Astro 501: Radiative Processes
Lecture 22
March 8, 2013

Announcements:
- **Problem Set 6** due today 5pm
- **Problem Set 7** out this weekend, due next Friday
- Midterm Exam: bad grading elves! bad!

Last time: synchrotron

Today: Compton scattering

# Erratum: Carbon-14

radioactive isotope $^{14}$C, $t_{1/2} = 5730$ yr
- used in radiocarbon dating
- has its origin in cosmic rays

how? cosmic-ray ions hit Earth's atmosphere
collide with nuclei in air $\rightarrow$ $^{14}$C is part of debris
"rains out," incorporated into bio matter

in class I claimed: $p + {}^{14}\mathrm{N} \rightarrow n + {}^{14}\mathrm{C}$
in real time, sharp-eyed students saw this is *wrong!*
*Q: why?*

in fact: "radiocarbon" $^{14}$C is produced several ways
but the dominant channel is: $n + {}^{14}\mathrm{N} \rightarrow p + {}^{14}\mathrm{C}$
*Q: what questions does this raise?*

`www: neutron monitors`

# Astrophysical Context: Blazars

we met radio galaxies in the context of synchrotron radiation
but there are many beasts in the active galaxy zoo

## Blazars

- seen as luminous nuclear nuclear region
  at center of giant elliptical galaxies
  `www: optical blazar images (`$R$`-band)`
- but *do not* show the elongated jets seen in radio galaxies
- flux shows rapid and large-amplitude time variability
- subclasses: BL Lacertae objects–weak radio emission
  optically violent variables (OVV)–strong radio emission
- demographics: many fewer blazars than other AGN
  e.g., Seyfert galaxies
  `www: AGN demographics plot (INTEGRAL)`
- blazar emission spans radio to TeV gamma rays

*Q: what does this suggest about the nature of blazars?*

# Blazars: Staring Down the Jet

*AGN "Unification Model"* `www: unification cartoon`
idea: all active galaxies have similar physical conditions

- a supermassive black hole (SMBH)
  possibly actively accreting matter
- a surrounding accretion disk, and dusty torus
- a relativistic jet, if SMBH is actively accreting

in unification picture: *blazar = jet pointing directly at us!*
"looking down the barrel of the gun"
emission from small region of jet "tip" $\rightarrow$ highly variable

blazar spectra `www: example`
over full EM range, two large features

- power-law rise from radio, peaks near optical
- falls to X-rays, then peak and power-law fall at gamma-ray

*Q: what could be going on?*

# Blazar Spectra

Power-law rise from radio to ∼optical

- nonthermal
- similarity with radio galaxies suggests *synchrotron origin* from relativistic electrons in jet

Peak and power-law fall in gamma rays

- in non-flare ("quiescent") state, gamm-ray energy content similar to synchrotron
- suggests similar origin
  → perhaps a *reprocessing* of the synchrotron photos
- reprocessed how? *by the relativistic electrons themselves!*

Thus: we want to understand how relativistic electrons interact with photons *Q: the name for which is...?*



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Note: origin of blazar high-energy emission still debated!

# Compton Scattering

# Thomson Scattering

We already discussed the scattering of light by electrons in the context of *Thomson scattering*

Thomson highlights:

energies of incident photon $\epsilon$ and scattered photon $\epsilon_1$ related by

$$\epsilon = \epsilon_1 \quad (1)$$

differential cross section, with $\hat{k} \cdot \hat{k}_1 = \cos\theta$

$$\frac{d\sigma_{\rm T}}{d\Omega} = \frac{1}{2} r_0^2 \left(1 + \cos^2\theta\right) \quad (2)$$

total cross section, with $r_0 = e^2/m_e c^2$

$$\sigma_{\rm T} = \frac{8\pi}{3} r_0^2 \quad (3)$$



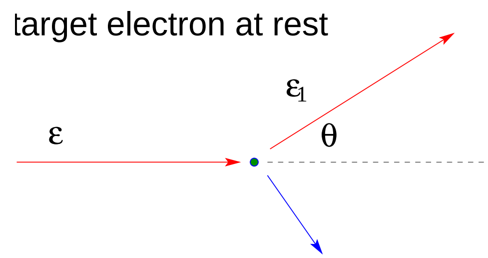
*Q: what assumptions went into this? When will they fail?*

# Enter the Quantum: Compton Scattering

Thomson scattering derived for classical EM wave
$\nu = \nu_1$ classically
carrying this to photon picture: $h\nu = h\nu_1$
$\rightarrow$ coherent or elastic scattering

but really: photon quanta carry momentum and energy
$\rightarrow$ and electron will *recoil* and carry away energy
$\rightarrow$ expect scattered photon to have less energy,
and to move in a different direction

Compton: treat light as massless particle




for photon incident on electron *at rest*
conservation of energy and momentum implies

$$\epsilon_1 = \frac{\epsilon}{1 + (\epsilon/m_e c^2)(1 - \cos\theta)} \quad (4)$$

scattered photon energy is lower, and direction different

so the wavelength shifts by

$$\lambda_1 - \lambda = \lambda_C (1 - \cos\theta) \quad (5)$$

where the electron *Compton wavelength* $\lambda_C = h/m_e c = 0.02426$ Å

*Q: what energy does a photon with* $\lambda_C$ *have?*
*Q: What region of the spectrum is this?*



*Q: when is the wavelength shift important? negligible?*

# Cross Section for Compton Scattering

Compton wavelength shift is $\Delta\lambda \sim \lambda_{\rm C}$

- *small* if $\lambda \gg \lambda_{\rm C}$ i.e., $h\nu \ll m_e c^2$
  i.e., radio through soft X-rays
- *large* if $h\nu \gg m_e c^2$: hard X-rays, gamma rays

differential cross section: **Klein-Nishina** formula

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\,\frac{\epsilon_1^2}{\epsilon^2}\,\left(\frac{\epsilon}{\epsilon_1} + \frac{\epsilon_1}{\epsilon} - \sin^2\theta\right) \tag{6}$$

- classical Thomson expression recovered when $\epsilon \sim \epsilon_1$
- main effect: *smaller* cross section at high energy
- total cross section, with $x = h\nu/m_e c^2$

$$\sigma \to \begin{cases} \sigma_{\rm T}\ (1 - 2x + \cdots) & x \ll 1 \\ 3\sigma_{\rm T}/8\ x^{-1}(\ln 2x + \cdots) & x \gg 1 \end{cases} \tag{7}$$

recall: to understand blazars, we are interested in

- high-energy electrons interacting with ambient photons

*Q: why* can't *we just use the Compton scattering formulae?*

*Q: how* can *we use the formulae?*

# Inverse Compton Scattering

the usual Compton scattering expressions
assume the electron is initially *at rest*
and the *photon loses energy* in scattering
$\rightarrow$ "ordinary kinematics"
but this is not the case we are interested in!

in a frame where the electron is relativistic
- then there can be a momentum and energy transfer and the photon *gains energy*
- "upscattered" to higher frequencies

$\rightarrow$ "inverse kinematics" – **inverse Compton scattering**

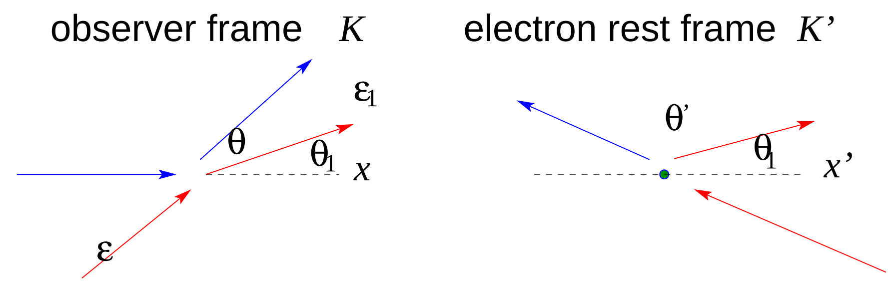
strategy: use Lorentz transformations *twice*
0. start in "lab frame" were $e$ is relativistic
1. boost to $e$ rest frame, find scattered photon energy/momentum
2. boost back to lab frame to find scattered photon energy

Lab/observer frame $K$:

- initial electron *relativistic*
- Lorentz factor $\gamma$, speed $\beta = v/c$

electron rest frame $K'$:

- ordinary kinematics




Doppler expression: find photon energies in rest frame

$$\epsilon' = \gamma\, \epsilon\, (1 - \beta \cos\theta) \quad (8)$$

$$\epsilon'_1 = \gamma\, \epsilon_1\, (1 - \beta \cos\theta_1) \quad (9)$$

Compton: with $\hat{k}' \cdot \hat{k}'_1 = \cos\Theta$, and assuming $\epsilon' \ll m_e c^2$

$$\epsilon'_1 \approx \epsilon \left[ 1 - \frac{\epsilon'}{m_e c^2} (1 - \cos\Theta) \right] \quad (10)$$

if initial lab-frame photon energy is $\epsilon$

*Q: initial photon energy in $e$ rest frame, roughly?*

*Q: scattered photon energy in $e$ rest frame, roughly?*

*Q: scattered photon energy lab frame, roughly?*

# Inverse Compton: Order of Magnitude

if initial lab-frame photon energy is $\epsilon$
and lab-frame electron with $\gamma \gg 1$:
in $e$ rest frame: photon energy *boosted*
$\rightarrow$ initial energy $\epsilon' \sim \gamma\epsilon$

still in $e$ rest frame:
if $\epsilon' \ll m_e c^2 \rightarrow$ small photon energy change (Thomson)
scattered energy $\epsilon'_1 \sim \epsilon' \sim \gamma\epsilon$

back to lab frame:
scattered photon energy *boosted* to $\epsilon_1 \sim \gamma\epsilon'_1 \sim \gamma^2\epsilon_1$

Bottom line: upscattered photon energy $\epsilon_1 \sim \gamma^2\epsilon$
*Q: implications for blazars?*

# Inverse Compton Power for Single-Electron Scattering

Consider a relativistic electron $(\gamma, \beta)$
incident on an isotropic distribution of ambient photons
$\rightarrow$ find power going into inverse Compton

Order of magnitude estimate:

- if typical ambient photon energy is $\epsilon$
  then typical *upscattered energy* is $\epsilon_1 \sim \gamma^2 \epsilon$
- if ambient photon number density is $n_\gamma$
  then *scattering rate per electron* is $\Gamma \sim n_\gamma \sigma_\mathrm{T} c$ *Q: why?*

thus expect power = rate of energy into inverse Compton

$$\frac{dE_1}{dt} \sim \Gamma\ \epsilon_1 \sim \gamma^2 \epsilon n_\gamma \sigma_\mathrm{T} c \sim \gamma^2 \sigma_\mathrm{T} c u_\gamma \tag{11}$$

where $u_\gamma = \langle \epsilon \rangle\, n_\gamma$ is the ambient photon energy density
*Q: looks familiar?*