Astro 596/496 NPA

Lecture 41

Dec. 7, 2009

Announcements:

- Final Problem Set posted, due next Monday at 5pm
  open book, open notes, open web
  but please do not collaborate
- all homework solutions posted by end of today

Last time: signatures of cosmic-ray interactions

Q: LiBeB–why unusual? how do cosmic rays make them?

Q: gamma rays–what do we learn from the Fermi *sky?*

Q: what causes emission in the Galactic plane?

Q: what theoretical tools needed to describe gamma-ray sky?

Gamma-Ray Radiation Transfer

Gamma-ray number intensity (surface brightness)

$I_\gamma(E) = dN/dA\,dt\,d\Omega\ dE$

$$\frac{d}{ds} I_\gamma = -n\sigma I_\gamma + \frac{q_\gamma}{4\pi} \tag{1}$$

source $q_\gamma = dN_{\rm inj}/dV\,dt\,dE$ (assume isotropic)

line-of-sight path $ds = cdt$

matter-radiation interaction:

for $E_\gamma \gtrsim 100$ MeV, $\gamma \to e^+ e^-$ dominates

$\sigma \simeq const \simeq 23$ mb

$\Rightarrow$ mean free path in ISM $\ell_{\rm mfp} \sim 14$ Mpc $(1\ {\rm cm}^{-3}/n)$

Q: Which means?

gamma-ray $\ell_{\rm mfp}^{\rm ism} \gg$ ISM size:

Galaxy is transparent to γ-rays

$\Rightarrow$ radiation transfer simplifies to $\boxed{dI_\gamma/ds \simeq q_\gamma/4\pi}$

integrate over line of sight path s:

$$I_\gamma(E) = \int_{\rm los} ds \, \frac{q_\gamma(E)}{4\pi} \tag{2}$$

source function: $q_\gamma(E_\gamma) = \Gamma(E_\gamma)\, n_{\rm H}$

$\Rightarrow$ each line of sight has $\boxed{I_\gamma(E) = \Gamma(E) N_{\rm H}}$

- energy dependence: $\Gamma = \int_{E_\gamma}^{\infty} dE \ \sigma(E, E_\gamma) \ \phi_{\rm cr}(E)$
  the γ production rate per H atom
- spatial dependence: $N_{\rm H} = \int_{\rm los} ds \ n$
  total H column density along line of sight

Diffuse Gamma-Rays Observed

`www:` γ`-ray sky` > 100 `MeV`

γ-ray sky > 100 MeV dominated by diffuse emission from disk cosmic-ray $+$ interstellar-medium interactions

Galactic gamma-rays as probes

⋆ given cosmic-ray spatial distribution: probe of Galactic H

⋆ given H spatial distribution: probe of Galactic cosmic rays

⋆ spectrum: encodes info on source mechanism(s)
Fermi $\rightarrow$ hadronic interactions dominate emission from plane

⋆ angular distribution: emerging powerful tool to identify/discriminate sources

Diffuse Galactic γ-Rays: Models

Theory: model distributions of
projectiles: Galactic CRs
targets: starlight, gas, mag field

good news:

can fit spatial distribution fairly well
and now can also fit energy spectrum

bad(?) news:

no evidence yet (?) for exotica, e.g., dark matter annihilation

Extragalactic Gamma-Rays

Gamma-rays seen even from Galactic poles
At some level there must be extragalactic gammas

Sources for the γ-ray background?
two guaranteed = unresolved counterparts of esolved sources

(a) Blazars: AGNs seen in high-E γs
`www: unification cartoon`
EGRE resolved ~ 100; new sources found by *Fermi*
unresolved $\rightarrow$ some (most?) of background

(b) star-forming galaxies: CR-ISM γs as in MW
a few local/luminous galaxies now *observed* by *Fermi*
in past: star-formation higher, more gas (fewer stars) in ISM
$\rightarrow$ galaxies γ-ray bright, significant contribution to background
$\Rightarrow$ *Fermi* preliminary results encouraging!

Cosmic Ray Finale:

ATMOSPHERIC NEUTRINOS

Atmospheric Neutrinos: Theory

cosmic-ray interactions in atmosphere produce neutrinos:

initial interactions at "top" of atmosphere, $\sim 15-20$ km

$$
\begin{array}{rcl}
p_{\rm cr} + {}^{14}{\rm N}_{\rm atm} & \to & \pi^+ + \cdots \\
& & \pi^+ \to \mu^+ + \nu_\mu \\
& & \quad \mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu
\end{array}
$$

Clear prediction for flavor ratio

$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \simeq \boxed{2} \qquad (3)$$

8 *Q: but what about decays of atmospheric π^-?*

Absolute ν flux, for $\nu \in \overset{(-)}{\nu}_\mu, \overset{(-)}{\nu}_e$

neutrino production

$$\frac{d\phi_\nu}{ds} \simeq n_{\rm atm}\ \sigma(p + {\rm atm} \to \pi)\ \phi_p$$

but cosmic rays lost to these and other interactions

$$\frac{d\phi_p}{ds} \simeq -\ n_{\rm atm}\ \sigma(p + {\rm atm} \to {\rm inelastic})\ \phi_p$$

$\to$ cosmic-ray mean free path $\ell_{\rm mfp} = 1/n_{\rm atm}\sigma_{p,{\rm inel}}$

Integrate neutrino production over $\Delta s \simeq \ell_{\rm mfp}$:

$$\phi_\nu \simeq (n_{\rm atm}\sigma_\pi \Delta s)\phi_p \quad (4)$$

$$= \frac{\sigma_{p+{\rm air}\to\pi}}{\sigma_{p+{\rm air}\to{\rm inel}}}\phi_p \simeq 0.05\ \phi_p \quad (5)$$

so expect $\Phi_\nu(> 1\ \text{GeV}) \sim 0.05\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$

$\Rightarrow$ atm ν flux $\ll$ solar ν flux, but much higher E

Atmospheric Neutrinos: Angular Dependence

to good approx:

- CR flux at top of atm is isotropic
- atm. is spherical

Without oscillations, predict:

- *Q: upgoing vs downgoing flux–for each flavor?*
- *Q: flavor ratio–upgoing vs downgoing?*

Atmospheric Neutrinos: Angular Dependence

We view neutrino sources from inside earth
i.e., inside sphere with isotropic ν sources
observed from off-center position

observe oso in angular area Ω:

- sources at distance r cover area $A = \Omega r^2$
- but flux drops as $\Phi \propto 1/r^2$

$\rightarrow$ intensity = flux in a given detection = surface brightness
$I \propto \Phi/\Omega = const \;\; \Rightarrow$ *isotropic flux*
this restates Newton's "iron sphere" theorem

In particular, without oscillations, predict:

upgoing ν flux = downgoing ν flux

i.e., $\phi(\cos\theta_z = -1) = \phi(\cos\theta_z = +1)$
$\Rightarrow$ up/down asymmetry is evidence for new ν physics

Super-K measures both ν_e-like and ν_μ-like events

ν_μ/ν_e quoted in terms of
"double ratio"

$$R \equiv \frac{(\nu_\mu/\nu_e)_{\text{data}}}{(\nu_\mu/\nu_e)_{\text{MC}}} \tag{6}$$

where MC=theory (Monte Carlo) prediction
Standard Model (no ν osc'n): $\boxed{R = 1}$

Super-K finds:

$$R = 0.658 \pm 0.016 \pm 0.035 \tag{7}$$

$\Rightarrow$ new ν physics afoot!

Who's to blame?

Super-K Up/Down (A)symmetries

ν_e-like

`www: Super-K` ν `angular distributions`

flux up $\simeq$ flux down

angular distribution predictions match theory (w/o oscillations)

No oscillations of ν_e! (at these energies...)

ν_μ-like

flux up $\neq$ flux down!

angular distributions $\neq$ theory:

deficit of upward νs, increases with L/E_ν

$\Rightarrow$ oscillation! Not into ν_e, so

$\Rightarrow$ $\nu_\mu - \nu_\tau$ oscillation!

Q: what does this imply about oscillation length?

no oscillation for downgoing: $L \sim h_{\text{atm}} \sim 10 - 15$ km
substantial oscillation for upgoing: $L \sim 2R_{\oplus}$

for 2-species oscillations in vacuum, survival

$$P(\nu_i \rightarrow \nu_i) = 1 - \sin^2(2\theta)\ \sin^2\left(1.27\frac{\Delta m^2_{\text{eV}^2} L_{\text{km}}}{2E_{\text{GeV}}}\right)$$

to see an effect when $L \sim 2R_{\oplus}$ and $E \sim E_{\text{cr}}$ GeV
$\Rightarrow \Delta m^2 \sim 4E_{\text{cr}}\hbar c/R_{\oplus} \sim 10^{-3}\ \text{eV}^2$

best fit: $\Delta m^2 = 2.5 \times 10^{-3}\ \text{eV}^2$
and within ability to measure, $\sin^2 2\theta = 1$: maximal mixing!

Verification

Experimental verification:
make ν_μ beam at accelerator (from decaying $\pi^\pm$)
aim at underground ν detector
- look for ν_μ disappearance
- test L, E dependence

Notation: solar νs $\longrightarrow$ masses m_1, m_2
$\longrightarrow$ measures $\Delta m^2_{12} = m^2_2 - m^2_1$ and $\sin^2 2\theta_{12}$
atmospheric νs: masses m_2, m_3 $\Rightarrow$ Δm^2_{23} and $\sin^2 2\theta_{23}$

K2K, Japan `www: K2K`
KEK accelerator $\longrightarrow$ Super-K: $L \sim 250$ km, $E_\nu \sim 1.3$ GeV
good agreement with osc'n solution!

MINOS (Fermilab $\longrightarrow$ Soudan, Minn.), USA `www: MINOS`
- $\Delta m^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2
- $\sin^2 2\theta > 0.85$

Neutrino Masses: Current Status

Tie together ν physics we have covered:

- solar ν problem: $\nu_e - \nu_x$ oscillation:
  $x = \mu, \tau$ or combo (?)
  favored LMA solution:
  $\Delta m_{12}^2 = m_2^2 - m_1^2 = (7.59 \pm 0.20) \times 10^{-5}$ eV^2

- atmospheric ν problem: $\nu_\mu - \nu_\tau$ oscillation:
  best-fit: $\Delta m_{23}^2 = m_3^2 - m_2^2 = (2.43 \pm 0.13) \times 10^{-3}$ eV^2

So what does this say about the m_i?

Neutrino Masses

will show in Final PS that:

None of m_i fixed, but :

- *all* mass-square differences Δm^2 fixed
- beta decay experiments add info ν_e mass components

Cosmological implications:

- oscillations alone set *lower limit* to Ω_ν
- oscillations+β decays sets *upper limit* to Ω_ν

In particular, upper limit gives: $\Omega_\nu < \Omega_{\text{matter}}$

$\Rightarrow$ Last question on Final:

Q: why is this result centrally important to cosmology and particle physics?