Radiative Processes

All e.m. radiation arises from transition between levels with difference in electric or magnetic moment

- Levels could be discrete or in continuum
- Between each pair of levels emission and absorption
- Transitions dipole / higher multipole

Transition probability \[ \propto | \langle f | \exp(ik.r) \hat{l} \cdot \hat{\nabla} | i \rangle |^2 \]

\[ \text{[ dipole approximation } \exp(ik.r) = 1 \text{ ]} \]

\[ g_2 B_{21} = g_1 B_{12} \quad ; \quad A_{21} = 2\hbar \nu^3 B_{21}/c^2 \]
Continuum Radiation

\[ P = \frac{2}{3c^3} (\ddot{a})^2 = \frac{2e^2}{3c^3} a^2 \]

Classically any accelerated charge would radiate

Different physical situations involve different mechanisms of acceleration
- Radiation mechanism classified according to source of acceleration
- Radiation reaction slows the charge

Bremsstrahlung

Synchrotron Radiation
Inverse Compton Scattering

Related processes: Compton Scattering, Thomson Scattering

Scattering processes
Non-resonant / resonant
Spectrum

Electric field received by the observer is time dependent

Fourier transform of the electric field yields the spectrum

Net observed spectrum is a sum over all emitting particles
Polarization

\[ \vec{E} \propto \hat{n} \times [(\hat{n} - \vec{\beta}) \times \dot{\vec{\beta}}] \]

At a single particle level, over short times, radiation is always polarized.

For slowly moving particle (or \( \vec{\beta} \) nearly \( \parallel \) to \( \hat{n} \)) polarization is \( \parallel \) to the projected instantaneous acceleration.

Net observed polarization involves average over the particle’s trajectory, and over the distribution of emitting particles.
Radiation Pattern

Motion introduces aberration and relativistic beaming
Cyclotron Radiation Pattern

*circular motion*
Synchrotron Radiation

\[ \tau = \frac{2\pi}{\omega_H} \]

\[ \Delta t \sim \frac{mc}{eH_\perp} \left( \frac{mc^2}{E} \right)^2 \]
Synchrotron radiation pattern

single emitter
Synchrotron spectrum from single emitter

\[ F(x) = x \int K_{5/3}(\eta) \, d\eta \]

\[ x = \frac{\omega}{\omega_c} \]

\[ \omega_c = \gamma^3 \omega_H \sin \alpha \propto E^2 \]
Radio image of the active galaxy Cygnus A
- Example of a powerful synchrotron source
Curvature Radiation

*Relativistic Charged Particles moving along curved field lines*

- Shares most properties of Synchrotron Radiation
  (replace Larmor radius by the radius of curvature of field lines)

- Polarization \(\parallel\) to the projected field lines
  (Synchrotron: polarization perp. to projected B)
Inverse Compton Scattering

Scattering processes

Non-resonant / resonant

Related processes: Compton Scattering, Thomson Scattering
Thomson scattering geometry

\[
\text{Pol.} \quad \frac{1 - \cos^2 \theta}{1 + \cos^2 \theta}
\]

"radial" component of incident electric field

"radial" component of electron motion

"radial" component of scattered electric field

Scattering Volume

Observer

Thomson scattering geometry
Scattering cross section

**Thomson**

\[ \sigma_T = \frac{8\pi}{3} r_0^2 = \frac{8\pi}{3} \left( \frac{e^2}{mc^2} \right)^2 \]

**Compton**

\[ \sigma \approx \sigma_T \left( 1 - 2x + \frac{26x^2}{5} + \cdots \right), \quad x \equiv \frac{\nu}{mc^2} \ll 1 \]

\[ \sigma = \frac{3}{8} \sigma_T x^{-1} \left( \ln 2x + \frac{1}{2} \right), \quad x \gg 1 \]
Synchrotron Self Compton

Synchrotron power \[ \frac{4}{3} \sigma_T c \beta^2 \gamma^2 U_B \]

Compton power \[ \frac{4}{3} \sigma_T c \beta^2 \gamma^2 U_{ph} \]

\[ L_{\text{comp}} \propto L_{\text{sy}} : \text{Compton Catastrophe : Brightness Temperature limit} \sim 10^{12} \text{ K} \]
Bulk Comptonization / Compton Drag

Strong radiation beams collimated within $1/\Gamma_{\text{bulk}}$ can be produced by Inverse Compton Scattering by relativistic bulk flow of charged particles.

Due to aberration effects, can generate very high polarization

\[ P(\theta') = \frac{\theta'}{\pi} \]

Lazzati et al. 2004
Spectra

Radiation received from a source is the sum of emission from a large population of particles.

Energy distribution of the particles shape the spectra

Thermal distribution
*Maxwell-Boltzmann*

Non-thermal distribution
*Non-Maxwellian, e.g. power-law*
What is emitted is not what we see

Radiation is modified during propagation through matter

Radiative transfer

\[ \frac{dI_v}{ds} = -\alpha_v I_v + j_v \]

\[ \frac{dI_v}{d\tau_v} = -I_v + S_v \]

\( S_v \) for a thermal source is the Planck function \( B_v \)

\[ B_v = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1} \]
At large optical depth a thermal source will emit blackbody intensity. Emission will be received from a *photosphere*.

Optical depth is frequency-dependent. A source could be optically thick at some frequencies, optically thin at others.
X-ray emission (pink) by hot gas in Bullet Cluster
- *Primarily Thermal Bremsstrahlung emission*
Strong polarization in ordered field: \[ \frac{p + 1}{p + \frac{7}{3}} \] (up to 70%)
Jitter radiation can steepen the low-frequency cutoff:
- Low energy particles have longer duration of E-field pulse per orbit
- More affected by pitch angle scattering before pulse completion

(Medvedev 2000)
GRB Afterglow spectral evolution

Synchrotron
Fireball model
3C 279
Blazar

Compton

Synchrotron (seed)
What is emitted is not what we see
Radiation is modified during propagation through matter

Plasma effects

**Dispersion**

$$\frac{v_{\text{ph}}}{c} = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{-1/2}$$

**In magnetic field,**
**Faraday Rotation**

$$\left(\frac{v_{\text{ph}}}{c}\right)_{R,L} = \left(1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_B)}\right)^{-1/2}$$
Dust Extinction, Polarization

Unpolarized star radiation (optical)

Dust grain

Transmitted (optical)

IR dust radiation

Observer

Galactic Extinction curve
Absorption by the Earth’s Atmosphere

- Gamma rays
- Ultraviolet
- Visible light
- Infrared
- Radio waves

Altitude (kilometers)

Wavelength (angstroms)

Wavelength (centimeters)

Ballons are enough
Need rockets or spacecraft
Infrared windows
Accessible from the ground

© 2007 Thomson Higher Education
Nuclear / particle processes

*Change in binding energy → photon emission*

- Radioactivity (e.g. $\text{Al}^{26}$)

- Decay of heavy mesons (e.g. $\Pi^0 \rightarrow 2\gamma$)
  generated in nuclear scattering ($p + p \rightarrow \Pi^0$)

- Fusion

- Pair Annihilation
Diffuse gamma-ray emission from gal. plane

\[ \text{CR} + \text{gas} \rightarrow \Pi^0 \rightarrow 2\gamma \]
Pulsars
Pulsars

Non-accreting magnetized neutron stars - radiating via magnetospheric processes

Main presence at radio wavelengths (~2000)

A few dozen at higher energies.

Fermi single-handedly increased the number of gamma-ray pulsars from half a dozen to > 50. (Abdo et al 2009)

Surface Magnetic field $\sim 10^8 - 10^{13}$ G
(Cyclotron fundamental $\sim 1$eV - 100 keV)

How do we know the field strength?
- Rotation-powered pulsars: spindown torque
- Accreting X-ray pulsars: cyclotron features
Pulsar emission is a magnetospheric phenomenon
Crab Nebula
Vacuum Dipole Model

Spinning magnet generates magnetic dipole radiation

Radiated power \( = \frac{2}{3c^3} (\ddot{m})^2 = \frac{2}{3c^3} B^2 R^6 \Omega^4 \sin^2 \alpha \)

\[ = - I \Omega \ddot{\Omega} \quad \text{(Rate of loss of rotational energy)} \]

Yields \( B^2 \propto P \dot{P} \)

Measurement of spindown rate helps estimate \( B \)

\[ B_{12} = \sqrt{P_s \dot{P}_{-15}} \]

Age: \( \sim \frac{P}{\dot{P}} \quad \text{young objects often found in SNRs} \)
Coloured Dots are gamma-ray pulsars

Pulsar P-Pdot diagram

(Abdo et al 2009)
Spin period-Magnetic field distribution of observed Pulsars
Spin period-Magnetic field distribution of observed Pulsars

![Spin period-Magnetic field distribution of observed Pulsars](image)

- Log B (G) vs Log P (s)
- Graveyard
- Death line
The Pulsar Magnetosphere
Basic concepts: Goldreich & Julian 1969

- A vacuum exterior would have potential drop exceeding $10^{15}$ V

- Space charge must exist, $\mathbf{E} \cdot \mathbf{B} = 0$

- Co-rotating magnetosphere can be maintained up to the light cylinder, $\rho \approx -\Omega \mathbf{B}/2\pi c$

- With pair production, no. density of charged particles may far exceed $\rho$

- $\rho$ passes through 0 and changes sign in the magnetosphere

Plasma on open field lines cannot co-rotate. Current flows out along these lines, creates toroidal mag. field which provides the dipole spin-down torque.

A charge-starved gap is likely on the null $\rho$ surface at the boundary of the closed magnetosphere: The Outer Gap (Cheng et al. 86, Romani 94)
Force-free magnetosphere
(Spitkovsky 2006)

\[ \rho \mathbf{E} + (\mathbf{j} \times \mathbf{B}) / c = 0 \]
everywhere

*poor approximation near LC, current sheets*
Radio Pulsar emission phenomenology

- Sharp pulses, low duty cycle: strong beaming
- High Brightness Temp ($\sim 10^{20}$ K): coherent emission [Radio only]
- Frequency-dependent pulse width: radius-to-frequency mapping
- Strong linear polarization with S-pattern
  position-angle sweep: curvature radiation, rotating vector model
- Strong pulse-to-pulse variation but stable average profile:
  stochastic phenomena within a geometric envelope
- Drifting subpulses: rotating carousel of sparks, $E \times B$ drift

Complications:
Cone-core dichotomy, Orthogonal polarization modes, Multiple comp.,
Mode changes, Nulling, non-RVM pol sweep, circular pol......
Pulse energy vs Single-pulse sequence

Pulse Numbers vs Longitude (deg.)

5000

140, 160, 180, 200

Deshpande & Rankin 99
Outer gap modelling of gamma ray pulsation: (Romani et al 1992.....)
Placing an “Annular Gap” at Current Sheets in FF magnetosphere solution
(Bai and Spitkovsky 2009)
Pulse modelling slot-gap vs outer gap

(Romani & Watters 2010)

Vela Pulsar Fermi obs (black) and model (red)
Supernova Remnants

- Sites of supernova explosions
- Ejected material interacts with surrounding matter
- Shock heating of swept up gas and ejecta: X-ray emission continuum and lines characteristic of ejected species
- Shock acceleration of relativistic particles (electrons and protons)
- Synchrotron emission from electrons: Radio - X-rays
- Inverse Compton and Bremsstrahlung: X - γ
- γ-rays also produced by interactions of relativistic protons with local gas
  * secondary pairs
  * pion production and decay
Thermodynamic variables across a shock

Conservation conditions:

mass \[ \rho_2 \nu_2 = \rho_1 \nu_1 \]
momentum \[ P_2 + \rho_2 \nu_2^2 = P_1 + \rho_1 \nu_1^2 \]
energy \[ \nu_2(u_2 + P_2 + \rho_2 \nu_2^2/2) = \nu_1(u_1 + P_1 + \rho_1 \nu_1^2/2) \]

For a strong shock \( \nu_2 = \nu_1/4; \quad \rho_2 = 4\rho_1 \)
In a relativistic shock \( \nu_2 = 4\Gamma_{\text{shock}} \nu_1 \)
Supernova Remnants: Dynamical Phases

**Early Coasting Phase** \((t < \text{a few hundred years})\)
- small amount of mass sweep-up; constant expansion speed: \(R \propto t\)

**Adiabatic Sedov Phase** \((\text{a few hundred years} < t < \text{several thousand years})\)
- swept up mass causes deceleration; constant total energy: \(R \propto t^{2/5}\)

**Radiative Phase** \((t > \text{a few thousand years})\)
- radiative energy loss significant; expansion slows rapidly: \(R \propto t^{1/4}\)

**Stall** \((t > \text{a few hundred thousand years})\)
- expansion speed reaches interstellar sound speed; SNR dissipates
Magnetic Field is amplified behind the shock

- Swept up matter $\sim 4$ times denser; frozen-in field increases by this factor

- Contact discontinuity prone to Rayleigh-Taylor instability: drives turbulence and hence turbulent dynamo (Gull 1975)

- In very high speed (relativistic) shocks two-stream Weibel instability can efficiently generate magnetic field (Medvedev & Loeb 99)
Diffusive Shock Acceleration

Magnetic scattering of fast particles on both sides of shock
- Multiple crossings; energy gain in each cycle of crossing
- Finite escape probability in each crossing

\[
\langle \frac{\Delta E}{E} \rangle_{\text{cyc}} = \eta
\]

\[
E_n = E_0(1 + \eta)^n ; \quad N_n = N_0(1 - P_{\text{esc}})^n
\]

\[
\frac{N}{N_0}(> E) = \left( \frac{E}{E_0} \right)^{-x}, \quad x = -\frac{\ln(1 - P_{\text{esc}})}{\ln(1 + \eta)}
\]

\[
N(E)dE = KE^{-p}dE, \quad p = 1 + x
\]

Max. energy decided by confinement: $R_L >$ acceleration zone escape. Radiative losses can also limit the energy acquired.

Any acceleration process in which
- Relative energy gain $\propto$ time $[dE/E \propto dt]$
- Escape prob. per unit time $\sim$ constant $[-dN/N \propto dt]$

Will lead to a power-law energy distribution

SN shocks would accelerate all species of charged particles $\Rightarrow$ Cosmic Rays
Veil Nebula, an old supernova remnant in Cygnus

Optical (Hα)
Multiwavelength view of the remnant of Tycho Brahe’s supernova

Optical is faint, suffers from dust extinction

Bright radio non-thermal synchrotron emission

X-rays primarily from thermal emission by hot shocked gas
Most of this is thermal emission from reverse-shocked ejecta.
Cas A heavy element map in reverse-shocked ejecta
Cosmic Ray Production in Supernova Remnants

Fermi acceleration in shocks

ASCA observations of the supernova remnant SN 1006 have revealed the first strong observational evidence for the production of cosmic rays in the shock wave of a supernova remnant. These results come from the detection of non-thermal synchrotron radiation from two oppositely located regions in the rapidly expanding supernova remnant. The remainder of the supernova remnant, in contrast, produces thermal X-ray emission showing Oxygen, Neon, Magnesium, Silicon, Sulfur, and Iron line emission.

VLA Radio image of Cas A
Cas A from CXO

Blue rim is non-thermal emission
W44 imaged by Fermi LAT

Green contours: IR image

(Abdo et al 2010)
Evolution of non-thermal emission in supernova remnants

(Fang & Zhang 2007)