REYNOLDS
lecture 7/84

Radiative Processes in Astrophysics
Outline

I. Definitions: thermal + non, black body, Maxwellian; relations (Kirchoff's law). I_ν indep of dist, $\propto \frac{S_\nu}{\theta^2}$.

II. Single-particle radiation processes
- A. Involving bound states (QM)
- B. Free-particle (include IC; just upgrades, not really "new" photons)

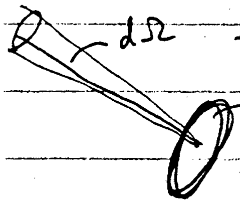
III. Detail on TB + SR from ensembles
- A. Brems.
- B. Synchrotron rad'n

Definitions

What do you need to know to describe radiation fully?

How much power? (en/time)? From how much sky? How big the detector? What frequency? What polarization?

All of these except pol. are part of



Specific Intensity.

$$I_\nu \, dt \, dA \, d\nu \, d\Omega = dE = \text{energy } \overbrace{\text{received}}^{\text{in time } dt} \text{ from } \text{~~unit~~ solid angle } d\Omega \text{ through area } dA \text{ in band } d\nu.$$

So units I_ν: erg s^{-1} cm^{-2} Hz^{-1} sr^{-1} (or W m^{-2} Hz^{-1} sr^{-1})

Let a source emit L_ν erg s^{-1} Hz^{-1}, - at dist. d, with radius R. ($d << R$,

What is I_ν?

$$dE(\text{em.}) = L_\nu \, dt \, d\nu \cancel{\left(\frac{1}{4\pi d^2}\right)} \left(\frac{dA}{4\pi d^2}\right)$$

$$dE(\text{rec.}) = I_\nu \, dt \, d\nu \, dA \left(\frac{\pi R^2}{d^2}\right)$$

So $$I_\nu = \frac{L_\nu}{\frac{\cancel{dA}}{\cancel{4\pi d^2}}\left(\frac{\pi R^2}{d^2}\right) 4\pi d^2} = \frac{L_\nu}{4\pi^2 R^2}$$ independent of d!

How can this be? What about inverse-square law?

Ans: As you get farther away, source subtends less Ω, $\propto \frac{1}{d^2}$.

What is your $d\Omega$? Beam. Can't look at less $\Delta\Omega$ at a time than this. (But can look at more.) So as long as $\Omega_{\text{source}} > \Delta\Omega$ (beam), measure const. intensity.

If $\Omega_{\text{source}} < \Omega_{\text{beam}}$, want another quantity:

Spectral Flux. $S_\nu \equiv \int I_\nu \, d\Omega$ over area of interest (e.g., a source

units = erg cm^{-2} s^{-1} Hz^{-1} (not sr^{-1} anymore)

So $d\Omega = \frac{\text{Area}}{d^2}$, $\underline{S_\nu \propto \frac{1}{d^2}}$ for a source. If subtends θ rad,
$\theta \ll 1$, $\Delta\Omega \sim \theta^2$;
$S_\nu \approx I_\nu \Delta\Omega$

I_ν : indep. of dist but refers to different fraction of source at different ~~freqs~~ dists. $\left(I_\nu = \frac{S_\nu}{\theta^2}\right)$

S_ν: $\propto \frac{1}{d^2}$ but ~~a~~ describes whole source $S_\nu \simeq I_\nu \theta^2$

Can define ~~total~~ flux (integrated flux) $\equiv \int S_\nu \, d\nu$ = en/area time ($\mathrm{W\,m^{-2}}$
$\mathrm{erg\,s^{-1}\,cm^{-2}}$)

Where does radiation come from?

Define emissivity. (How much power? In which direction? what freq.? How much volume?)

$$j_\nu \, dt \, dV \, d\nu \, d\Omega = dE \text{ (produced)}$$

so $[j_\nu] = \mathrm{erg\ s^{-1}\ cm^{-3}\ Hz^{-1}\ st^{-1}}$

$(= \mathrm{W\ m^{-3}\ Hz^{-1}\ st^{-1}})$

Sim. to I_ν but not quite; $[I_\nu] = [j_\nu] \times \text{length}$

Absorption? This depends on how much intensity already there. (no $I_\nu \Rightarrow$ no abs!) So define

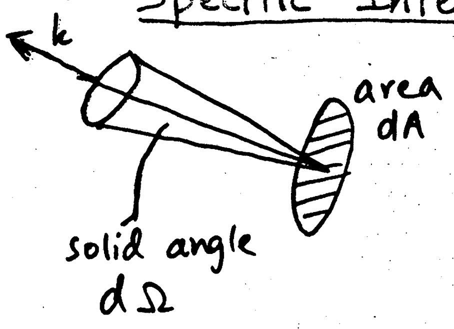
$$\kappa_\nu I_\nu = dE \text{ (absorbed) } \underline{\text{in}} \ dt \, dV \, d\nu \, d\Omega .$$

so $[\kappa_\nu] \times$ [illegible] $= \frac{1}{\text{length}}$ only. (all the other units in I_ν.)

Radiative Quantities: Definitions

Describe all properties of radiation except polarization with

Specific Intensity I_ν



Energy received from $d\Omega$ about some direction $\hat{k}$, through area $dA \perp \hat{k}$, in time $d\nu$, in frequency interval $d\nu$:

$$dE = I_\nu \, dt \, dA \, d\nu \, d\Omega$$

so I_ν = energy/(time, area, frequency, solid angle)

units: $\text{erg s}^{-1}\text{cm}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ (cgs)

or $\text{W m}^{-2}\text{Hz}^{-1}\text{sr}^{-1}$ (SI)

Emissivity j_ν

Energy emitted from volume dV in time dt, frequency interval $d\nu$, solid angle $d\Omega$:

$$dE \equiv j_\nu \, dt \, dV \, d\nu \, d\Omega$$

j_ν = energy/(time, <u>volume</u>, frequency, solid angle)

units: $\text{erg s}^{-1}\text{cm}^{-3}\text{Hz}^{-1}\text{sr}^{-1}$

$\text{W m}^{-3}\text{Hz}^{-1}\text{sr}^{-1}$

Absorption Coefficient κ_ν

$\underline{\kappa_\nu I_\nu}$ is energy <u>absorbed</u> in vol dV, time dt, freq. $d\nu$, solid angle $d\Omega$.

$$dE \equiv (\kappa_\nu I_\nu) \, dt \, dV \, d\nu \, d\Omega$$

so κ_ν has units of $\underline{\frac{1}{\text{length}}}$ (cm^{-1})

Up from Disorder.

1) Thermal Equilibrium.

All detailed information is lost, swallowed in 1-parameter fn

$B_\nu(T)$.

True for matter & radiation strongly coupled & in equil.

Particles: Maxwellian. Photons: $B_\nu(T)$.

Examples: Stars. (photospheres)

2) Thermal Particle Dist.

Collisions equilibrate particles among themselves, but photon-particle interactions not suff. to get particle-photon equil. (Commonly tr

Particles: Maxwellian. Photons: optically thin something: lines, brems., …

Examples: HII region radio em, stellar chromospheres, X-ray SNR

3) Nonthermal Particle Dist.

Some process produces non-Maxwellian particle dist, & not enou interaction to bring particles to Maxwellian.

Examples: Synchrotron rad, masers.

Particles: SR: Power-law $N \propto E^{-s}$ Photons SR continuum power-la

masers. Inverted pops. lines, but amplified

Radiation Processes

Refs: Rybicki & Lightman
[Pacholczyk]
Longair

Radiation: ≡
Production of photons

Continuum

Thermal

Bremsstrahlung (radio, IR, optical, X-ray)
Collective (eg plasma osc.) (radio)

Nonthermal

Synchrotron radiation (usually radio, rarely opt, X-ray)
Inverse - Compton (usually opt → X-ray → γ-ray)

Line

Recombination	(f-b) (el. trans)	(radio → X-ray)
Hyperfine ~~Molecular~~	(b-b) el. trans	radio
Molecular rot.	(b-b)	radio
vibr		radio → IR

Radiation Processes

2.

Detail: How do <u>individual</u> <u>particles</u> radiate energy?

Recall: a) Accelerated charges radiate!

b) $P = \frac{2}{3}\frac{e^2}{c^3} a^2$ (cgs)

Forms of accel:

a) QM: Discrete change in en. levels, or into (or out of) quantized level ~~to~~ from (to) continuum. <u>Non-classical</u>.

b) Free electrons:

a) <u>Collisions</u>. Deflected.

b) E-M fields. Electric (why not important?)

Magnetic: gyrate in field.

<u>a</u>: b-b, b-f, f-b. Lines or "edges". Not further discussed.

<u>b</u>: a) Bremsstrahlung: braking rad.

b) (Magn) <u>Synchrotron rad</u>. if extreme rel. (magnetobrems

Cyclotron rad. if NR.

Note: In principle, either brems or SR can be thermal or nonthermal depending on ensemble of particles thusly radiating.

<u>What</u> particles radiate?

Classically: $P \propto a^2$. For given F, $a \propto \frac{1}{m}$. <u>Lightest</u> $\Rightarrow \underline{\underline{e^-}}$.

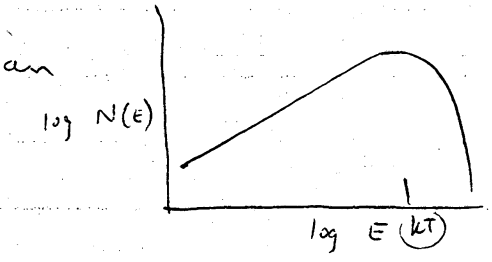
Brems: e^- & p^+ collide; F's equal; $P_{el} \sim \underline{\underline{4 \times 10^6}} \times P_{proton}$.

Radiation Processes

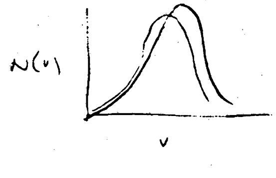
3.

What is "thermal"? - ~~Stemming~~ Having to do with a thermal distribution of particle energies.

Maxwellian



$$N(E) \propto E^{\frac{1}{2}} e^{-\frac{E}{kT}} T^{-\frac{1}{2}}$$



If $kT \gg m_e c^2$, can have relativistic Maxwellian.

$$N(E) \propto E^2 e^{-\frac{E}{kT}} T^{-3}$$

Very common distr., char. only by T. Get by colls ⇒ "thermaliz."

To lowest order: All particles have $E \sim kT$.

Examples:	Dense Mol. cloud	$T \sim 10^\circ$
	HI cloud	$T \sim 50^\circ$
	HII region	$T \sim 10^4$
	& Young SNR	$T \sim 10^7$

So: "Nonthermal" ⇒ coming from any other distr. N(E)!

In practice, only other commonly inferred N(E) is power law,

$N(E) \propto E^{-s}$. For electrons in radio sources, $s \sim 2$-3

cosmic rays: $s \sim 2.6$

Later we'll get to how this is inferred.

So usually nonthermal ⇒ synchrotron;

thermal ⇒ brems.

So restrict attention to Brems. + SR, from electrons.

R+L
pp 155 - 165

Brems: Almost always concerned with thermal (TB).
Ensemble of ionized ~~gas~~ atoms, els, thermal vel $\Rightarrow$ collisions, radiation.

[Note: $v^2 \propto T$ so higher $T \Rightarrow$ more ~~violent~~ frequent colls $\Rightarrow$ greater

Get emissivity j_ν in erg $\mathrm{cm^{-3}\,s^{-1}\,Hz^{-1}\,st^{-1}}$, by integrating over colls & over distr. of vels given by Maxwellian distribution.

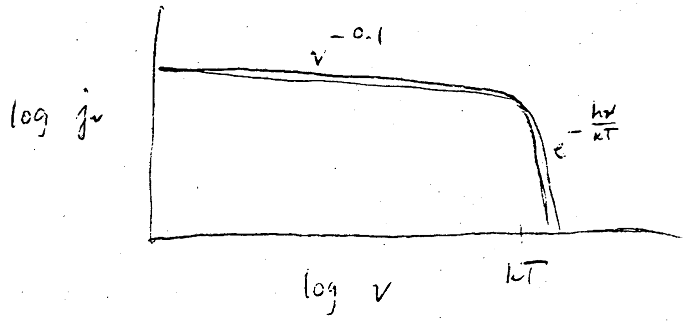
1 collision: High $v \Rightarrow$ brief $\Rightarrow$ smaller effect; power per Hz $\propto \frac{1}{v} \propto \frac{1}{\sqrt{T}}$.

Many collisions: $j_\nu \propto n_e^2$ (binary collisions)

$\propto T^{-\frac{1}{2}}$ as above

$\propto e^{-\frac{h\nu}{kT}}$ (run out of fast electrons; can't have $E(\text{photon}) = h\nu \gg kT$ often)

$$\text{So} \quad j_\nu \propto n_e^2\, T^{-\frac{1}{2}}\, e^{-\frac{h\nu}{kT}}\, g_{ff} \longleftarrow \text{"Gaunt factor"}$$



Roughly Constant.

So If absorption is small, emitted spectrum is

$$L_\nu = (\text{Vol})(4\pi j_\nu) \quad \text{erg s}^{-1}\,\text{Hz}^{-1}.$$ which has same ν-dep.

Total power: Int. over $\nu \Rightarrow P_{tot} \propto \underline{\underline{n_e^2\, T^{\frac{1}{2}}}}$ erg $\mathrm{s^{-1}}$.
($P_{tot} \sim (h\nu) L_\nu$)

Radiation Processes
5.

<u>Absorption</u>? $\frac{j_\nu}{\kappa_\nu} = B_\nu$ (Lockman notation: I_{BB})

so <u>radio</u>: $B_\nu \simeq \frac{2kT}{\lambda^2} \propto T\nu^2$.

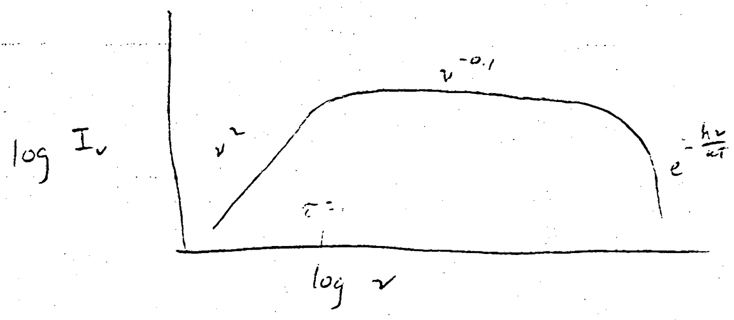
So since $j_\nu \propto \nu^{-0.1} T^{-\frac{1}{2}}_{\xi}$, $\kappa_\nu \propto \frac{j_\nu}{B_\nu} \propto \underline{\nu^{-2.1} T^{-3/2}}$

Can calculate τ of a cloud $\propto \underline{\nu^{-2.1} T^{-3/2} \ell \, n_e^2}$

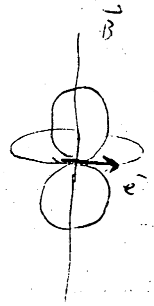
What if $\tau \gg 1$? (When? For <u>given</u> <u>cloud</u>, look to <u>low ν</u>.)

$\tau \gg 1$ <u>means</u> photons experience many absorptions - re-emissions
- <u>thermalized</u> $\Rightarrow$ BB!

So Low Freqs. ($\tau \gg 1$): $I_\nu \propto \nu^2$
High Freqs ($\tau \ll 1$) $I_\nu \simeq j_\nu \ell \propto \nu^{-0.1}$



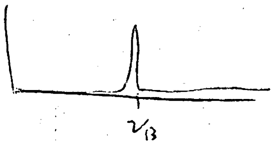
Synchrotron Radiation.



Cyclotron: Radn at ~~period~~ freq. of orbit, ang. dist. ∝ $\sin^2\theta$.

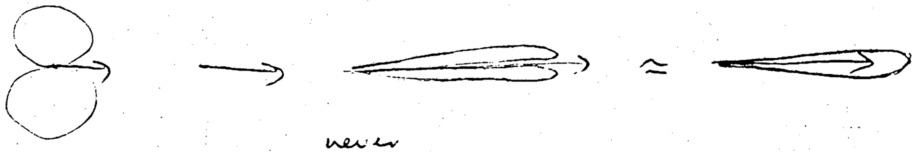
Freq. is $\nu_B \equiv \frac{eB}{2\pi mc}$.

So a <u>line</u>.



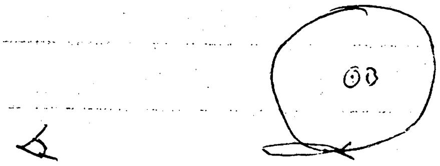
But if el. is relativistic, $E \gg m_e c^2$, 2 differences:

1) Beaming:



(~~[illegible]~~ unlike NR where ~~no~~ never radiation along $\vec a$)

So see electron only for brief part of orbit.



2) v is almost c so pulse is shorter than it would be if static.

Both effects ⇒ see electron for small fraction of orbital period, Δt.

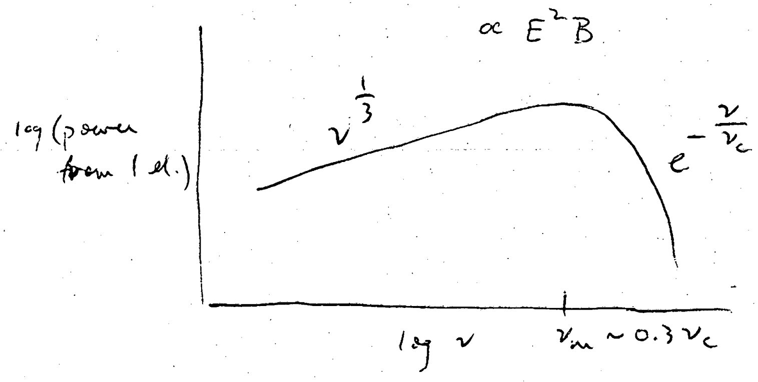
Fourier theory: Change in Δt ⇒ radiation up to $\nu \sim \frac{1}{\Delta t}$

So get much higher frequencies. Actually, discrete harmonics of orbital freq, but so close that essentially a continuum is produced.

Radiative Processes
7.

Result: $\nu_m \simeq \underline{\underline{\gamma^2 \nu_B}}$ $\quad \gamma \equiv \dfrac{E}{m_e c^2} \gg 1$ for this to work at all

$\propto E^2 B$



Numbers: Interstellar field

$B \sim 3\mu G \Rightarrow \nu_B = \underline{\underline{8.4 \text{ Hz}}}$!

But $\gamma = 10{,}000 \Rightarrow$ (observed cr) $\underline{840 \text{ MHz}}$.

Galactic SR background.

More extreme: Pulsar light cylinder; $B \sim 10^6 G \Rightarrow \nu_B \sim \underline{3 \times 10^{12}}$.

$\gamma \sim 1000 \Rightarrow \nu_m \sim 3 \times 10^{18}$ $\underline{\underline{\text{X-rays}}}$!

~~Ensemble~~ This radiation is <u>polarized</u> ⊥ to projection of $\vec{B}$

<u>Ensemble of electrons:</u>

When we look at SR sources (how do we know: $T_B \gg$ reason pol, not a thermal spectrum), see <u>power-laws</u>

$S_\nu \propto \nu^{-\alpha}$, $\quad \alpha \sim 0.3 - 1.5$ or so.

Infer power-law spectrum of <u>electrons</u>,

$N(E) = \underline{K} E^{-s}$ els cm^{-3} erg^{-1}.

SR theory $\Rightarrow$ $\underline{s = 2\alpha + 1}$ so Tycho's SNR has $\alpha = 0.6 \Rightarrow s = 2.2$

Very <u>different</u> from Maxwellian, all els have mean kT. If $s = 2$, total energy is spread equally over all electrons.

$j_\nu \propto \underline{K} B^{\alpha+1} \nu^{-\alpha}$

Radiative Processes
8.

Synchrotron Self-Absorption.

Can we say $\kappa_\nu = \frac{j_\nu}{B_\nu}$? <u>No</u> - <u>particles</u> do not have thermal distr.! But certainly
$\frac{j_\nu}{\kappa_\nu} \leq B_\nu(\text{"}T\text{"})$

At each ν, eff. "kT" is energy of electrons producing radiation at that ν.

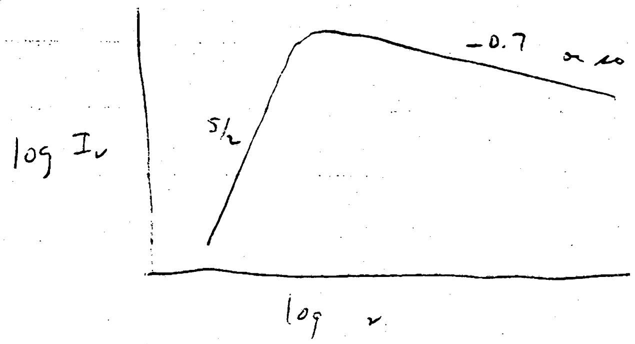
Since $\nu_m \propto E^2 B$, $\quad \text{"}T\text{"}(\nu) \simeq E(\nu) \propto \nu^{+\frac{1}{2}}$.

So $\kappa_\nu \propto j_\nu \frac{1}{B_\nu(\text{"}T\text{"})} \propto \nu^{-\alpha} \left[\text{"}T\text{"}\,\nu^2\right]^{-1} \propto \underline{\underline{\nu^{-\alpha + -5/2}}}$

$(\kappa_\nu \propto \underline{K}\, B^{\alpha+3/2}\, \nu^{-\alpha-5/2})$

Note: If ν low enough, $\tau = \int \kappa_\nu\, dl > 1$ so

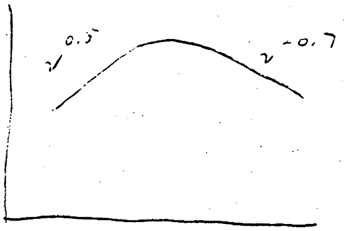
$I_\nu = \frac{j_\nu}{\kappa_\nu} \propto \nu^{-\alpha+\alpha+5/2} = \underline{\underline{\nu^{5/2}}}$ independent of α
(why not $\propto \nu^2$?)



<u>Never</u> see this.

Why?

a) Inhomogeneous sources
b) Superpos of different sources
c) Other effects as ν decreases



more typical.

Can relate ν_B, S_ν (thin), θ to infer $\underline{B}$. (but dangerous!)