Astro 501: Radiative Processes
Lecture 39: The Final Frontier
December 12, 2018

Announcements:

- **Final Exam – Friday Dec 14.**
- take home. Questions assigned 2pm, due by 10pm.
- designed to take 3 hours
- open book, open notes. No internet, no collaboration.

last time:

inverse Compton scattering *Q: what's that?*

awesome example: Sunyaev-Zel'dovich effect *Q: what's that?*

today: the Big Finale!

CMB Scattering by Intracluster Gas

mean free path is that for Thompson scattering:
$\ell_\nu^{-1} = \alpha_\nu = n_e \sigma_{\mathrm{T}}$ independent of frequency
and thus optical depth is integral over cloud sightline

$$\tau_\nu = \int \alpha_\nu \; ds = \sigma_{\mathrm{T}} \int n_e \; ds \tag{1}$$

thus transmission probability is $e^{-\tau_\nu}$, and so
absorption probability is $1 - e^{-\tau_\nu}$

but for galaxy clusters: $\tau < 10^{-3} \ll 1$,
and so *absorption probability* is just τ
Q: implications?
Q: effect of scattering if electrons cold, scattering is elastic?
Q: what if electrons are hot?

if electrons are hot, they transfer energy to CMB photons
change temperature pattern, in frequency-dependent way

What is net change in energy?
initial photon energy density is $u_0 = u_{\rm cmb} = 4\pi B(T_{\rm cmb})/c$
power transfer per electron is $P_{\rm Compt} = 4(kT_e/m_e c^2)\sigma_{\rm T} c\ u_0$, so

$$\frac{\partial u}{\partial t} = P_{\rm Compt}\ n_e = 4\frac{kT_e}{m_e c^2}\sigma_{\rm T} c\ u_0\ n_e \tag{2}$$

and thus net energy density change

$$\Delta u = 4\sigma_{\rm T}\ u_0 \int \frac{n_e\ kT_e}{m_e c^2} ds = 4\frac{kT_e}{m_e c^2}\tau\ u_0 \tag{3}$$

Q: implications?

CMB energy density change through cluster

$$\Delta u = 4\sigma_{\mathrm{T}}\ u_0 \int \frac{n_e\ kT_e}{m_e c^2} ds = 4\frac{kT_e}{m_e c^2}\tau\ u_0 \equiv 4y\ u_0 \qquad (4)$$

- dimensionless **Compton-y parameter**

$$y \equiv \sigma_{\mathrm{T}} \int \frac{n_e\ kT_e}{m_e c^2} ds \simeq \tau \frac{kT_e}{m_e c^2} \simeq 3\tau\beta^2 \qquad (5)$$

- note $n_e kT_e = P_e$ electron pressure
  $\rightarrow y$ set by line-of-sight pressure

fractional change in (integrated) energy density $\Delta u/u_0 = 4y$
- positive change $\rightarrow$ (small) net heating of CMB photons
- since $u \propto I$, this also means

$$\frac{\Delta I_{\mathrm{cmb}}}{I_{\mathrm{cmb}}} = 4y \qquad (6)$$

cluster generated net CMB "hotspot"

Q: expected frequency dependence?

SZ Effect: Frequency Dependence

on average, we expect photons to gain energy
adding intensity at high ν, at the expense of low ν

but note that in isotropic electron population

- some scatterings will reduce energy
- while others will increase it

detailed derivation is involved:

- allow for ordinary and stimulated emission
- include effects of electron energy distribution
- allow for Compton shift in energy
- use Thomson (Klein-Nishina) angular distribution

SZ Effect: Spectrum

recall: Compton scattering conserves photon number

- SZ in a cluster makes *no change* in total CMB photons
- upscattered high-ν photons come at expense of low-ν photons

We see that SZ *decreases low-frequency intensity*
and *increases high-frequency intensity*
$\rightarrow$ there must be a transition that crosses zero!
$\rightarrow$ frequency $\nu_{\rm null}$ must exist at which $\Delta I_\nu / I_\nu = 0$: **SZ null**
where upscattering from lower ν balances loss to higher ν

Q: how to exploit SZ frequency dependence?

Q: SZ applications for cluster astrophysics?

Thermal SZ Effect as a Probe of Galaxy Cluster

in each line of sight
SZ measures Comptonization parameter in a cluster:

$$y = \sigma_{\mathrm{T}} \int \frac{n_e \, kT_e}{m_e c^2} ds = \frac{\sigma_{\mathrm{T}}}{m_e c^2} \int P_e \, ds \approx \frac{\sigma_{\mathrm{T}} \, kT_e}{m_e c^2} \int n_e \, ds \qquad (7)$$

direct measurement of *projected pressure* in column
and if T_e known, a measure of electron column density

SZ flux measures

$$\int \cos\theta \; y \; d\Omega \approx \int y \; d\Omega = \frac{\int y \; dA}{D_{\mathrm{A}}^2} \qquad (8)$$

where $D_{\mathrm{A}}(z)$ is the (angular diameter) distance

$$\int y \; dA \approx \frac{\sigma_{\mathrm{T}} \, kT_e}{m_e c^2} \int n_e \; ds \; dA \propto M_{\mathrm{gas}} \qquad (9)$$

$\rightarrow$ SZ flux gives *intracluster cluster gas mass!* *Q: cosmo apps?*

SZ Effect: Cosmological Applications

- *SZ identifies all clusters without redshift bias!*
  $\rightarrow$ SZ can be used to discover high-z clusters

- SZ + X-ray gives cluster size, gas mass, T_e
  if cluster physics well-understood (Ricker, Vijayaraghavan)
  $\rightarrow$ *cluster mass*

- cluster number density ("abundance") and mass vs z
  i.e., cluster *mass function* a sensitive probe of cosmology

today: clusters are the *largest bound objects*; in early U: rare number and mass vs time sensitive to *cosmic acceleration* that competes with *structure growth via gravitational instability*
$\Rightarrow$ clusters probe this competition

Q: so how to find clusters, measure redshifts?

note that SZ redshift independence also means
SZ does not give cluster redshift

Dark Energy Survey key project:
optical images, redshifts of clusters
compare with SZ survey by South Pole Telescope

`www: SPT survey image`

Gamma Rays

MeV Gamma Rays

consider photons with $E_\gamma \sim 0.5 - 10$ MeV
these have been observed astrophysically

Q: what physical processes can make MeV gammas?
hint: some we have discussed already, some we have not...

Q: what are possible astrophysical sites for these processes

MeV Gamma Rays: Emission Processes

MeV photons are high energy
can be made by nonthermal processes we have already seen

- nonthermal bremsstrahlung from cosmic-ray electrons
- inverse Compton of starlight by cosmic-ray electrons

But the MeV scale has other charms

- $m_e c^2 = 0.511$ MeV
  positron annihilation $e^{\pm} \to \gamma\gamma$
  emits back-to-back 511 keV photons (in rest frame)
- *atomic nuclei are quantum bound states*
  with energy level spacings ~ 1 MeV
  `www: nuclear energy level diagram`

Astrophysical sources?

- positrons $e^{+} \to 511$ keV photons
- excited nuclei $\to$ MeV lines

Q: expected sky distribution for each?

The Postitronic Sky

The 511 keV Sky `www: sky map`
line emission seen!
- concentrated in Galactic center, but not point source
- a faint disk component present

this requires huge numbers of positrons!
an open question where they came from
decay of radioactive nucleosynthesis products? cosmic rays? dark matter?

The Radioactive Sky

The Sky at 1.8 MeV

aluminum isotope ^{26}Al is unstable: $t_{1/2} = 1.5$ Myr

decays to excited state: $^{26}\mathrm{Al} \rightarrow {}^{26}\mathrm{Mg}^{*} \rightarrow {}^{26}\mathrm{Mg}^{\mathrm{g.s.}} + \gamma$

each decay produces 1.8 MeV line

`www: 1.8 MeV line sky map`

Q: implications of line detection/existence?

Q: features of map? origin?

Aluminum-26 Gamma-Rays: Mapping Element Production

emission seen across Galactic plane (*CGRO*/COMPTEL, *INTEGRAL*/SPI)

- strongest towards Galactic center: longest sightline
- features in plane: spiral arm tangents, star-forming regions
- beware! angular resolution $\sim 1^\circ$! "impressionist" view

Presence of 1.8 MeV line: decays onging
$\rightarrow$ sources are ^{26}Al made in last $\sim t_{1/2} = 1.5 Myr$
$\ll$ Galaxy age: fresh!
$\rightarrow$ nucleosynthesis is ongoing in the Galaxy
$\rightarrow$ line intensity measures total recent ^{26}Al production
and also Milky Way supernova rate!

Finale

Summing Up: Overview of Galaxy Spectra

The spectrum of a galaxy sums over all sources in the galaxy stars, stellar remnants, supermassive black holes, gas, dust, cosmic rays

spectrum depends sensitively on star formation history both past and current

Q: sources arising from past star-formation history?
Q: sources arising from current star-formation history?

Q: dominant UVOIR sources for elliptical galaxies? absorption?

Elliptical Galaxy Spectra Overview

elliptical/early-type galaxies:

- very little atomic or molecular gas, nor dust
- very little ongoing star formation

radiation sources:

- emission dominated by stars, with little reddening, extinction
- no star formation $\rightarrow$ no massive stars (short lived)
- most luminous stars are giants (red giants, AGB)
- reflect star formation when progenitors born, Gyr ago

  "red and dead"

UVOIR spectrum: dominated by features from cool giants

- continuum: multi-T blackbody
- strongest absorption lines visible, e.g., Balmer, Ca, Na
- discontinuities: due to Balmer jump and metal line $\gtrsim 4000$ Å

Q: what about spiral galaxies?

Spiral Galaxy Spectra Overview

spiral galaxies:

- cool gas and dust present: ongoing star formation
- but older stellar populations also present

radiation sources:

- emission from *stars*, but some reprocessed by *gas and dust*
- hot massive stars dominate luminosity: *blue*
- reflects ongoing star formation
- UV absorbed, reprocessed: gas $\rightarrow$ lines, dust $\rightarrow$ continuum
- extinction large if edge-on

UVOIR spectrum:

- continuum: multi-T blackbody
- strongest absorption lines visible, e.g., Balmer, Mg
- discontinuities: due to Balmer jump and metal line $\gtrsim 4000$ Å
- emission lines: especially Hα, C$^+$
- thermal-ish IR from dust

The Multiwavelength Sky Revisited: Holistic Milky Way

continuum emission at the lowest and highest energies
radio continuum, GeV and TeV
emission is *nonthermal*, due to cosmic rays

line emission important at low and high energies
- atoms: 21 cm
- molecules: CO
- nuclei: ^{26}Al
- annihilation: e^+e^-

continuum emission intermediate energies: *thermal*
- starlight
- dust emission = reprocessed starlight

Flexing Your Radiative Muscles

We have come a long way!

You now know – at least in outline –

- how to *predict* the way things *should look*
- how to *understand* the way things *do look*

We only had time to scratch the surface
but you have the tools now to learn more
...and to teach us all more!

Go forth and radiate!

Thank You!

Director's Cut Extras

SZ Effect: More Cosmological Applications

even for clusters not clearly imaged in SZ
SZ effect from all clusters still imprinted on CMB
affects $\Delta T_{\rm cmb}$ perturbation pattern on sky

typical angular size of cluster SZ:
for large cluster $\theta_{cluster} \sim R_{\rm cluster}/d_{\rm H} \sim 3$ Mpc/4 Gpc ~ 3 arcmin
i.e., SZ affects small angular scales
in C_ℓ multipole space this corresponds to $\ell \sim 200/\theta_{\rm deg} \sim 4000$

SZ statistical imprint on CMB anisotropies:
exquisitely sensitive measure of *cosmic structure*
for experts: angular power spectrum $C_\ell^{\rm SZ} \propto \sigma_8^7$!

To date: SZ contribution to power spectrum not seen! *Planck*?

Kinetic SZ Effect and Cosmology

Thus far: implicitly assumed that cluster is *at rest*
relative to CMB frame ("fundamental observers")

but if cluster moving along line of sight with velocity $v_{\rm los}$
bulk motion adds *uniform Doppler shift*
to usual thermal SZ effect
→ kinematic or **kinetic SZ effect** ("kSZ")

at lowe frequencies (Rayleigh-Jeans), kSZ has

$$\frac{\Delta I_\nu}{I_\nu} \approx -\tau \, \frac{v_{\rm los}}{c} \tag{10}$$

what causes cluster motion = bulk flows?
→ large-scale density perturbations

Q: but how do we tell between kSZ and thermal SZ?

Other SZ Applications

SZ is sensitive to *any* population of high-energy electrons

should be a SZ contribution from relativistic electrons
in intracluster medium, arising from
• cosmic-rays escaped from galaxies, or from
• "structure formation cosmic rays" accelerated by cosmological shocks
nonthermal SZ

also recall that AGN jets lead to electron acceleration
in principle can measure jet electrons in SZ

GeV and TeV Gamma Rays

consider photons with $E_\gamma \sim 1$ GeV to 10 TeV $= 10^{12}$ eV
these have been observed astrophysically

Q: what physical processes can make GeV/TeV gammas?
hint: some we have discussed already, some we have not...

Q: what are possible astrophysical sites for these processes

GeV/TeV Gamma Rays: Emission Processes

GeV/TeV photons have gi-normous energies
difficult to make even with cosmic-ray electrons
inverse Compton can work, but requires electrons with $E_e \gg E_\gamma$
these lose energy fast: $(dE_e/dt)_{\rm IC} = 4/3\ \sigma_{\rm T} u_{\rm bg} \gamma^2$

But the GeV/TeV scale has other charms
• *cosmic-ray protons* interact with interstellar proton (hydrogen)

$$p_{\rm cr} + p_{\rm ism} \rightarrow pp\pi^0 \qquad (11)$$

makes *neutral pi-meson* ("pion") π^0
rapidly decays: $\pi^0 \rightarrow \gamma\gamma$, with $E_\gamma = m_\pi c^2/2 = 67$ MeV
but decay is *in flight*: on γ boosted to high energy
• *dark matter* is expected to be an elementary particle
an in many models can annihilate with itself
annihilation products are known (Standard Model) particles
which can make gamma rays

The GeV and TeV Sky

The GeV Sky `www: Fermi sky map`

diffuse emission predominantly in *Galactic plane*

makes sense! $p_{\rm cr} + p_{\rm ism} \to \pi^0 \to \gamma\gamma$ requires both

- cosmic ray proton *projectiles*, but also
- interstellar hydrogen *targets*

and the Galactic gas lives in the disk plane

Implications:

Galactic γ-ray intensity $I_\gamma \propto N({\rm H_{tot}})$: total hydrogen column

tests other measures of neutral, molecular, and ionized H

GeV Point Sources

- in Galactic plane: pulsars
- out of plane: AGN, star-forming galaxies

The TeV Sky `www: H.E.S.S. Galactic plane map`

- Galactic plane: supernova remnants (resolved!)
- extragalactic: blazars
- Galactic center: TeV signal seen!
  why? open question
  large cosmic ray flux? Sgr A^*? dark matter?