Astro 596/496 NPA
Lecture 38
Nov. 30, 2009

Announcements:

- Problem Set 6 due next time
  office hours 3-4pm tomorrow
- High-Energy Seminar, 464 Loomis–right after class today!
  Josh Klein, U. Pennsylvania
  "Into the Muck: Results of the Search for the MSW Effect at the Sudbury Neutrino Observatory"

Last time: *r*-process
physics: rapid neutron capture $\Gamma_{n,\gamma} \gg \Gamma_\beta$
i.e., $\tau_{n,\gamma} \ll \tau_\beta$
Q: possible astrophysical site(s)?

Neutron-Capture Nucleosynthesis: Open Questions

s-process – success story!

- basic physics, nuclear inputs, astrophysics well-understood
- going to the next level: can we use presolar grains to understand detailed nuclear/astro processes in AGB stars of different masses? (see Director's Cut Extras below)

r-process – job security

- what is astrophysical site of the (main?) *r*-process?
- how many *r*-processes are there? ...evidence for a "weak" component at low A
- can *r*-process species give "fossil" signatures of past gamma-ray bursts, neutron-star mergers?
- what is responsible for the stunning regularity in halo-star vs solar-system *r*-process abundances?

Cosmic Rays

The Mystery of the Ionizing Radiation

Early history: $\sim 1900 - 1912$

pioneers of radioactivity studies knew that α, β, γ-rays
 were powerful ionizing agents
 with different ranges = “penetrating power”

Q: for, e.g., $\sim few$ MeV, which is most, least penetrating?

But soon realized that even *without* radioactive samples
 ionization gauges give nonzero signal!

$\Rightarrow$ “background” radiation

Q: possible sources?

Q: how would you design an experiment to
 discriminate among then using 1912 technology?

Victor Hess and the Discovery of Cosmic Rays

possible background ionization sources:
- terrestrial: trace radioactive isotopes in Earth's crust
- extraterrestrial: from Sun?

Victor Hess, 1912: take ionization detectors on hot-air balloon
- ionization signal first goes *down*,
  but by $h \sim 5$ km goes *up* to $\sim few\times$ sea level rate!

⇒ terrestrial ionization sources dominant at ground
...but extraterrestrial sources exist!
- survive passage thru atmosphere ⇒ very penetrating: γ rays?

Hess repeated balloon experiment during solar eclipse:
- no reduction in signal

⇒ radiation does not come from Sun!
⇒ *"cosmic radiation"* = **cosmic rays**

`www: 1936 Nobel Prize in Physics`

Cosmic Rays: Vital Statistics

Cosmic rays: population of particles which are

- electrically charged
- energetic ($\gtrsim 1$ MeV)
- nonthermal *Q: meaning?*

Cosmic Ray Sources:

- solar flares: ~ 0.1 MeV to ~ 1 GeV, typically few MeV

  `www: Solar Flares`
- all others = bulk of cosmic rays: origin outside solar system

`www: real-time satellite data`

composition: mostly nuclei (fully stripped of e^-)

- nuclear (hadronic) component:
  90% are protons
  of remainder, 90% are α
  elements up to Se detected
  `www: CR vs solar elt composition`

- electron/positron (leptonic) component: mostly e^-, some e^+
  leptonic flux $\sim 1/100$ of nucleon component

angular distribution:
isotropic over most of energy range

⌟ cosmic rays are often annoyance to non-CR astronomers *Q: why?*

Observed Nucleonic Component

Experimental techniques:

- balloons
- space missions
- ground-based (high-energy): atm Čerenkov, air shower arrays

flux at top of atmosphere depends on location *Q: why?*
and on time

anti-correlation between CR flux at Earth and solar activity
⇒ solar "modulation" of CR

- excludes $\lesssim 100$ MeV particles
- reduces $\lesssim 1$ GeV flux

∞ must correct for solar effects ("demodulate") to infer interstellar spectra

Cosmic Ray Spectrum

Usually give distribution vs $\varepsilon = T/A$: *kinetic energy per nucleon*

relativistic kinetic energy: $T = \gamma m \approx \gamma A m_u$

so $\varepsilon \approx \gamma m_u$ depends only on v since $\gamma = 1/\sqrt{1 - v^2}$

intensity spectral density

(in terms of particle number flow, not energy)

sketch geometry

$$I(\varepsilon) = \frac{d\mathcal{N}}{dA\,dt\,d\Omega\,d\varepsilon} \quad (1)$$

$$= v(\varepsilon)\frac{d\mathcal{N}}{dV\,d\Omega\,d\varepsilon} \quad (2)$$

Q: what would this look like if thermal? e.g., thermal photons?

`www: CR spectrum`

cosmic ray spectrum clearly **nonthermal**
rather: a succession of *power laws*

- protons w/ 1 GeV $\lesssim E \lesssim$ 300 TeV:

$$I_p(E) \simeq 1.4 \left(\frac{E}{\mathrm{GeV}}\right)^{-\gamma} \ \text{protons cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\text{GeV}^{-1} \tag{3}$$

  where spectral index (“slope”) $\gamma \simeq 2.7$
- beyond “knee’ at $E_{\mathrm{knee}} \sim 10^{15}$ eV
  power law index steepens to $\gamma \sim 3$
- then beyond “ankle” at $E_{\mathrm{anlke}} \simeq 10^{18}$ eV, flattens again

Note high energies $\gg$ Tevatron, LHC
historically: many particles first discovered via CRs

Q: in which regime are most CR particles? most CR energy?

What's typical?

cosmic-ray number flux
$\Phi(>\varepsilon) = 4\pi \int I(\varepsilon)\ d\varepsilon = 4\pi \int \varepsilon\ I(\varepsilon)\ d\ln\varepsilon$
per log energy interval, number distribution is
$d\Phi/d\ln\varepsilon \sim \varepsilon\ I(\varepsilon) \sim \varepsilon^{-(\gamma-1)}$
→ number peaks at smallest (relativistic) energies
typical proton: $\varepsilon \sim 1$ GeV

cosmic-ray energy flux $F(>\varepsilon) = 4\pi \int \varepsilon\ I(\varepsilon)\ d\varepsilon$
per log energy interval, $dF/d\ln\varepsilon \sim \varepsilon^2\ I(\varepsilon) \sim \varepsilon^{-(\gamma-2)}$
⇒ since $\gamma > 2$, energy also peaks at low energies

ensemble of cosmic rays acts as *mildly relativistic gas*

spectrum poses questions:
- origin(s) of the power-law behavior?
- what leads to the different regimes?

Connecting Theory and Observation

recall: to characterize particle ensembles
must specify distribution function f

$$d\mathcal{N} = \frac{g}{(2\pi\hbar)^3} f(\vec{x},\vec{p})\, d^3x\ d^3p \tag{4}$$

How to recover this from cosmic-ray observables?

recall that $I(\varepsilon) = v dN/dV\, d\Omega d\varepsilon$
substitute for $dN/dV = dN/d^3x$:

$$\begin{aligned} I(\varepsilon) &= \frac{g}{(2\pi\hbar)^3} v \frac{d^3p}{d\varepsilon d\Omega} f(p) = \frac{g}{(2\pi\hbar)^3} v \frac{p^2\, dp\, d\Omega}{d\varepsilon\, d\Omega} f(p) \qquad (5) \\ &= A \frac{g}{(2\pi\hbar)^3} p^2 f(p) \qquad (6) \end{aligned}$$

where we used $A(\varepsilon + m_p) = E$; $v = p/E$
$E^2 = p^2 + m^2 \Rightarrow p\, dp = E\, dE$
and $f(\vec{p}) = f(p)$ (isotropy)

Cosmic Ray Astrophysics

To understand CR, must untangle particle histories:
(1) injection
(2) acceleration
(3) propagation
work backwards from observations: propagation first

Propagation

Unlike γ, ν, cosmic rays do *not* point back to source!

Q: what's the problem?
Q: what sets scale for departures from straight-line motion?

Cosmic rays are *charged particles*
→ couple to Galactic (and intergalactic!) magnetic fields

Locally: cosmic rays spiral along $\vec{B}$ field
feel Lorentz force

$$\dot{\vec{p}} = \frac{Ze}{c}\vec{v} \times \vec{B} = \frac{Zec}{E}\vec{p} \times \vec{B} = -\vec{\omega} \times \vec{p} \tag{7}$$

$\Rightarrow$ spiral with gyrofrequency $\omega = ZecB/E$

deflection lengthscale: gyroradius

$$r_g = \frac{v}{\omega} = \frac{cp}{ZeB} \sim \frac{E}{ZeB} \sim 0.2\ \mathrm{AU}\ \left(\frac{E}{1\,\mathrm{GeV}}\right)\left(\frac{1\ \mu\mathrm{G}}{B}\right) \tag{8}$$

tiny! “forget” initial direction for all but highest E

Globally:

cosmic-ray sources: acceleration site(s)
sinks: energy losses to ISM, collisions, escape from Galaxy

"primary": produced at source: p, α, CNO...
"secondary": produced in flight: $\bar{p}$, Li, Be, B
Q: how $\bar{p}$ *made in flight?*

Director’s Cut Extras: Presolar Grains

New Clues – Presolar Grains

1960's–70's: anomalous noble gas isotopes (Ne, Xe) in some meteorites
⇒ some meteoritic material survived prosolar nebula "uncooked"
⇒ look for sites of anomalies in meteorites

1987: carriers of anomalies found in $\sim few$ nm particles
micro-diamonds and silicon carbide (SiC) !
"burn down haystack to find needle"
`www: presolar grain micrographs`

huge isotopic variations among these **presolar grains**
orders of magnitude beyond $\lesssim 1\%$ chemical "fractionation"
`www: isotopic ratios`

Q: what could the grains be? why are they interesting?

Presolar Grains: Isotopic Probes of Nucleosynthesis Events

presolar grains are *interstellar dust particles* which

- were produced from ejecta of individual stars
- survived intact in the interstellar medium
- to be included in the protosolar nebula material
- and were incorporated intact in meteorites

presolar grains thus

- directly sample individual nucleosynthesis events
- can be measured in the lab to high precision
- with detailed isotopic information

bulk of grain population:

- consistent with AGB star nucleosynthesis
- give detailed view of *s*-process
- confirm and drive improvements in detailed AGB models