^\circ$ K → $\lambda_{peak} \sim 30$ A (if BB)

Density $\sim 10^{6\text{-}8}$ atom/cc

http://hinode.nao.ac.jp/latest/

I-1. Why X-ray astronomy?

2. Cluster of Galaxies

Optical image : Component galaxies

Emission from stars

Visible mass ~ **M**

X-ray image : Hot plasma

T ~ $10^{7\text{-}8}$° K

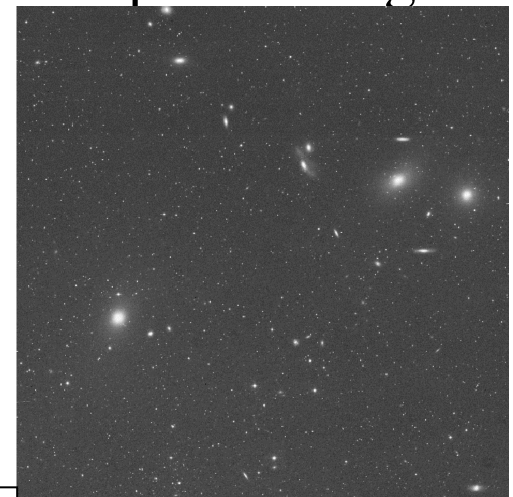
Plasma mass ~ **1-5 M**

Mass to bind hot gas in clusters

Dark matter

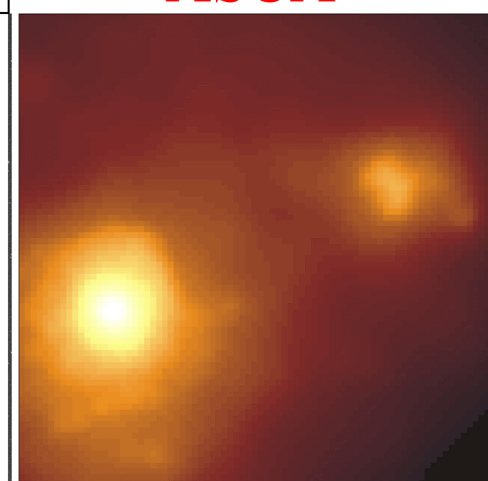
Mass ~ **5-20 M**

Optical Image



Virgo Cluster

X-ray Image by ASCA



Radiation and related physical processes

Radio λ= 0.1 - 100 mm

Molecular emission

Vibration, rotation

FM Radio frequency
80.7 MHz
$\lambda = 3\text{x}10^{10}\text{cm}/8.07\text{x}10^{7}$
$= 4\ \text{x}10^{2}\ \text{cm}$

Infrared λ= 1-100 micron

Dust emission

Low temp. stars

Black body radiation
37℃ => 310° K
~ 9 micron

Optical λ=4000-7000 Å

Main sequence stars

T= 6430° K→ λ_{peak}~4500 A

Absorption & emission lines from excited atoms

H Ly-α **1215 Å**
Ly limit **912 Å**
H Ba-α (H-α) **6562 Å**

Radiation and related physical processes

Ultra-violet λ= 100-4000 Å

Early type stars(<7000° K)

Emission lines

Binding energy
(Outer most electron)
H (13.6 eV), He (24.6 eV),
Li (5.4eV), Be(9.3eV)

X-rays λ= 1-100 Å

Plasma temp. 10^{5-8} K

Emission lines

(transition between levels)

Binding energy
(Inner most electron)
C(280eV), O(550eV)
Ar(3.1keV), Fe(7.1keV)

Gamma rays λ< 1 Å

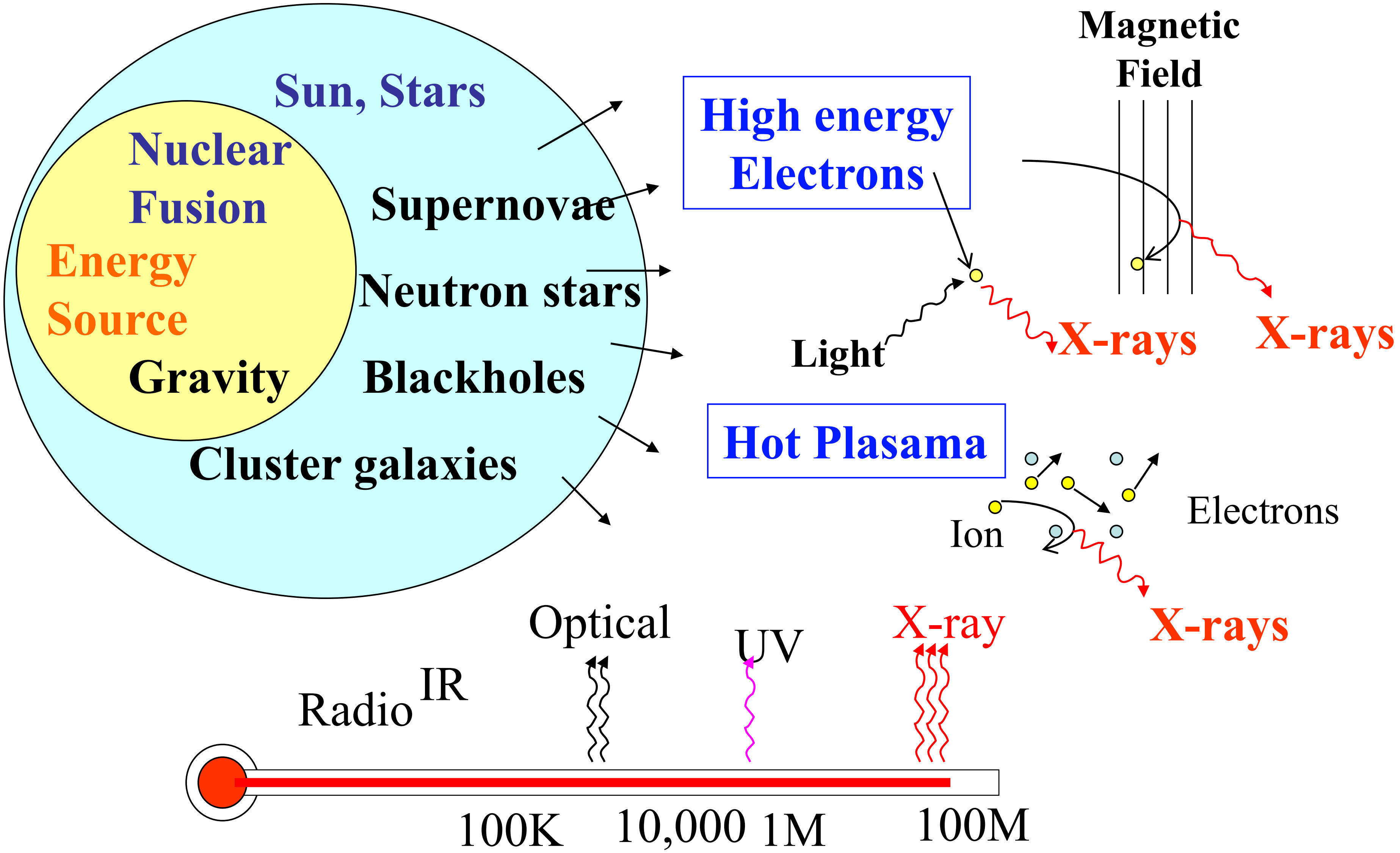
Nuclear transition

High energy particles

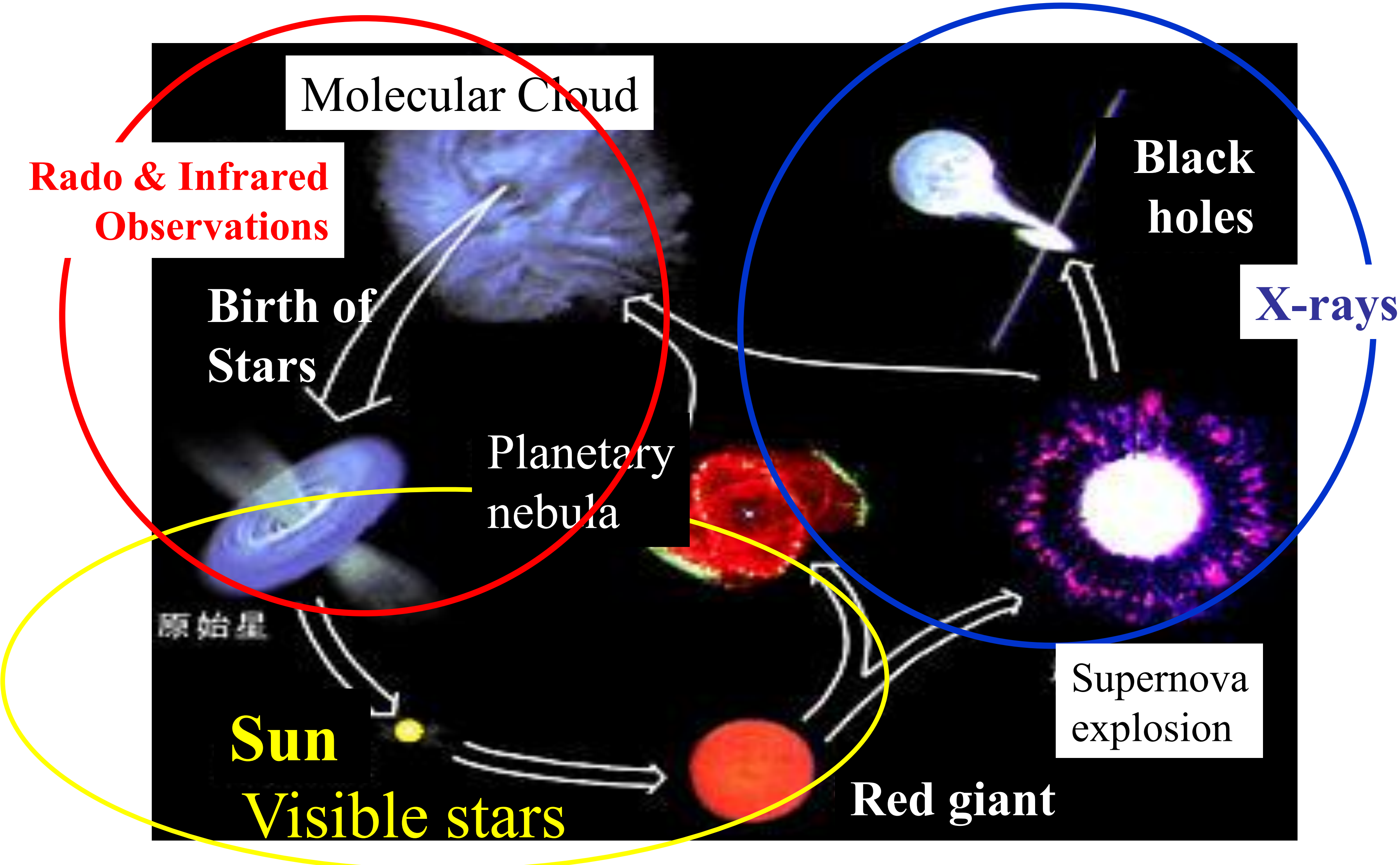
Synchrotron rad.

Compton rad.

Radiation mechanisms of X-rays

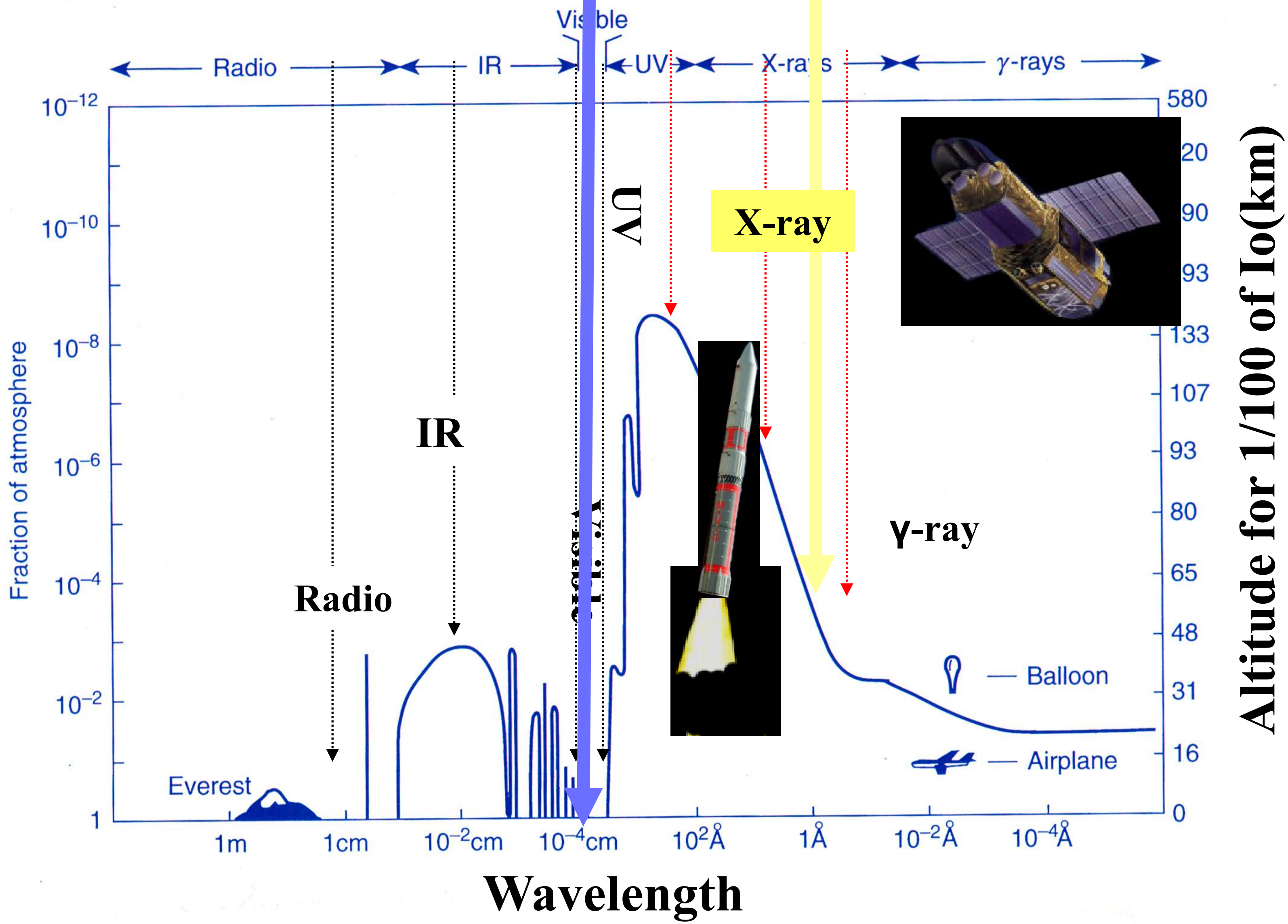


Life cycle of stars



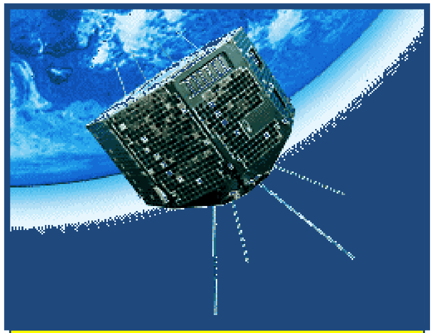
Narrow window at Visible light

X-rays are observable from out side atmosphere

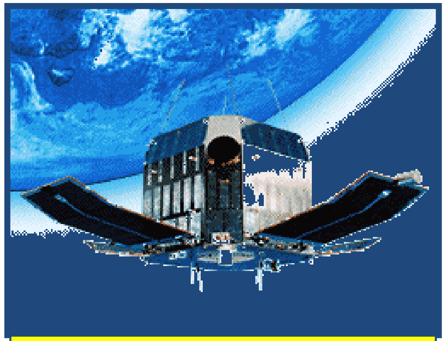


X-ray Telescope

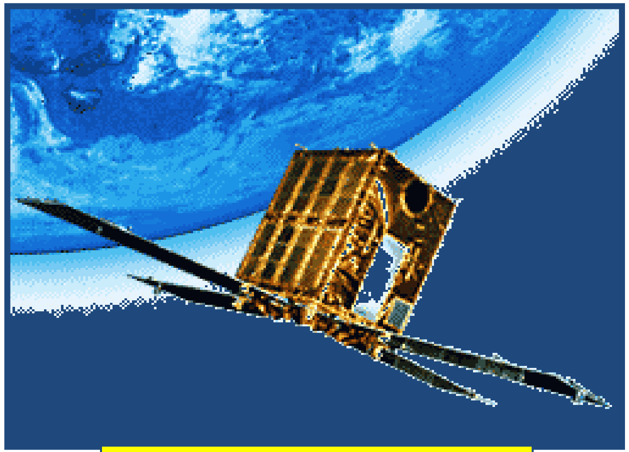
Japanese X-ray Satellites



Hakucho (1979)
90kg



Tenma (1983)
200kg



Ginga (1987)
420kg

ASCA (1993) 420kg

Suzaku (2005) 1700kg

JAXA

II-2: Emission mechanisms

1. Black body radiation

Thermometry of steel furnaces based on the radiation

$E(\nu)\, d\nu = 2\, Z(\nu) kT\, d\nu$ **$Z(\nu)$: lattice points in phase space**

(1) Long wave side : Rayleigh-Jeans distribution

$$Z(\nu)\, d\nu = \frac{4\pi L^3}{C^3} \nu^2\, d\nu$$

$$U(\nu)\, d\nu = \frac{E(\nu)\, d\nu}{L^3} = \frac{8\pi kT}{C^3} \nu^2\, d\nu$$

When ν --> small, it well represents observed spectra
but when ν is large, U will become infinity.

II-2: Emission mechanisms

1. Black body radiation

(2) Short Wave side : Wien distribution

$$Z(\nu)\, d\nu = \frac{4\pi L^3}{C^3} \nu^2 \exp(-h\nu/kT)\, d\nu$$

$$U(\nu)\, d\nu = \frac{2\, Z(\nu)\, h\nu\, d\nu}{L^3} = \frac{8\pi h}{c^3} \nu^3 \exp(-h\nu/kT)\, d\nu$$

When $h\nu/kT \gg 1$, it well represents observed spectra but does not match with the data when $h\nu/kT \ll 1$

II-2: Emission mechanisms

1. Black body radiation

(3) Interpolation : Planck distribution

$$U(\nu) = \frac{8\pi h}{c^3} \, \frac{1}{\exp(h\nu/kT) - 1} \, \nu^3 \, d\nu \qquad \textbf{Planck distribution}$$

When $h\nu/kT \ll 1$, $\exp(-h\nu/kT) = 1 + h\nu/kT$

$$U(\nu)\, d\nu = \frac{8\pi kT}{c^3} \, \nu^2 \, d\nu \qquad \textbf{Rayleigh-Jeans}$$

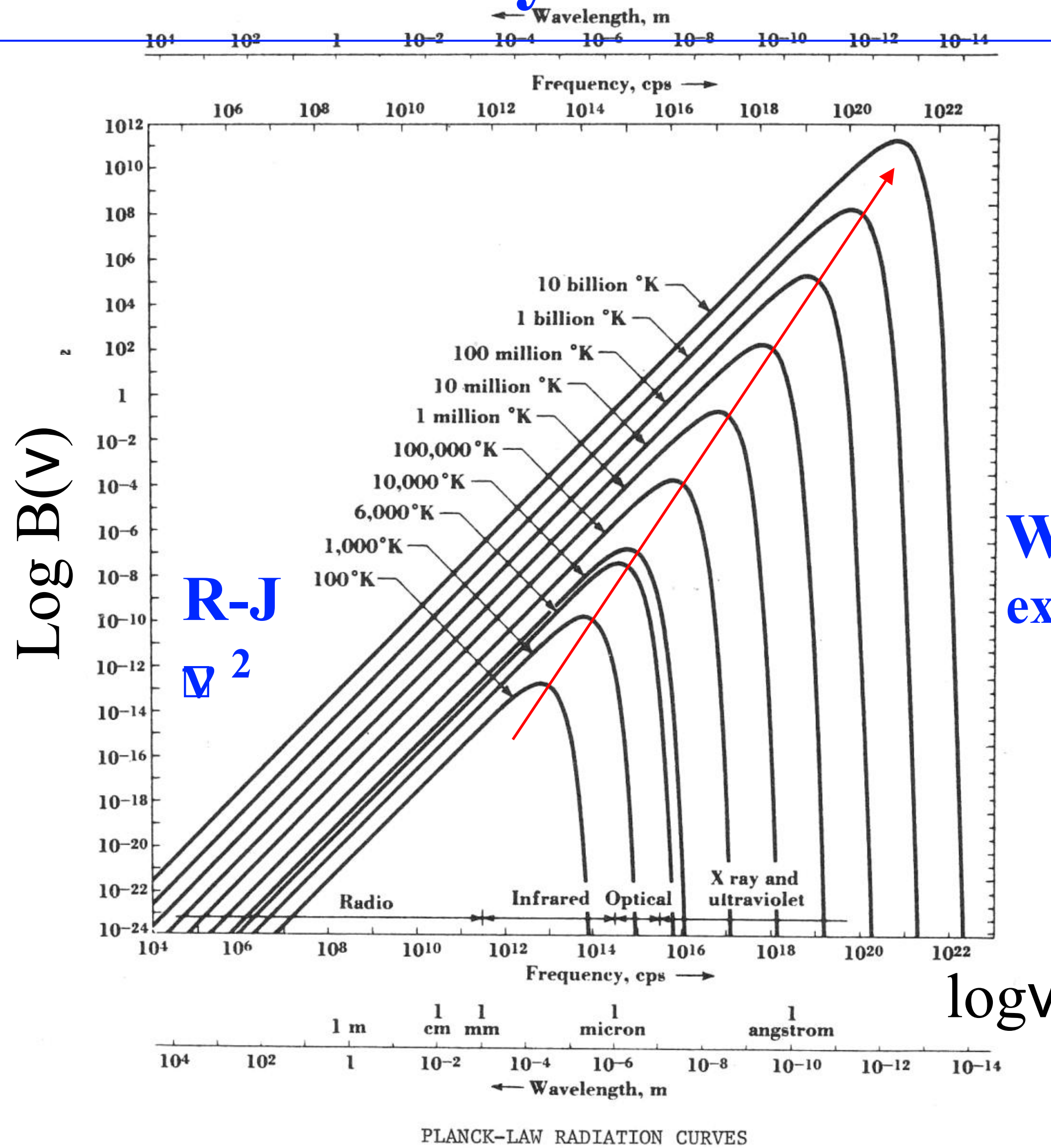
When $h\nu/kT \gg 1$, $\exp(h\nu/kT) \gg 1$

$$U(\nu)\, d\nu = \frac{8\pi kT}{c^3} \nu^3 \exp(-h\nu/kT)\, d\nu \qquad \textbf{Wein}$$

II-2: Emission mechanisms

1. Black body radiation

Planck distribution



Wien ∝ exp(-h ν /kT)

John D. Kraus, 1986: Radio Astronomy, Cygnus-Quasar Books ,81

II-2: Emission mechanisms

1. Black body radiation

Peak frequency : derivative of Planck's eq. = 0

$$U(\nu) = \frac{8\pi h}{c^3}\,\frac{1}{\exp(h\nu/kT) - 1}\,\nu^3\,d\nu$$

Planck distribution

$$f(x) = \frac{x^3}{e^x - 1}$$

when $x = h\nu/kT$

$$\frac{\partial f}{\partial x} = \frac{3x^2(e^x - 1) - x^3 e^x}{(e^x - 1)^2} = 0$$

$3(1 - e^x) = x$ left term $= 0(x=0)$, $=1.8(x=1)$, $=2.4(x=2)$, $=3(x=\infty)$

$x = 2.812$ $h\nu max = 2.82\ kT$

$\lambda maxT = 2900(\mu m \cdot K)$ **Wien's law**

II-2: Emission mechanisms

1. Black body radiation

Total brightness : Integration of Planck's eq.

$$B(\nu) = \frac{U(\nu)\, c}{4\pi}$$

$$\int B(\nu) d\nu = \frac{2\pi h}{c^2} \int \frac{1}{\exp(h\nu/kT) - 1} \nu^3 d\nu$$

When $x = h\nu/kT$

$$B = \frac{2h}{c^2} \left(\frac{kT}{h}\right)^4 \int \frac{x^3}{e^x - 1} dx \rightarrow = \frac{\pi^4}{15}$$

$$= \frac{2\pi^5 k^4}{15 c^2 h^3} T^4 = \sigma T^4$$

$\sigma = 5.67 \times 10^{-5}$ erg cm^{-2} deg^{-4} s^{-1} : Stefan-Boltzmann constant

II-2: Emission mechanisms

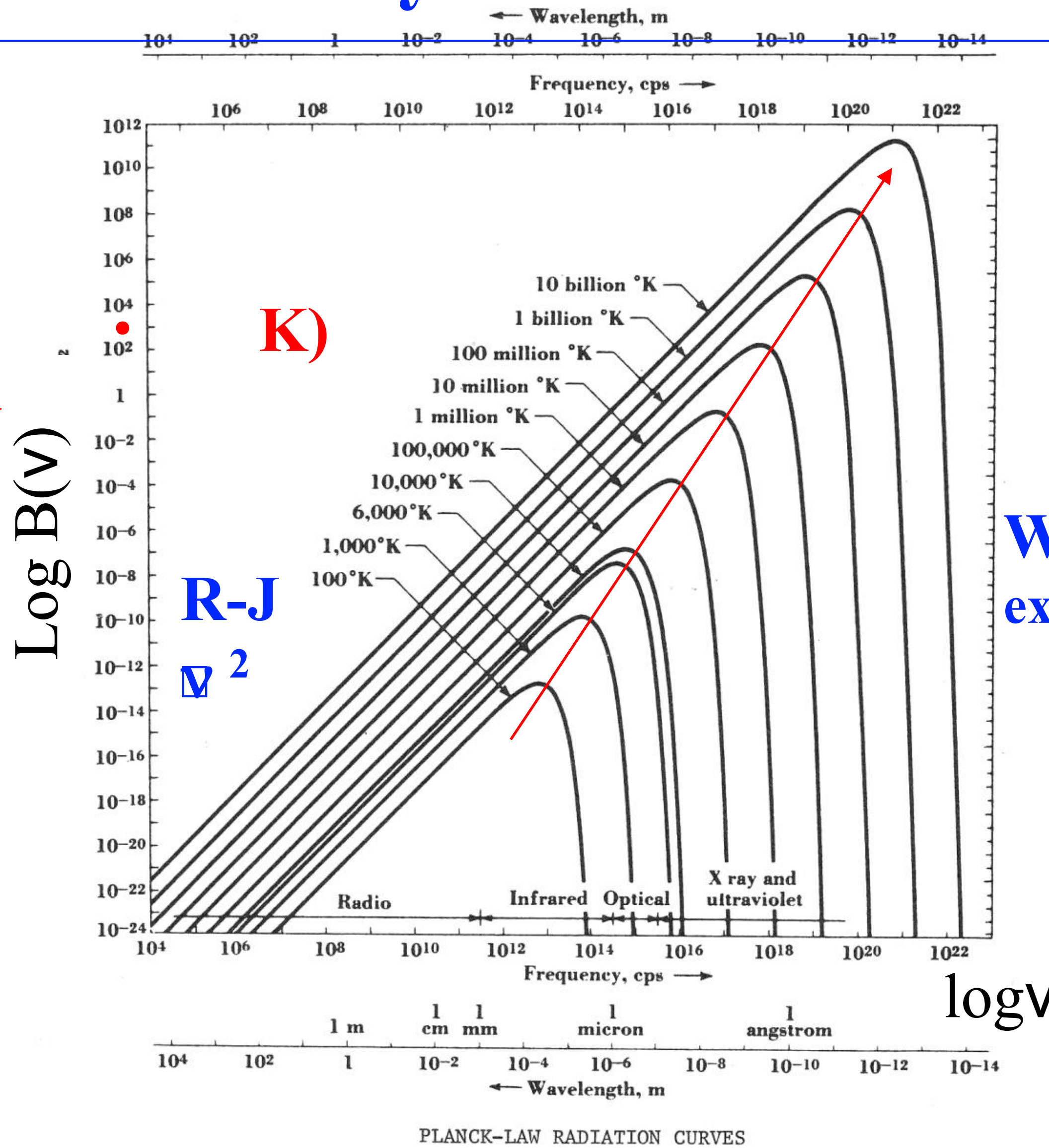
1. Black body radiation

Planck distribution

λ maxT=2900(μm · K)

Wien's law

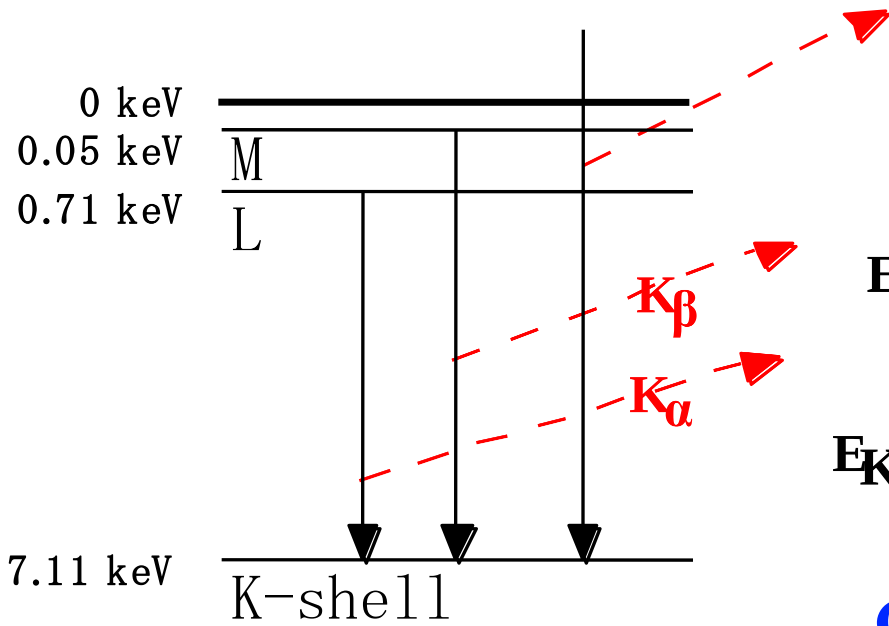
$\boxed{B = \sigma T^4}$



John D. Kraus, 1986:
Radio Astronomy,
Cygnus-Quasar Books ,81

2. Line emission and absorption

Emission from Fe atoms



$E_{RC} = E_C - E_K$
> 7.11 keV(<1.743 Å)

$E_{K\beta} = E_M - E_K$
$= 7.06$ keV(1.757 Å)

K X-rays

$E_{K\alpha} = E_L - E_K$
$= 6.40$ keV(1.937 Å)

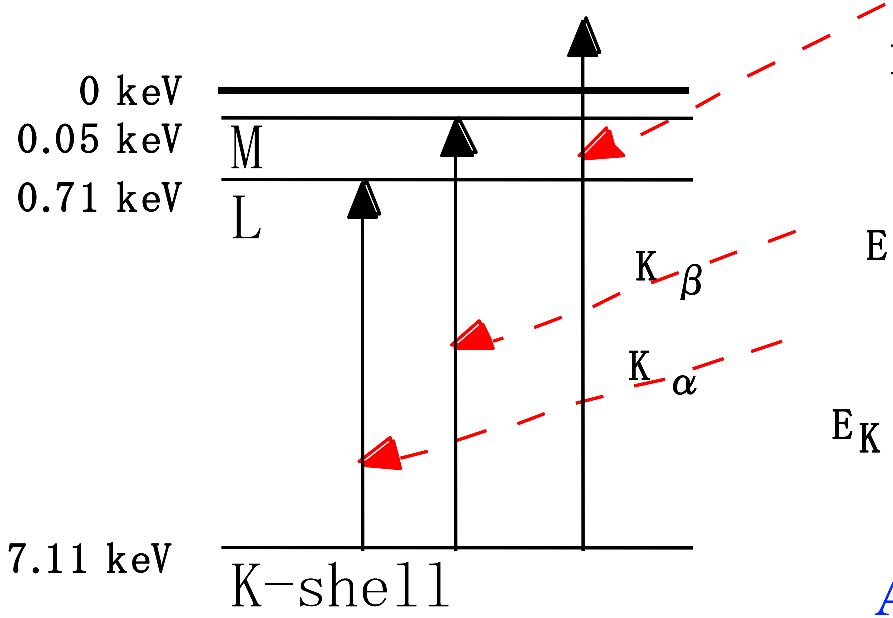
Characteristic X-rays

↓

Analysis of elements

2. Line emission and absorption

Absorption by Fe atom



Absorption edge

$E_{RC} = E_C - E_K$

> 7.11 keV (<1.743 Å)

$E_{K\beta} = E_M - E_K$

$= 7.06$ keV (1.757 Å)

$E_{K\alpha} = E_L - E_K$

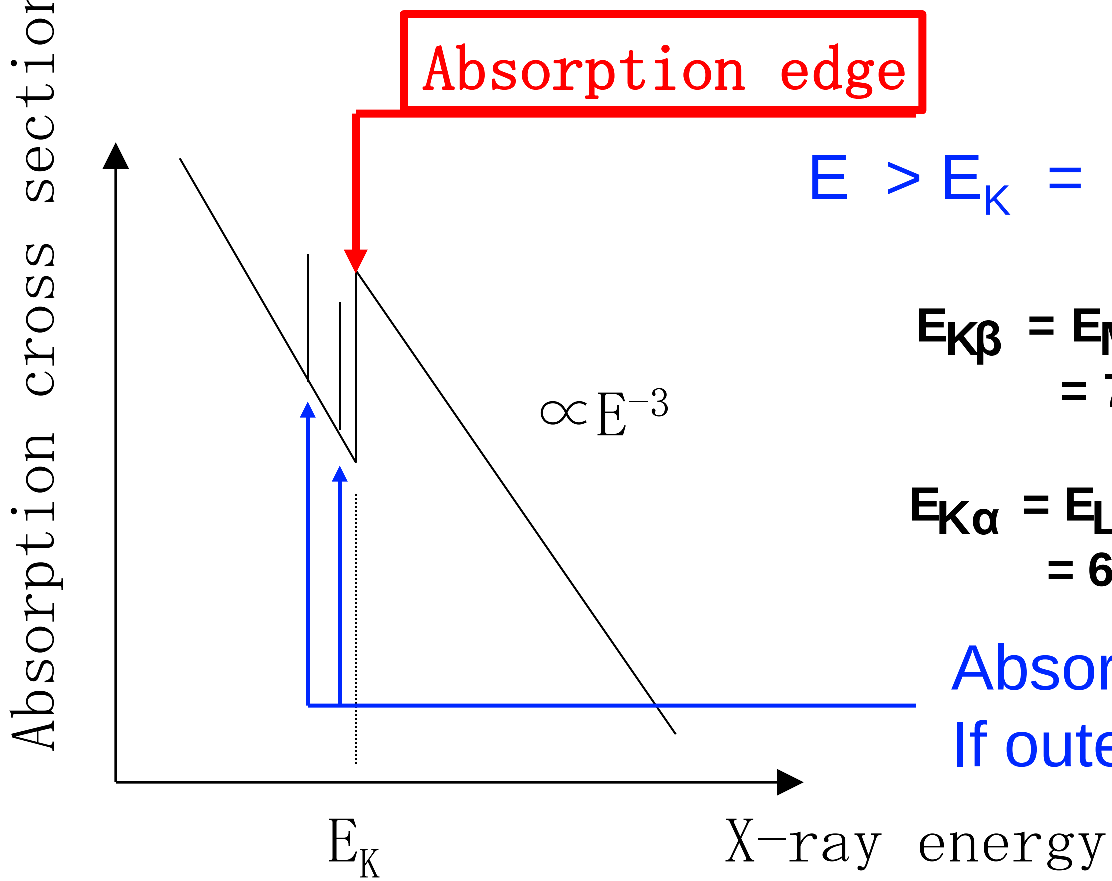
$= 6.40$ keV (1.937 Å)

Absorption lines

If outer electrons are ionized

2. Line emission and absorption

Absorption by Fe atom

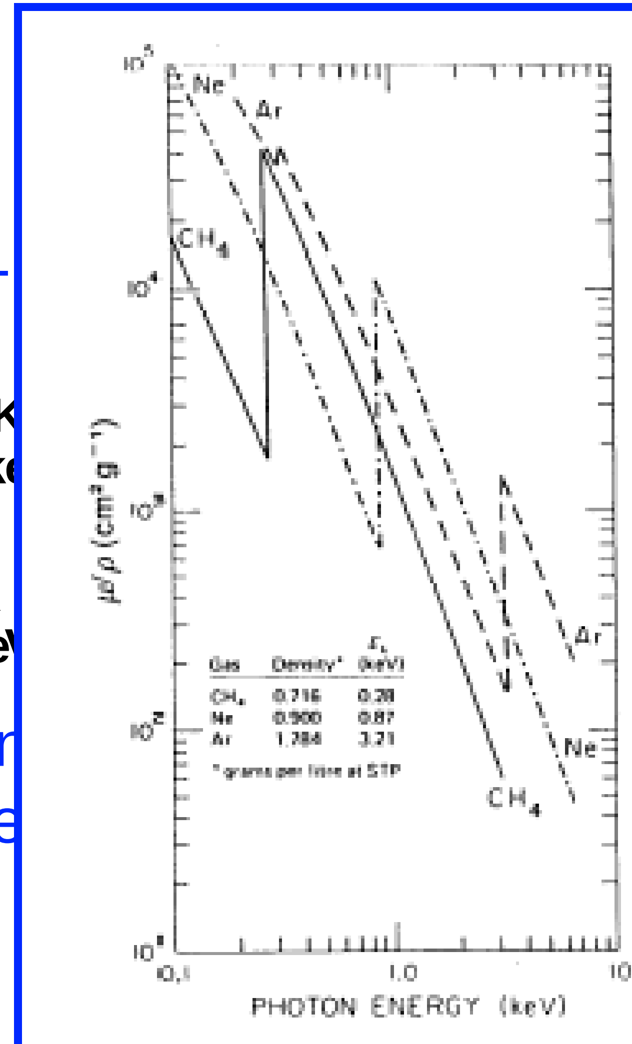


$E > E_K = 7.11$

$E_{K\beta} = E_M - E_K$
$= 7.06$ ke

$E_{K\alpha} = E_L - E_K$
$= 6.40$ keV

Absorption
If outer ele



II-2: Emission mechanisms

Emission from hot plasmas

Ionization state

Electron collision/Photo ionization Free electrons

Recombination Equilibrium

Lines from ionized ions

Binding energy increases after the removal of outer electrons

Fe XVII(16 electrons are removed) Fe Kα X-ray ∼6.4 keV

Fe XVIII -XXV ∼6.7 keV

Fe XXVI ∼6.9 keV

Line energy ---> Ionization state

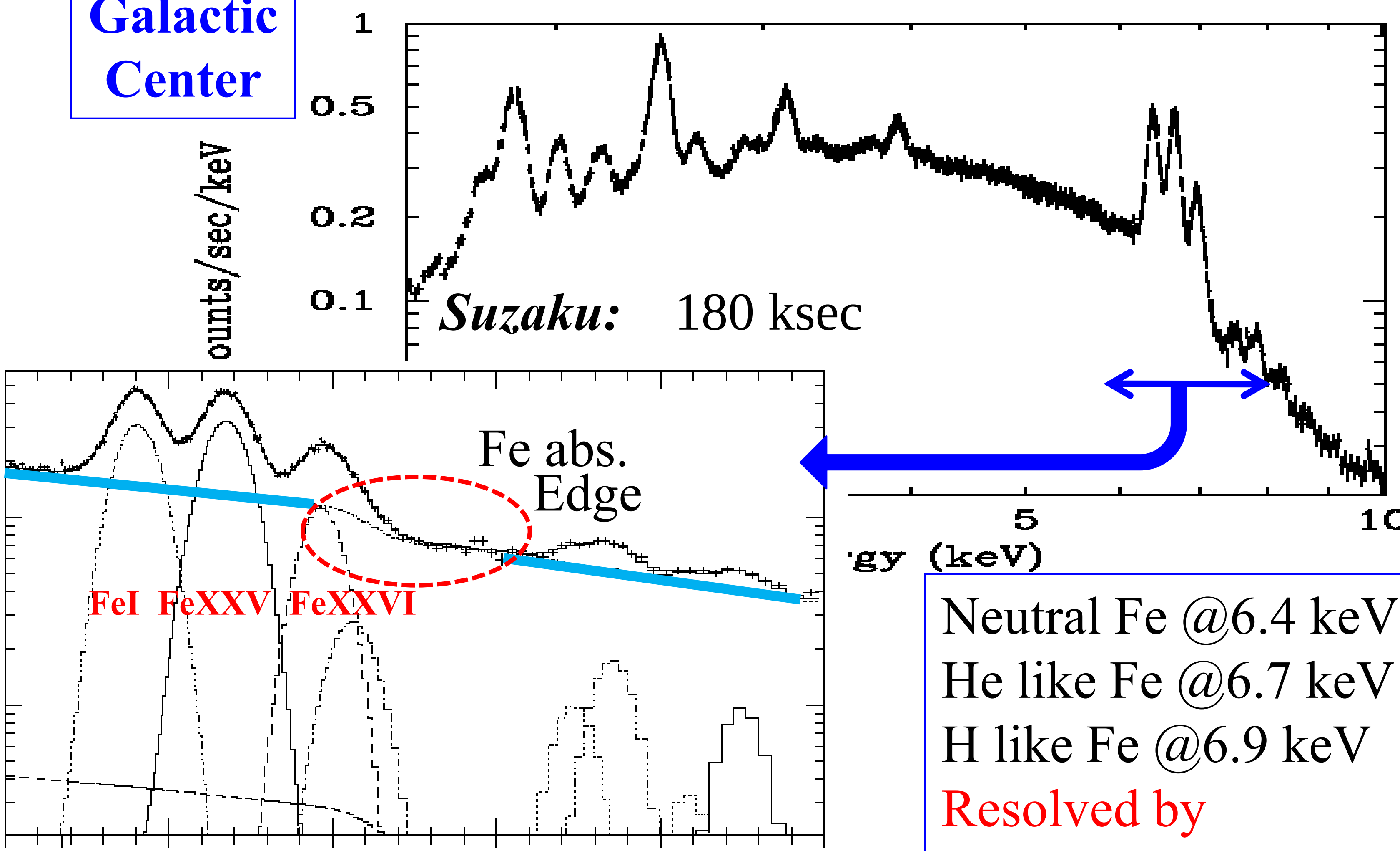
Line ratio of an element --->

Tion, Te (Balance of ionization/recomb.)

Line ratio ----> Atomic abundance

Emission from hot plasmas

Galactic Center

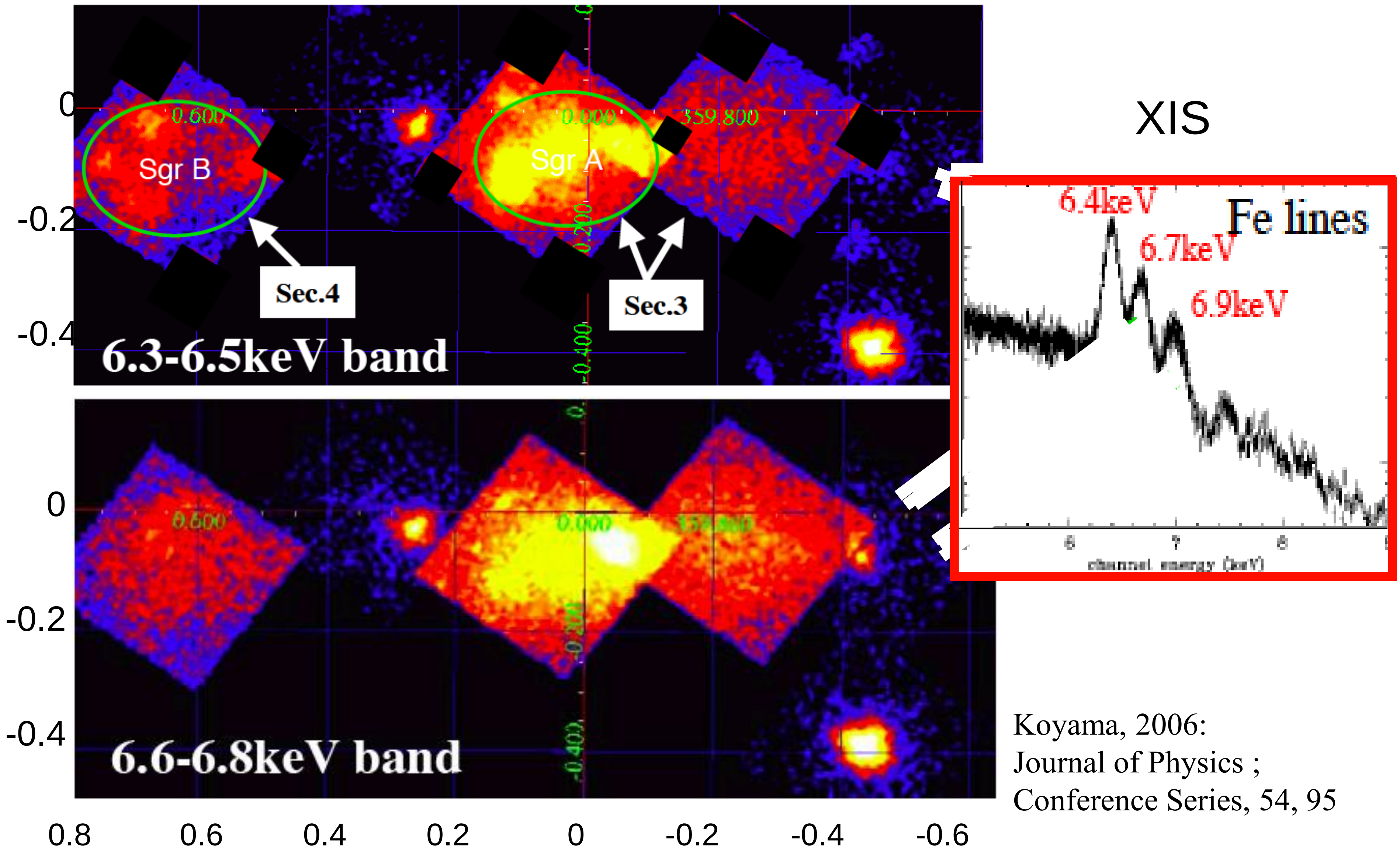


Neutral Fe @6.4 keV
He like Fe @6.7 keV
H like Fe @6.9 keV
Resolved by ΔE~140 eV of CCD

Koyama et al, 2007: Publ. Astron. Soc. Japan, 59, 221
Koyama et al, 2007: Publ. Astron. Soc. Japan, 59, 245

II-2: Emission mechanisms

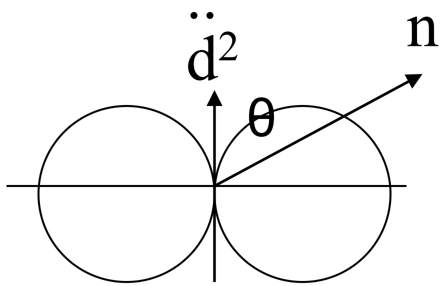
Emission from hot plasmas



Koyama, 2006:
Journal of Physics ;
Conference Series, 54, 95

3. Bremsstrahlung

Dipole **d** Radiation into the unit solid angle Ω



$$\frac{dP}{d\Omega} = \frac{\ddot{\mathbf{d}}^2}{4\pi c^3} \sin^2\theta$$

$$\frac{dW}{dt} = \frac{e^2}{16\pi^2\varepsilon_0 c} \int d\Omega\, (\mathbf{n}(t) \times (\mathbf{n}(t) \times \dot{\boldsymbol{\beta}}(t)))^2$$

If θ is the angle between $\dot{\boldsymbol{\beta}}(t)$ and n,

$$= \frac{e^2}{16\pi^2\varepsilon_0 c} \int d\Omega \sin^2\theta\, (\dot{\boldsymbol{\beta}}(t))^2 -$$

→Max. at perpendicular direction

$$= \frac{e^2}{16\pi^2\varepsilon_0 c} (\dot{\mathbf{v}}(t))^2 \int d\Omega \sin^2\theta\, (\dot{\boldsymbol{\beta}}(t))^2$$

$\boldsymbol{\beta} = v/c$

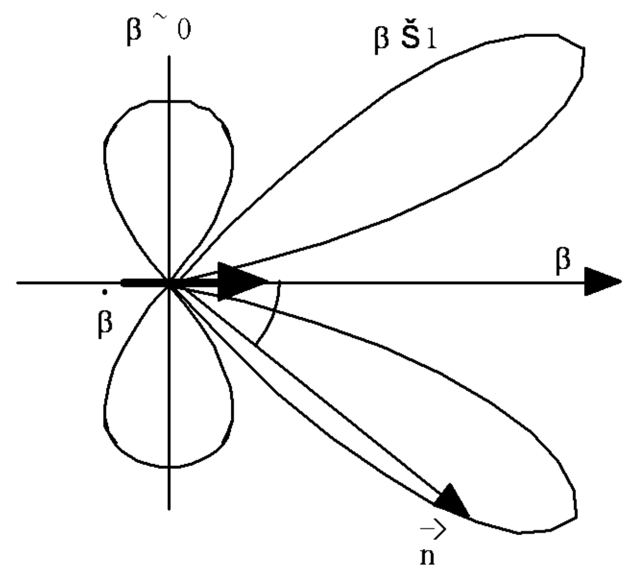
II-2: Emission mechanisms

3. Bremsstrahlung

When $d\Omega = \sin\theta \, d\theta \, d\psi$

$$\frac{dW}{dt} = \frac{e^2}{6\pi\varepsilon_0 c^3}(\dot{\mathbf{v}}(t))^2$$

$$\frac{dW}{dt} = \frac{e^2 v^2(t)}{16\pi^2\varepsilon_0 c}\int d\Omega \, \frac{\sin\theta}{(1-v(t)\cos\theta / c)^5}$$



When $\beta = v/c \rightarrow 1$

Isotropic in the rest frame

→ Lorentz transformation → **Beaming**

$$\boxed{\gamma = \frac{1}{\sqrt{(1 - v^2/c^2)}}}$$

3. Bremsstrahlung

Lorentz transformation

$$\gamma = \frac{1}{\sqrt{(1 - v^2/c^2)}}$$

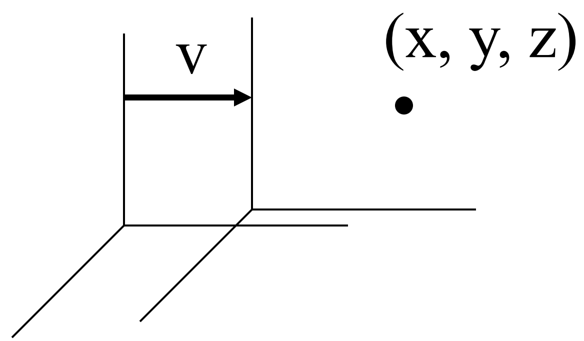
$$x' = \gamma(x - vt)$$
$$y' = y$$
$$z' = z$$
$$t' = \gamma(t - vx/c^2)$$

$$x = \gamma(x' + vt)$$
$$y = y'$$
$$z = z'$$
$$t = \gamma(t' + vx'/c^2)$$

$$u_x = dx/dt = \frac{\gamma(dx' + vdt')}{\gamma(dt' + vdx/c^2)} = \frac{u_x' + v}{1 + vu_x'/c^2}$$

$$u_y = \frac{u_y'}{\gamma(1 + vu_x'/c^2)}$$

$$u_z = \frac{u_z'}{\gamma(1 + vu_x'/c^2)}$$



3. Bremsstrahlung

Measured in the moving system

Velocity u', direction θ',

$$\gamma = \frac{1}{\sqrt{(1 - v^2/c^2)}}$$

Parallel component to v is affected by the motion v

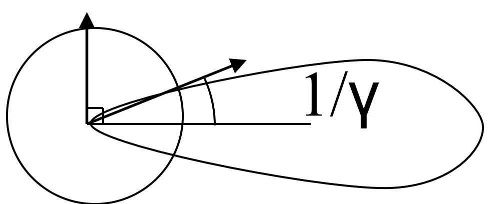
$$u_{\parallel} = \frac{u_{\parallel}' + v}{1 + v u_{\parallel}'/c^2} \qquad u_{\perp} = \frac{u_{\perp}'}{\gamma(1 + v u_{\parallel}'/c^2)}$$

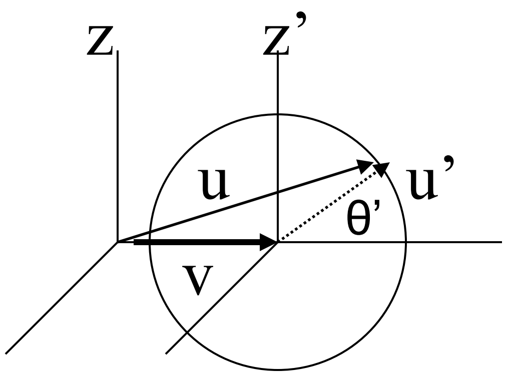
In the moving system, light direction is θ' is changed to θ

$$\sin\theta = \frac{u_{\perp}}{c} = \frac{c \sin\theta'}{c\gamma(1 + v\cos\theta/c)}$$

Here, $u' = c$, $u_{\parallel} = c\cos\theta$, $u_{\perp} = c\sin\theta$

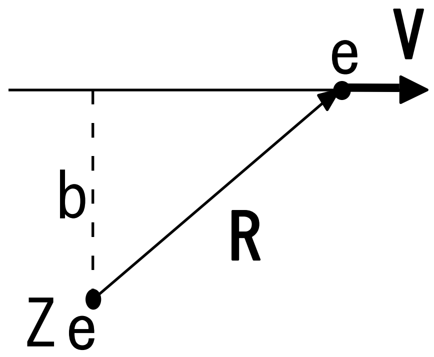
If $\theta = \pi/2$, $\sin\theta = 1/\gamma$





3. Bremsstrahlung

Thermal bremsstralung



Impact parameter b

$$\frac{dW}{d\omega} = \frac{2e^2}{3\pi c^3} \mid \boldsymbol{\Delta V} \mid^2 \qquad \omega\tau << 1 \qquad \tau = b / v$$

$$\boldsymbol{\Delta V} = \frac{Ze^2}{m} \int \frac{b\,dt}{(b^2 + v^2t^2)^{3/2}} = \frac{2Ze^2}{mbV}$$

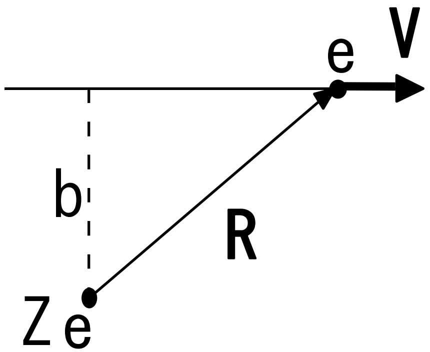
$$\frac{dW(b)}{d\omega} = \frac{8Z^2e^6}{3\pi c^3 m^2 v^2 b^2} \qquad b << v/\omega$$

3. Bremsstrahlung

Thermal bremsstralung

Ion density n_i electron density n_e

Integrate b from b_{min} to ∞



$$\frac{dW}{d\omega\, dV dt} = n_e\, n_i\, 2\pi v \int_{b_{min}}^{\infty} \frac{dW(b)}{d\omega}\, b\, db$$

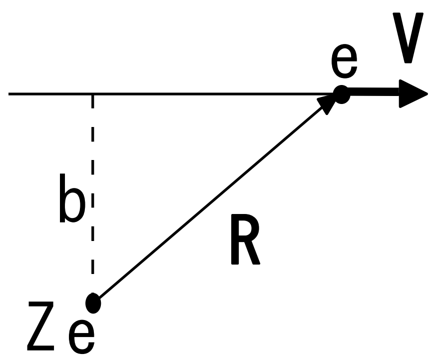
$$= \frac{16 e^6}{3 c^3 m^2 v}\, n_e\, n_i\, Z^2 \ln\left(\frac{b_{max}}{b_{min}}\right)$$

$$= \frac{16 \pi e^6}{3\sqrt{3}\, c^3 m^2 v}\, n_e\, n_i\, Z^2\, g_{ff}(v, \omega) \qquad \text{(eq 5.11)}$$

George B. Rybicki, Alan P. Lightman, 1979:
Radiative Processes in Astrophysics, Wiley-VC, 158

3. Bremsstrahlung

Thermal bremsstralung



Thermal distribution of electrons

$dP \propto \exp(-E/kT)\, d^3v = \exp(-mv^2/2kT)\, d^3v$

$$\frac{dW}{dV\,dt\,d\omega} = \frac{\displaystyle\int_{v_{min}}^{\infty} \frac{dW(v,\omega)}{d\omega\, dV\, dt}\, v^2 \exp(-mv^2/2kT)\, dv}{\displaystyle\int_0^{\infty} v^2 \exp(-mv^2/2kT)\, dv}$$

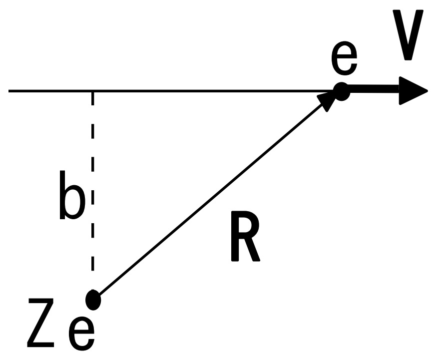
$$d\omega = 2\pi d\nu$$

$$\frac{dW}{dV\,dt\,d\nu} = \left(\frac{2\pi}{3km}\right)^{1/2} \frac{2^5 \pi e^6}{3mc^3}\, T^{1/2}\, Z^2\, n_e\, n_i\, e^{-h\nu/kT}\, g \qquad \textbf{(eq. 5.14a)}$$

George B. Rybicki, Alan P. Lightman, 1979: Radiative Processes in Astrophysics, Wiley-VC, 160

3. Bremsstrahlung

Thermal bremsstralung



Thermal distribution of electrons

$dP \propto \exp(-E/kT)\, d^3v = \exp(-mv^2/2kT)\, d^3v$

$$\frac{dW}{dV dt d\omega} = \frac{\displaystyle\int_{v_{min}}^{\infty} \frac{dW(v,\omega)}{d\omega dV dt} v^2 \exp(-mv^2/2kT)\, dv}{\displaystyle\int_{0}^{\infty} v^2 \exp(-mv^2/2kT)\, dv}$$

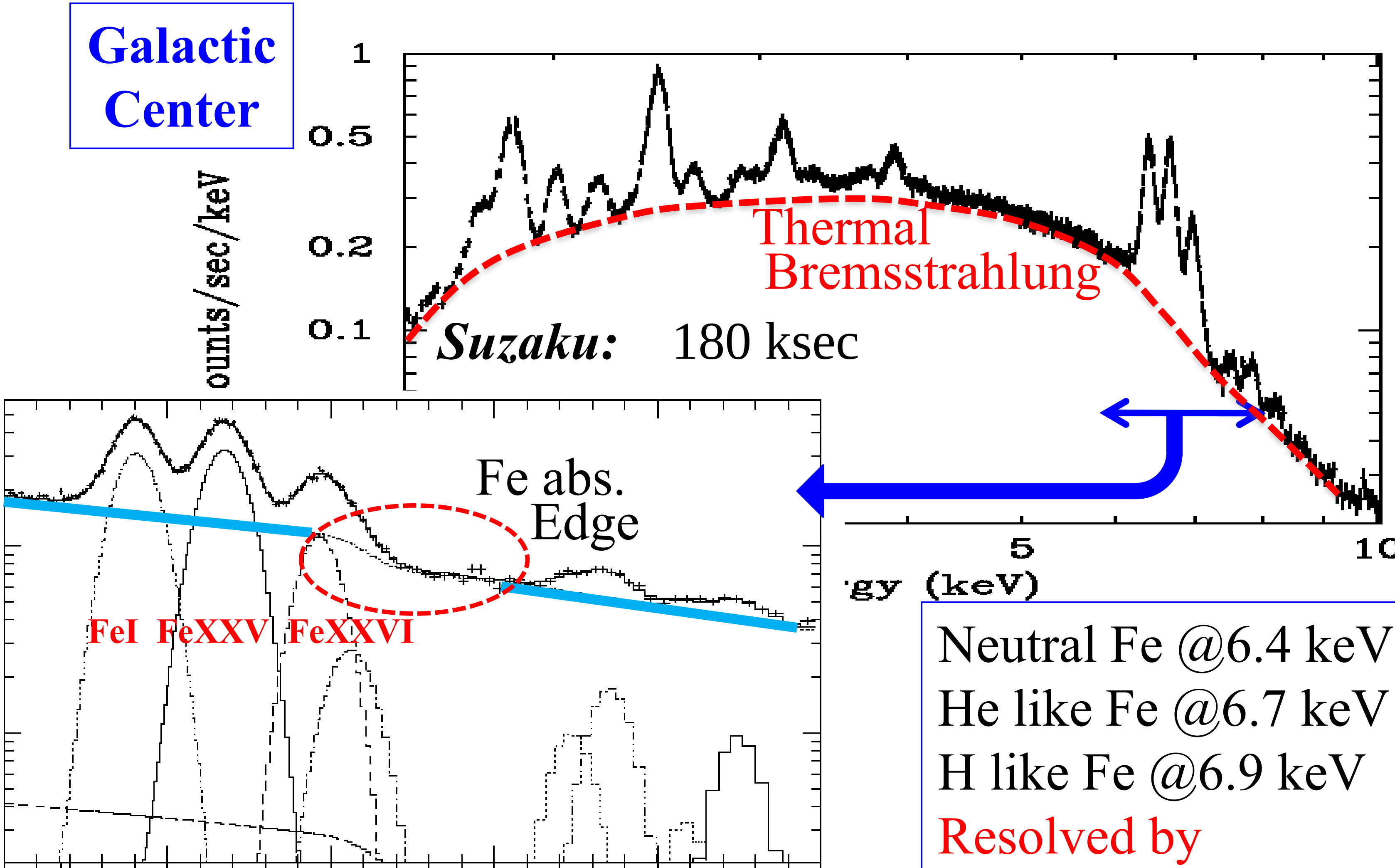
$d\omega = 2\pi d\nu$

$$\frac{dW}{dV\, dt\, d\nu} = \left(\frac{2\pi}{3km}\right)^{1/2} \frac{2^5 \pi e^6}{3mc^3} T^{1/2} Z^2 n_e n_i e^{-h\nu/kT} g \qquad \text{(eq. 5.14a)}$$

$$\frac{dW}{dV\, dt} = \left(\frac{2\pi kT}{3m}\right)^{1/2} \frac{2^5 \pi e^6}{3hmc^3} Z^2 n_e n_i g \qquad \text{(eq. 5.15a)}$$

George B. Rybicki, Alan P. Lightman, 1979: Radiative Processes in Astrophysics, Wiley-VC, 160-161

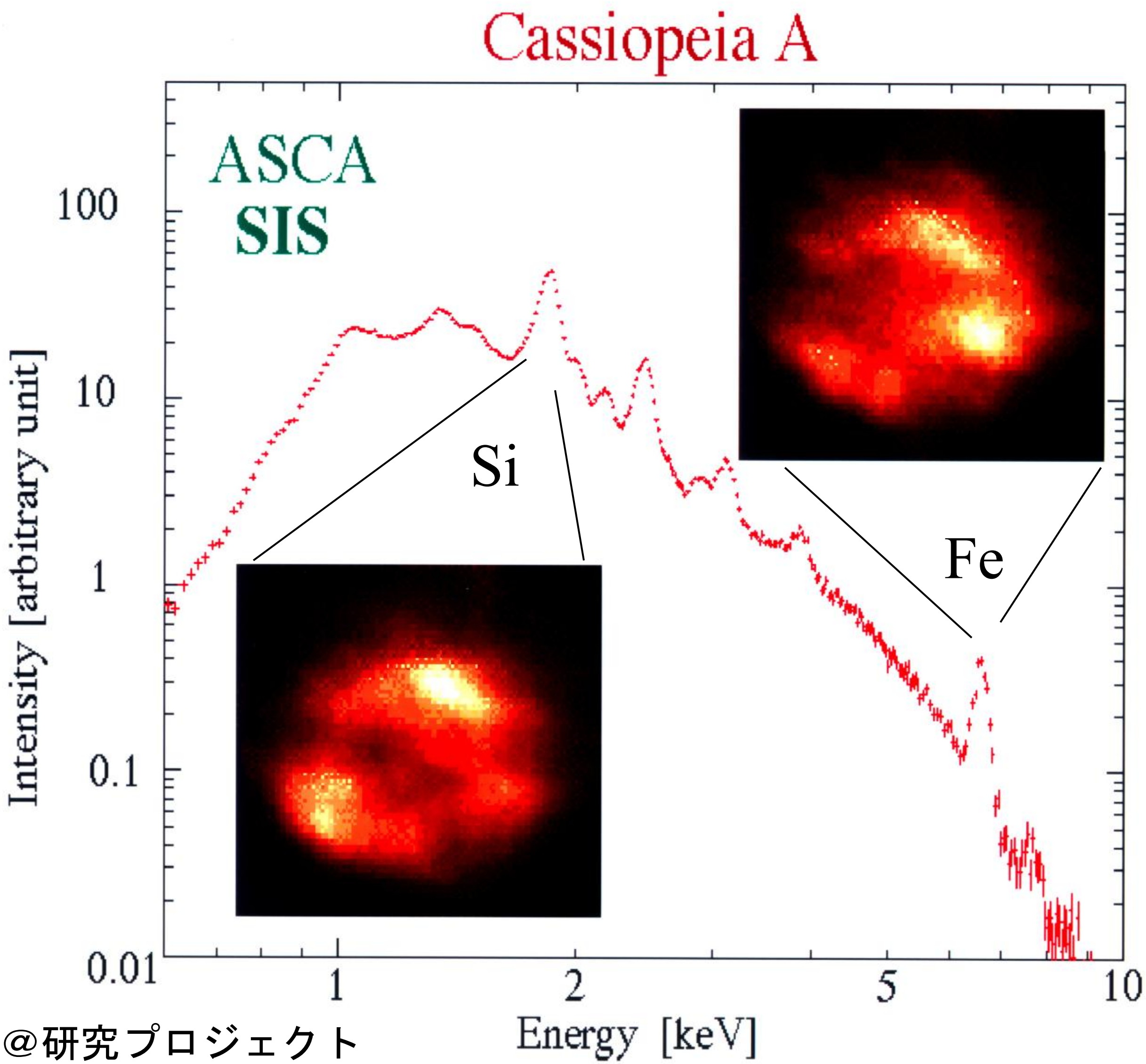
Emission from hot plasmas



Neutral Fe @6.4 keV
He like Fe @6.7 keV
H like Fe @6.9 keV
Resolved by
ΔE~140 eV of CCD

Koyama et al, 2007: Publ. Astron. Soc. Japan, 59, 221
Koyama et al, 2007: Publ. Astron. Soc. Japan, 59, 245

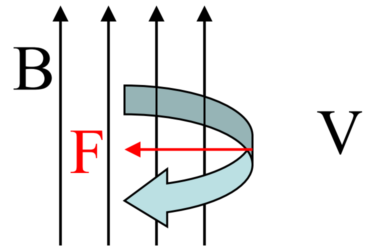
Thermal radiation from SNR



名古屋大学Ux研＠研究プロジェクト
http://www.u.phys.nagoya-u.ac.jp/r_e/r_e3_4.html

4. Synchrotron radiation

$$\frac{q}{c}\,\mathbf{v} \times \mathbf{B} = mr\omega^2 \qquad \boxed{= \frac{d}{dt}(\gamma m \mathbf{v})}$$



$$\omega = \frac{qB}{mc} \qquad \textbf{Cyclotron frequency} \qquad \boxed{= \frac{qB}{\gamma mc}}$$

$$< P > = \frac{2\, q^2 v_\perp{}^2 \omega^2}{3\, c^3}$$

$\gamma=(1-v^2/c^2)^{-1/2}$

$$\boxed{P = \frac{4}{3}\,\sigma_{Th}\, c\beta^2\gamma^2 U_B \qquad \text{(eq. 6. 7b)}}$$

dp/dt=

$U_B = B^2 / 8\pi$: Energy density of B

George B. Rybicki, Alan P. Lightman, 1979: Radiative Processes in Astrophysics, Wiley-VC, 169

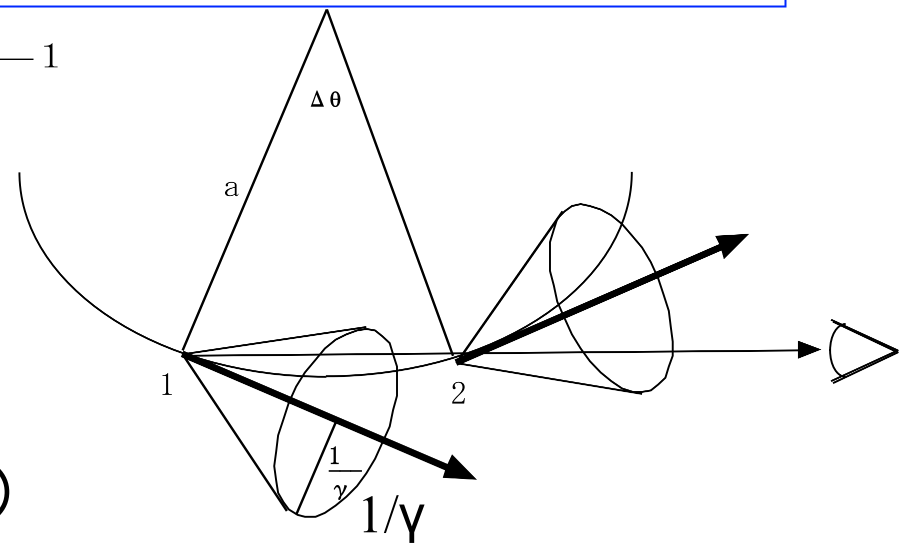
II-2: Emission mechanisms

4. Synchrotron radiation

Typical frequency $\Delta t = (\gamma^3 \omega_B \sin\alpha)^{-1}$

$$\omega_C = \frac{3}{2}\gamma^3 \omega_B \sin\alpha = \frac{3\gamma^2 qB \sin\alpha}{2mc}$$

$$P = \frac{2\, q^4 B^2 \gamma^2 \beta^2 \sin^2\alpha}{3m^2c^3}$$ (eq. 6. 17b)



If energy spectrum of electrons is power law,
$N(\gamma)\, d\gamma = C_2 \gamma^{-P}\, d\gamma$

$P_{tot}(\omega) \propto \omega^{-(p-1)/2} \int F(x)\, x^{(p-3)/2}\, dx$ (eq. 6. 22a)

$$s = \frac{p-1}{2}$$

George B. Rybicki, Alan P. Lightman, 1979:
Radiative Processes in Astrophysics, Wiley-VC, 173-174

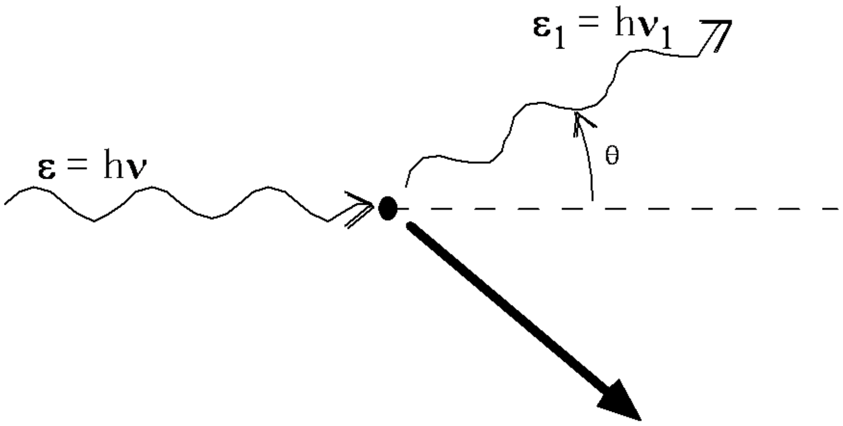
5. Compton scattering

$$\frac{d\sigma_T}{d\Omega} = \frac{1}{2} r_o^2 (1+\cos^2\theta)$$

$$\sigma_T = \frac{8\pi}{3} r_o^2$$

In relativistic cases,

$$\frac{\varepsilon}{\varepsilon_1} = 1 + \frac{\varepsilon}{mc^2}(1-\cos\theta)$$



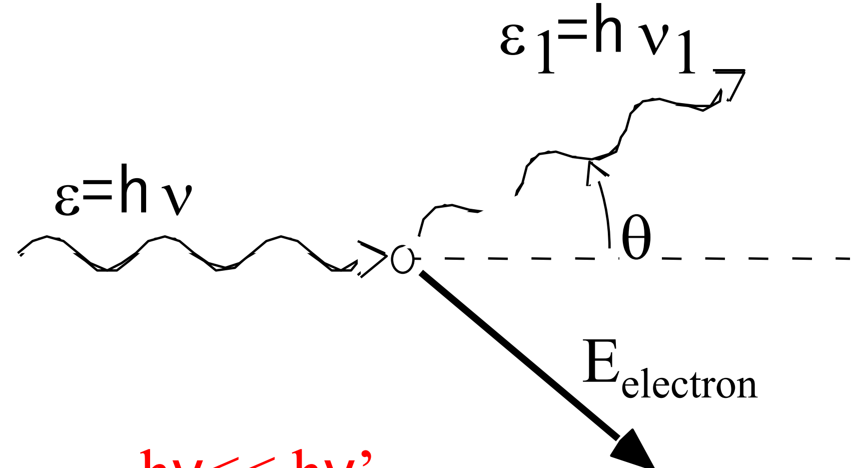
$$\frac{d\sigma}{d\Omega} = \frac{r_o^2\,\varepsilon_1^2}{2\,\varepsilon^2}\left(\frac{\varepsilon}{\varepsilon_1} + \frac{\varepsilon_1}{\varepsilon} - \sin^2\theta\right) \qquad \text{eq(7.4)}$$

George B. Rybicki, Alan P. Lightman, 1979: Radiative Processes in Astrophysics, Wiley-VC, 197

5. Compton scattering

Inverse

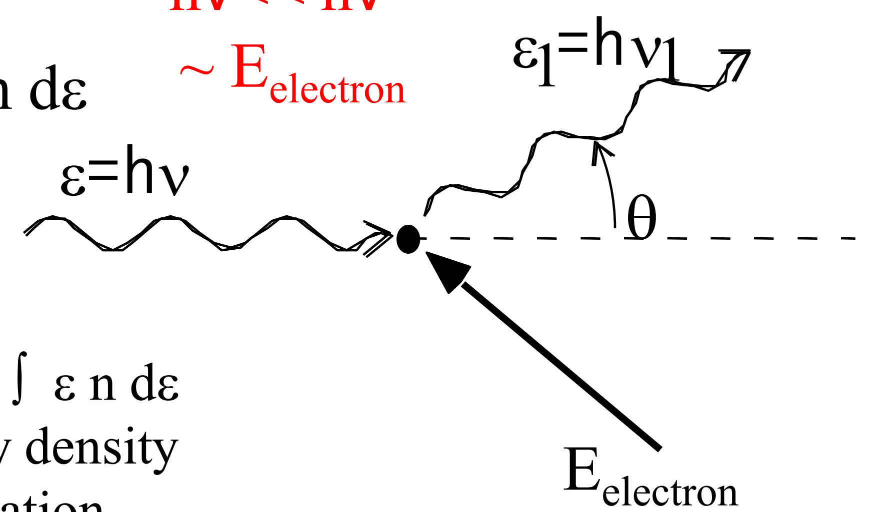
If E_{el} is large ($\gg m_e c2$), observer frame has to be referred to the incident photon



$$\varepsilon' = \varepsilon \gamma (1 - \beta \cos\theta)$$

hν<< hν'
~ $E_{electron}$

$$\frac{\square\square_1}{dt} = c\,\sigma_T \gamma^2 \int (1 - \beta\cos\theta)^2 \varepsilon n \, d\varepsilon$$



$$\boxed{P = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{PH}}$$

$U_{PH} = \int \varepsilon n \, d\varepsilon$
Energy density of radiation

Radiation Processes

Line emissions

Thermal Bremsstrahlung ------> Blackbody radiation

$$\frac{dW}{dV\,dt} = \left(\frac{2\pi kT}{3m}\right)^{1/2} \frac{2^5 \pi e^6}{3hmc^3} Z^2 n_e n_i g \qquad \text{(eq. 5.15a)}$$

Synchrotron

$$\boxed{P = \frac{4}{3} \sigma_{Th}\, c\beta^2\gamma^2 U_B \qquad \text{(eq. 6. 7b)}}$$

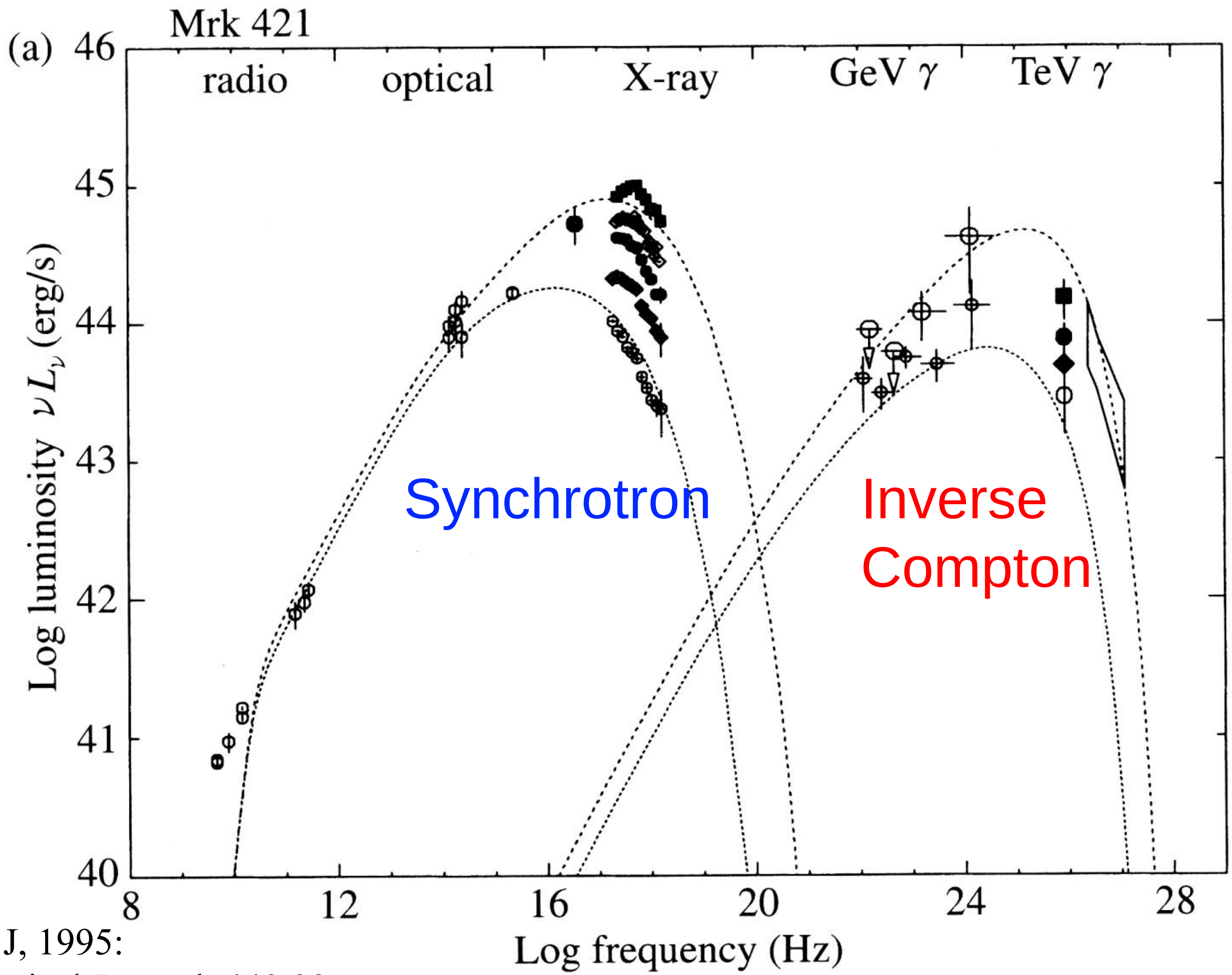
Inverse Compton

$$\boxed{P = \frac{4}{3} \sigma_T\, c\gamma^2\beta^2\, U_{PH}}$$

George B. Rybicki, Alan P. Lightman, 1979: Radiative Processes in Astrophysics, Wiley-VC, 161

II-2: Emission mechanisms of high energy photons

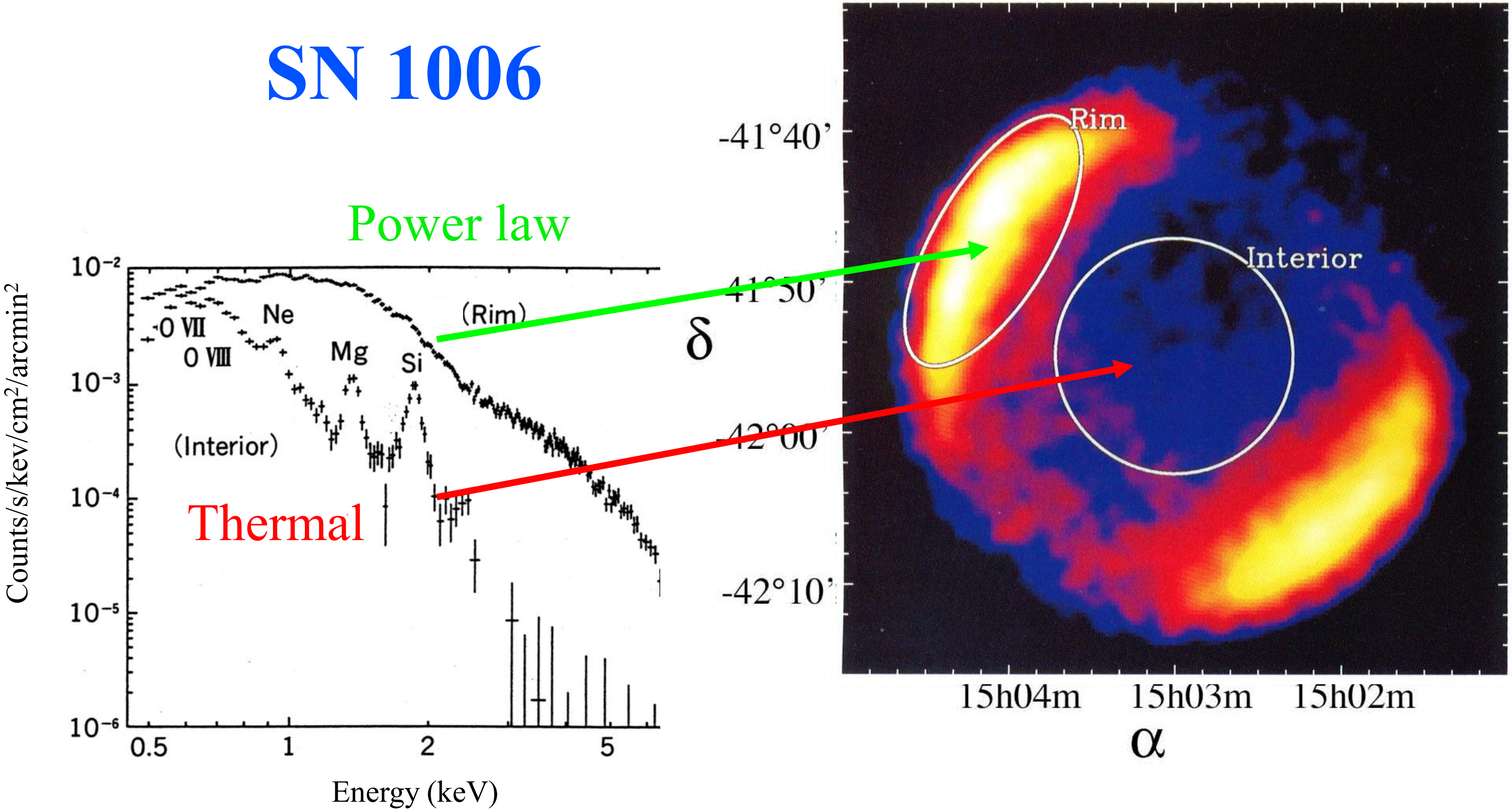
Synchrotron-self-Compton Model for a Blazer



Macomb, D, J, 1995:
The AstroPhysical Journal, 449,99

II-2: Emission mechanisms of high energy photons

Non-thermal component of SNR



I-3: Energy sources of high energy phenomena

Energy release of X-ray sources

Sun	$L_{opt} \sim 10^{33}$ erg/s	Nuclear fusion
	$L_X \sim 10^{27}$ erg/s	
SN	$E \sim 10^{51}$ erg	Gravitational Energy
AGN	$L \sim 10^{41\text{-}47}$ erg/sec	Gravitational Energy
Cluster	$E \sim 10^{60}$ erg	Dynamical+G Energy
γ burst	$E \sim 10^{52}$ erg/sec	Hypernovae?

1. Nuclear energy

SUN

Energy release of the Sun

--> Black body radiation

kT=6430° K、r = 600,000 km、σ= 5.67x10^{-5}

$L = 4\pi r^2 \sigma T^4 =$ **4.4×10^{33} erg/s**

$t = \underline{3600 \text{ s/h} \times 24 \text{ h/d} \times 365 \text{ d/y}} \times 46 \times 10^8 \text{ y}$

$= 1.45 \times 10^{17}$ sec

(3.15×10^7 sec/y)

$E = L \times t = 6 \times 10^{50}$ erg

1. Nuclear energy

SUN

Nuclear reactions

P-P chain (I) $p + p \rightarrow {}^2H + e^+ + \underline{\nu_e 0.16MeV}$

$^2H + p \rightarrow {}^3He + \gamma$ [6.7MeV/3H]

for $kT > 8\ 10^6 K$

$^3He + {}^3He \rightarrow {}^4He + 2p$ [**26.1MeV/4H**]

(II) $kT > 2\ 10^7 K$になると

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

$^7Be + p \rightarrow {}^8B + \gamma$

$^8B \rightarrow {}^8Be + e^+$ $\underline{\nu_e 7\ MeV}$ **Solar neutrino**

$^8Be \rightarrow 2\,{}^4He$

CNO cycle

He burning

C O burning---> Fe

2. Gravitational energy

Sun — 3.8×10^{48} erg

Supernova ↓

Neutron stars — $R = 10^{6}$ cm

$E = 2 \times 10^{53}$ erg → Neutrino

Neutrino → 1% → Mechanical E of Expanding shell

Neutrino → 99% → Escape

KAMIOKANDE

Blackholes — $1\ M_{Solar}$ — $R = 3 \times 10^{5}$ cm

$E = 7 \times 10^{53}$ erg

Escape velocity
$v_{es}^2 = 2GM/R$

At **Rg**, $v_{es} = c$

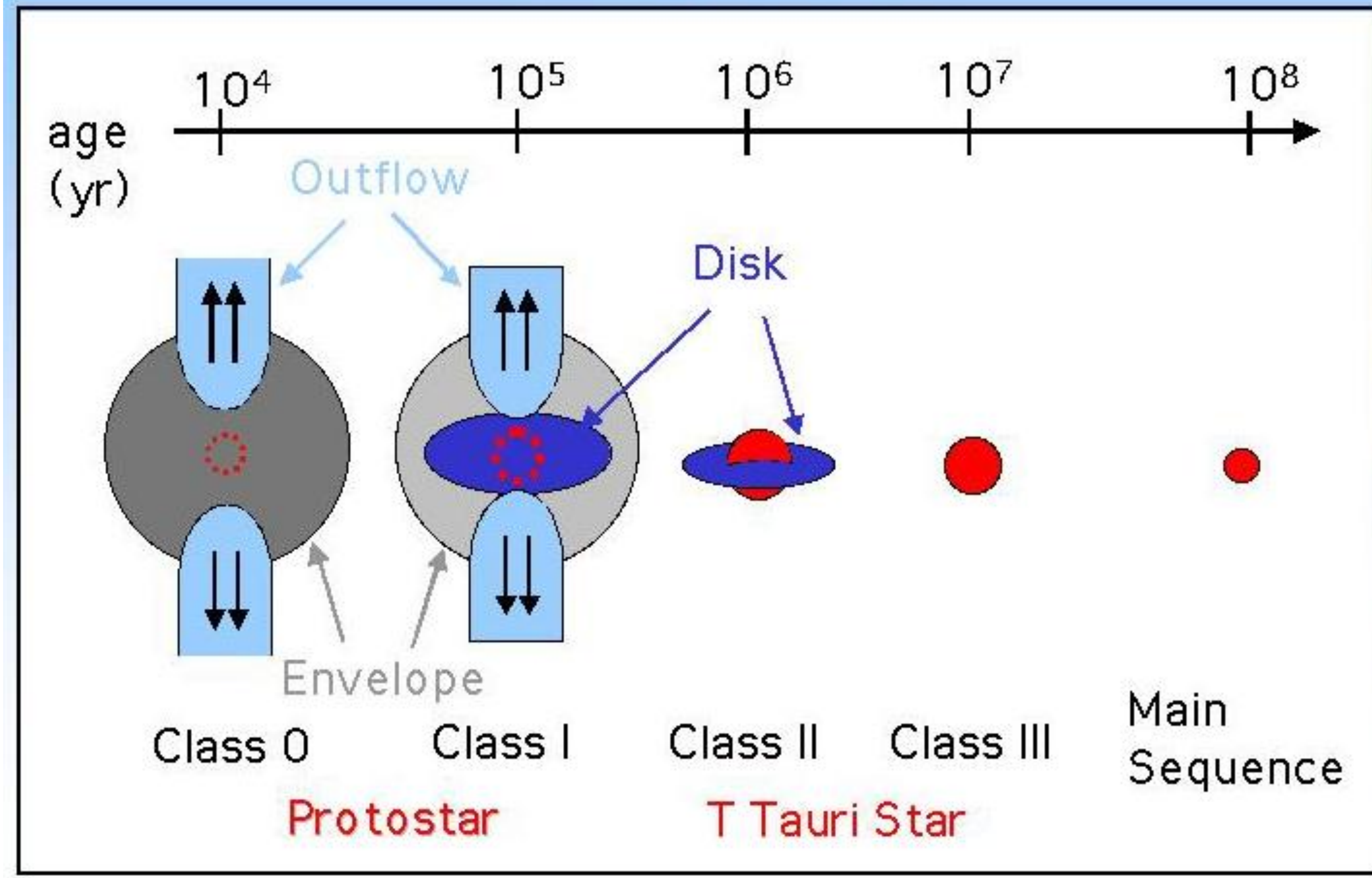
Then $Rg = 2GM/c^2$

$= 3\ (M/M_{solar})$ km

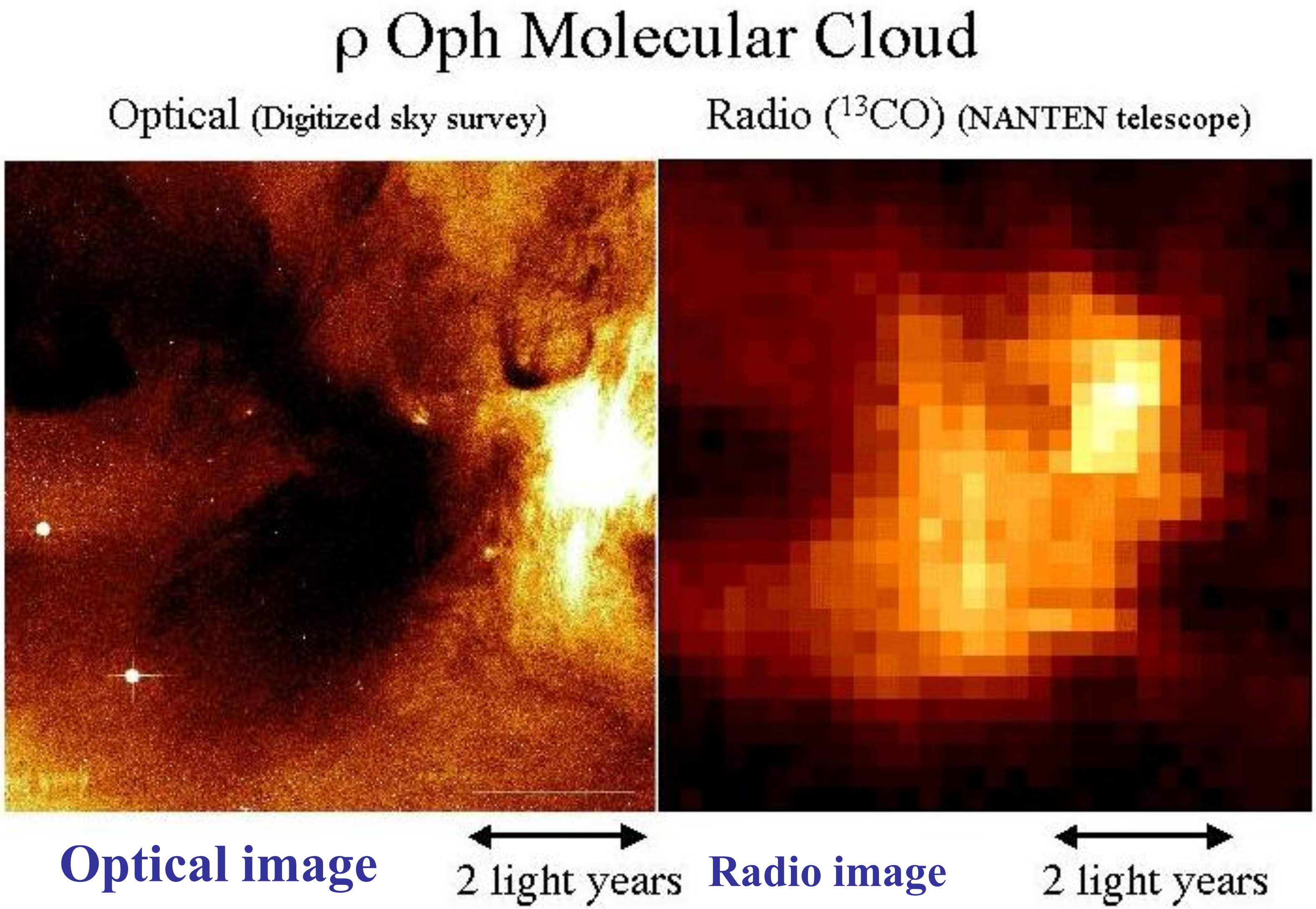
$E = GM^2/R$
$\sim Mc^2$

II. High energy phenomena
II-1 : Stellar X-ray emission

Evolution of a Star



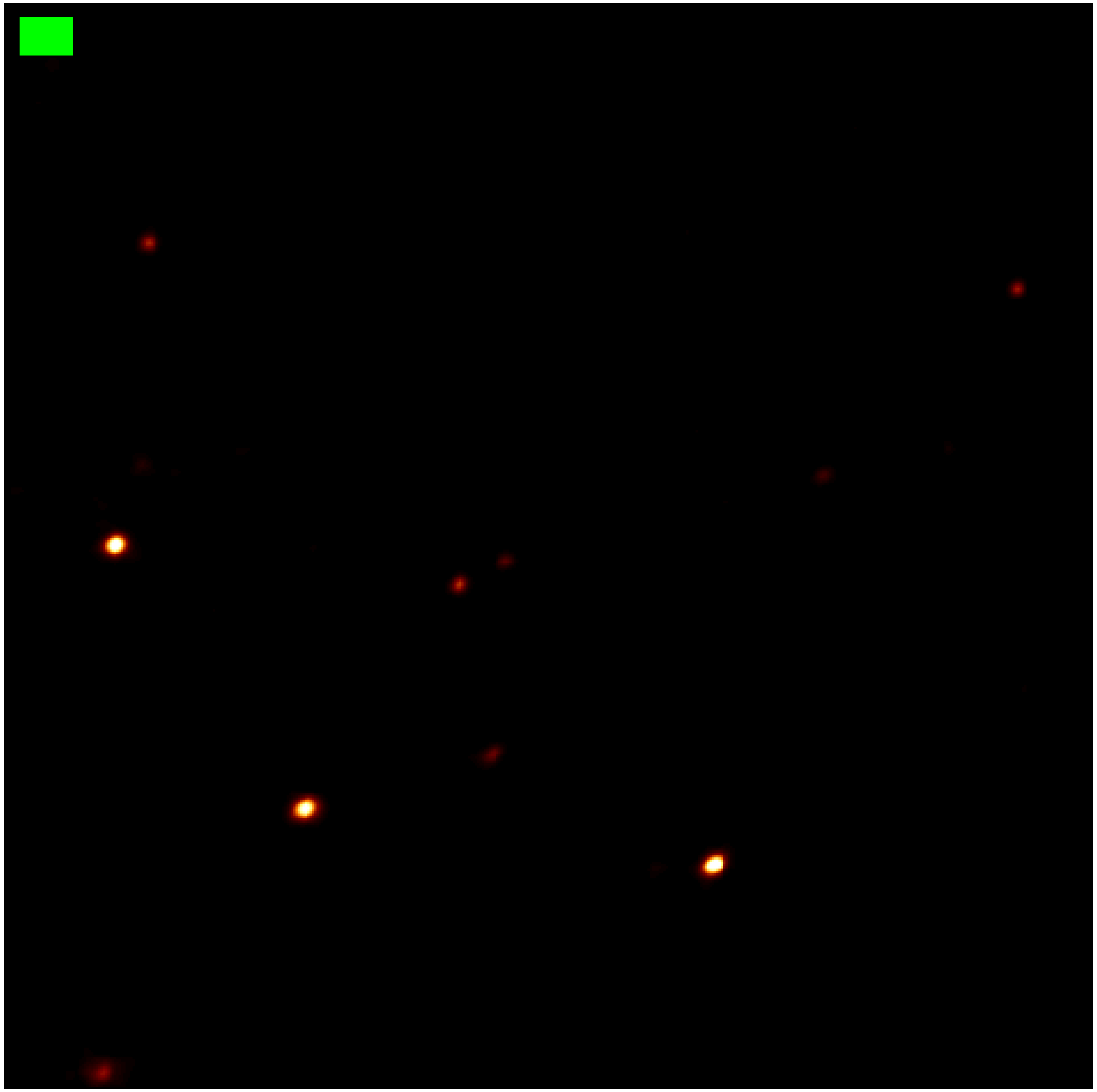
Star forming region



Optical image (Extinction)

Radio image (Molecular cloud

X-ray blinking of proto stars in SFR



(2) Solar X-rays

Main sequence stars

Core Temp. and Density --> Ignition of **Nuclear reaction**

Photo-sphere: T ~ 6000° K Blackbody

Corona: T ~ 10^{6-7} K --> several keV --> X-rays

Nuclear energy --> Convection/Rotation --> **B**

Solar magnetic field --> Extends into the atmosphere

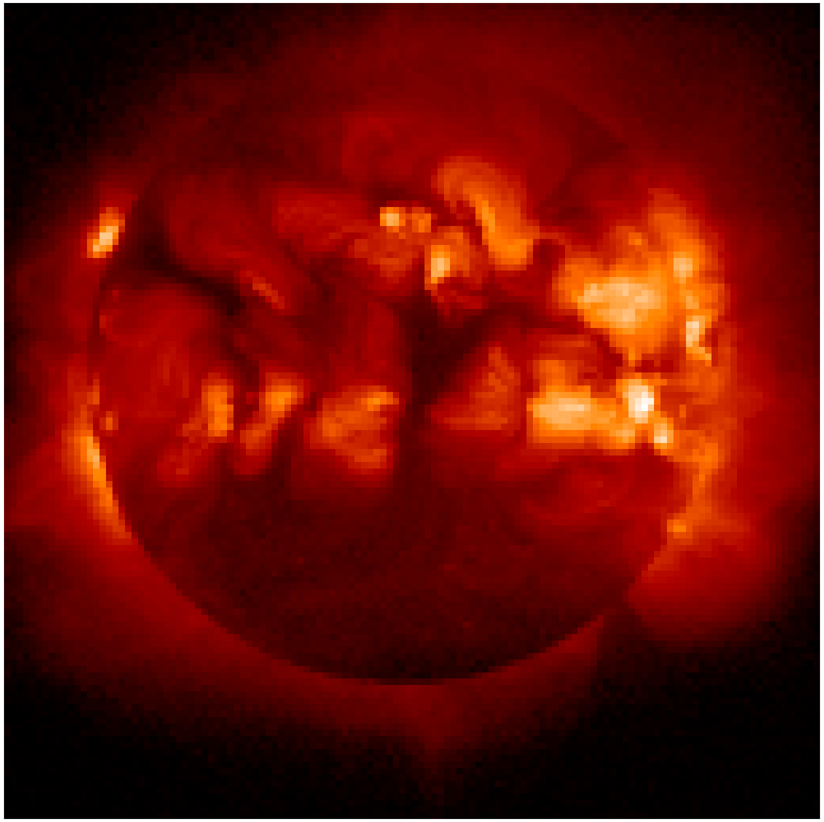
Reconnection --> **E** -->Acceleration of **e⁻**

Thermalization

Hard X-rays

Soft X-rays

Soft X-ray Movie of the Sun by Yohkoh



http://www.isas.jaxa.jp/home/solar/yohkoh/

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- ようこう
  http://www.isas.jaxa.jp/home/solar/yohkoh/