Astro 501: Radiative Processes
Lecture 14
Feb 15, 2013

Announcements:

- **Problem Set 4** today at 5pm
- **Problem Set 5** due next Friday

Last time: Thomson scattering

Q: what is Thomson scattering?

Q: what does the scattered power depend on?

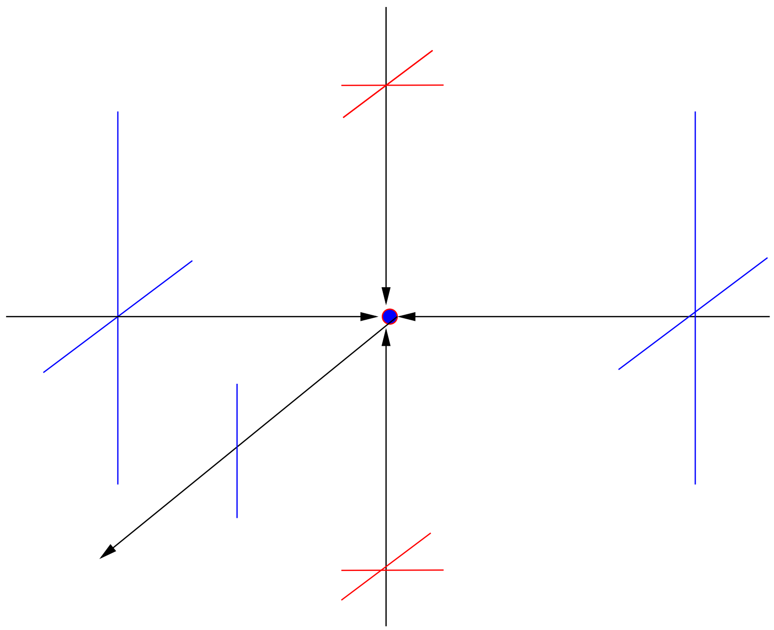
Q: what does $d\sigma/d\Omega$ depend on? and not?

Q: what does σ depend on? and not?

Q: lessons?

Q: when does Thomson scattering generate polarization?

if initial radiation field has quadrupole intensity pattern



linear polarization!

lesson: polarization arises from Thomson scattering
when electrons “see” quadrupole anisotropies in radiation field

Awesomest Example of Thompson Polarization: the CMB

The CMB is nearly isotropic radiation field
arises from $\tau = 1$ "surface of last scattering" at $z = 1000$
when free e and protons "re" combined $ep \to H$

- *before recombination:*
  Thomson scattering of CMB photons, Universe opaque
- after recombination: no free e, Universe transparent

consider electron during last scatterings
sees and anisotropic thermal radiation field

consider point at hot/cold "wall"
  locally sees *dipole* T anisotropy
  net polarization towards us: zero! *Q: why?*

Q: what about edge of circular hot spot? cold spot?

polarization tangential (ring) around hot spots
radial (spokes) around cold spots
(superpose to "+" = zero net polarization–check!)

`www: WMAP polarization observations of hot and cold spots`

Note: polarization & T anisotropies *linked*
$\rightarrow$ consistency test for CMB theory and hence hot big bang

Polarization Observed

First detection: pre-WMAP!
$\star$ DASI (2002) ground-based interferometer
at level predicted based on T anisotropies! Woo hoo!

WMAP (2003): first polarization-T correlation function

Planck (March 2013): much more sensitive to polarization
maybe a signature of inflation-generated gravitational radiation?

Bremsstrahlung

Bremsstrahlung

German lesson for today:

Bremse = break (as in stopping)

Strahlung = radiation

$\rightarrow$ Bremsstrahlung = "breaking radiation"

= radiation from decelerated charge particles

Consider a **dilute plasma** at temperature T, with

- free ions: charge $+Ze$, number density n_i
- free electrons: charge $-e$, number density n_e

Q: astrophysical examples? `www: awesome example`

Q: what microphysics what will cause the plasma to emit?

i.e., what interactions will occur?

Q: which particles will radiate more?

dilute plasma = low particle density = typical in astrophysics
→ three-body collisions unlikely; ignore these
→ focus on two-body collisions

possible interactions: Coulomb forces between particle pairs

- electron-electron
- ion-ion
- electron-ion

But note: for *two identical charged particles*
dipole moment in center of mass $\vec{d} = \sum q_i \vec{r}_i = 0$
no dipole radiation

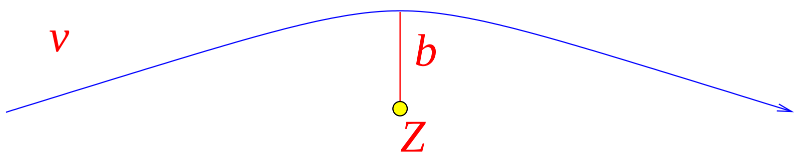
So: *electron-ion* dipole radiation dominates

electron and ion scattered by same Coulomb force (Newton III)
But $a_{\text{i}}/a_e = m_e/m_{\text{i}} < 10^{-3}$ → ion acceleration negligible
→ focus electron acceleration in static field of ion

Order of Magnitude Expectations

start with *classical, nonrelativistic* picture

consider a free, unbound electron with asymptotic speed v moving in Coulomb field of stationary ion



let $b =$ *the distance of closest approach* or **impact parameter**

Q: estimate of maximum acceleration?

Q: duration of acceleration? velocity change? radiation frequency

Recall the *Spirit of Order-of-Magnitude*:

- ignore all dimensionless constants, e.g., "small circle approximation" $2\pi \approx 1$
- lower expectations for precision
- use rough result to guide more careful calculations

maximum acceleration: Coulomb acceleration at closest approach

$$a_{\mathsf{max}} \sim \frac{Ze^2}{m_e b^2} \tag{1}$$

duration of acceleration: **collision time**

$$\tau \sim \frac{b}{v} \tag{2}$$

velocity change

$$\Delta v \sim a_{\mathsf{max}}\ \tau \sim \frac{Ze^2}{m_e b v} \sim \left(\frac{Ze^2/b}{m_e v^2}\right) v \tag{3}$$

frequency of radiation: use only timescale in problem

$$\omega \sim \frac{1}{\tau} \sim \frac{v}{b} \tag{4}$$

Q: what is maximum radiated power? radiated energy? energy per unit freq?

maximum radiated power is

$$P_{\mathsf{max}} \sim \frac{e^2 a_{\mathsf{max}}^2}{c^3} \sim \frac{e^2 \Delta v^2}{c^3\ \tau^2} \sim \frac{Z^2 e^6}{m_e v^2 b^2\ \tau^2} \tag{5}$$

radiated energy

$$\Delta W \sim P_{\mathsf{max}}\ \tau \sim \frac{Z^2 e^6}{m_e v^2 b^2\ \tau} \tag{6}$$

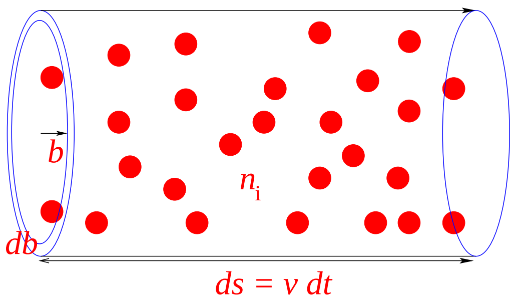
radiated energy per unit frequency

$$\frac{\Delta W}{\Delta \nu} \sim \frac{\Delta W}{\omega} \sim \frac{Z^2 e^6}{m_e v^2 b^2} \tag{7}$$

this energy radiated per electron-ion encounter at distance b

electron with speed v moves encounters ion number density n_{i}

- we want number of ions $d\mathcal{N}_{\mathsf{i}}$ that e encounters out to distance $\sim b$ in time dt *Q: which is?*
- *Q: what is typical rate of energy emitted per electron?*



in cylindrical distance $(b, b + db)$, volume swept is

$$dV = 2\pi \ b \ db \ ds = 2\pi \ v \ b \ db \ dt \tag{8}$$

i.e., $dV \sim b^2 \ v \ dt$

thus number of ions encountered is

$$d\mathcal{N}_{\rm i} = n_{\rm i} \ dV \ \ \sim n_{\rm i} \ b^2 \ v \ dt \tag{9}$$

Thus the rate of energy emitted $=$ *power emitted per* e is

$$\frac{dP_{\rm per}e}{d\nu} = \frac{\Delta W}{\Delta \nu}\frac{d\mathcal{N}_{\rm i}}{dt} \sim \frac{e^6 Z^2}{m_e c^3 v} n_{\rm i} \tag{10}$$

Q: and so what is emission coefficient j_ν*?*

Our order-of-magnitude estimate for the emission coefficient from nonrelativistic bremsstrahlung:

$$j_\nu = n_e \frac{dP_{\text{per}\,e}}{d\nu} \sim \frac{e^6 Z^2}{m_e c^3 v} n_e n_{\text{i}} \tag{11}$$

Q: what's the basic physical picture?

Q: notable features? what didn't we get from order of mag?

Q: how can we do the classical calculation more carefully?