Astronomy 501: Radiative Processes

Lecture 41

Dec 5, 2022

Announcements:

- **Take-Home Final Exam – Tuesday Dec 13.**
  info on Canvas

last time: EM propagation in plasmas

today: Grand Finale!

- Gamma Rays
- Meme Exhibition

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!

thermal production requires $T \gtrsim 1\,\mathrm{MeV}/k \sim 10^{10}$ K
• nothing this hot and optically thin

can be made by *nonthermal processes* we have already seen
• nonthermal bremsstrahlung from cosmic-ray electrons
• inverse Compton of starlight by cosmic-ray electrons

Q: other ways to create MeV photons?
Hint–what masses/bindings have MeV scales?

Physics at the MeV Scale

Mass: electron

- $m_e c^2 = 0.511$ MeV
  positron annihilation $e^{\pm} \rightarrow \gamma\gamma$
  emits back-to-back 511 keV photons (in rest frame)

Binding: nuclei

- *atomic nuclei are quantum bound states*
  with energy level spacings ~ 1 MeV
  `www: nuclear energy level diagram`

Astrophysical sources?

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

Q: expected sky distribution for each?

The Positronic Sky

The 511 keV Sky `www: sky map`
at $E_\gamma = m_e c^2 = 0.511$ MeV: line emission seen!
Q: what do you notice?

concentrated in Galactic center, but not point source
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: $^{26}\text{Al} \rightarrow {}^{26}\text{Mg}^{*} \rightarrow {}^{26}\text{Mg}^{\text{g.s.}} + \gamma$

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 are ongoing!*

$\rightarrow$ 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!

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)
- and excite one proton to higher energy level

$$p_{\rm cr} + p_{\rm ism} \to p + \Delta^+ \qquad (1)$$

Wut?! protons are not elementary!
- proton: ground state of bound quarks: 2 u=up + 1 d=down
  p=uud, spin $S(p) = 1/2$
- Δ^+: 1st excited state of uud, spin $S(\Delta) = 3/2$
  mass diff gives excitation: $m(\Delta^+) - m(p) = 294$ MeV
  Q: and so?

Neutral Pion Decay

Δ^+ baryon: excitation of proton

- to make requires high energy > 294 MeV in center of mass
  need high-energy collisions: cosmic rays
- unstable! just as atomic and nuclear excited states are short-lived
  decays in 5×10^{-24} sec to

$$\Delta^+ \longrightarrow p + \pi^0 \tag{2}$$

produces **neutral pi meson** π^0

- quantum superposition of quark-antiquark pair: $u\bar{u} + d\bar{d}$
- bound state of matter and antimatter!
- unstable–annihilates!

$$\pi^0 \longrightarrow \gamma\gamma \tag{3}$$

decay photons hvae high energy: gamma rays at last!

Pionic Gamma Rays from Cosmic-Ray Collisions with ISM

Net effect of high-energy proton collisions in ISM:

$$p_{\rm cr} + p_{\rm ism} \to pp\pi^0 \tag{4}$$

makes *neutral pi-meson* ("pion") π^0

rapidly decays: $\tau(\pi^0) = 8.5 \times 10^{-17}$ sec

in pion rest frame, $\pi^0 \to \gamma\gamma$ photons back-to-back
each has $E_\gamma = m_\pi c^2/2 = 67$ MeV

but Δ^+ and then π^0 are moving!
so decay is *in flight*:
- one γ boosted to higher energy, one to lower energy
- spectrum is symmetric around $m_\pi c^2/2$ (in log space)

`www: GeV sky` *Q: why does it have this pattern?*

The GeV and TeV Sky

The GeV Sky `www: Fermi sky map`
diffuse emission predominanty in *Galactic plane*

makes sense! $p_{\rm cr} + p_{\rm ism} \rightarrow \pi^0 \rightarrow \gamma\gamma$ 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 $I_\gamma \propto N(\mathrm{H_{tot}})$: 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?

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

Meme Exhibition

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!