Astro 596/496 NPA
Lecture 39
Dec. 2, 2009

Announcements:
- Problem Set 6 due

Last time: enlarged view of "**multi-messenger**" astrophysics
i.e., cosmic probes beyond photons
- neutrinos
- dark matter (?)
- gravity waves
- cosmic rays

Cosmic Rays: *Q: what are they?*
Q: how do they propagate?

Propagation and Cosmic-Ray Abundances

Consider “primary” cosmic ray species
abundant at source, e.g., Fe

eventually lost from CR, in one of two ways:

- escape
- fragmentation = “**spallation**”
  in interaction with interstellar gas, e.g.,
  $\mathrm{Fe}_{\mathrm{cr}} + p_{\mathrm{ism}} \rightarrow \mathrm{Mn} + \cdots$

in practice, escape dominates loss
but spallation not negligible

Q: how will spallation affect CR abundances?

Spallation and Cosmic-Ray Propagation

spallation "erodes" all primary species
especially the most abundant

- for primary species, spallation is a (small) *sink*

but also *produces* fragments, typically a few nucleons lighter

- for these **"secondary"** nuclei, spallation is *source*!

Net effect of spallation

- reduce CR abundance "peaks"
- and "fill in" CR abundance "valleys"

origin of CR abundance differences with solar!

`www: cosmic-ray vs solar abundances`

The Leaky Box Model

Realistic CR propagation controlled by magnetic ISM
$\vec{B}(\vec{x})$ inhomogeneities → CR *random walk*, jump field lines
→ cosmic-ray propagation is **diffusive**

full propagation equation complex: diffusion, advection, (re)acceleration
energy losses due to ionization, collisions

but to see main effects on spectrum, can simplify:
diffusion term → timescale for escape from Galaxy
"leaky box" model

Assume isotropic:
net particle flux $\phi(\varepsilon) = \int d\Omega I(\varepsilon) = 4\pi I(\varepsilon)$

For $n_\varepsilon = dn/d\varepsilon = \phi(\varepsilon)/v(\varepsilon)$, leaky box:

$$\begin{aligned} \frac{\partial n_\varepsilon}{\partial t} &= -\text{energy loss} - \text{collisions} - \text{escape} + \text{sources} \\ &= -\frac{\partial}{\partial \varepsilon}(b n_\varepsilon) - n_{\rm ISM}\sigma_{\rm inel} v n_\varepsilon - \frac{n_\varepsilon}{\tau_{\rm esc}} + q_\varepsilon \end{aligned}$$

where $b = |\partial E/\partial t|$ is rate of energy loss → ISM ionization

define matter "thickness" $dX = \rho_{\rm ISM} dx = \rho_{\rm ISM} v dt$

$$\frac{\partial \phi}{\partial X} = -\frac{\partial}{\partial \varepsilon}(w\phi) - \frac{\phi}{\Lambda_{\rm inel}} - \frac{\phi}{\Lambda_{\rm esc}} + Q_\varepsilon \tag{1}$$

where $w = b/\rho v$, $\Lambda_{\rm inel} = m/\sigma_{\rm inel}$, $\Lambda_{\rm esc} = \rho v \tau_{\rm esc}$, $Q = q/\rho$
$[\Lambda] = {\rm g/cm^2}$ "grammage"

for high ε, ioniz. scale $\varepsilon/w \ll \Lambda$: neglect
then in steady state: $\partial/\partial t = \partial/\partial X = 0$

$\phi = \Lambda Q = q\tau$: flux = sources × escape time

CR Sources:
primary (present at source): $Q_i \simeq Q_{\mathrm{accel}}$
secondary (made in flight): $Q_\ell \simeq Q_{\mathrm{spall}} = n_j \sigma_{ij}^\ell \phi_i / \rho$

From secondary/primary ratio $\phi_\ell / \phi_i \simeq \Lambda n_j \sigma_{ij}^\ell / \rho$
find $\Lambda_{\mathrm{esc}} \simeq 10\ \mathrm{g/cm^2} \ll \Lambda_{\mathrm{inel}}$
$\Rightarrow \tau_{\mathrm{esc}} \sim \Lambda / m_p \langle n \rangle c \simeq 6 \times 10^6$ yr
using $\langle n \rangle = \langle n \rangle_{\mathrm{ISM}} = 1\ \mathrm{cm^{-3}}$

Note: can make radioactive secondaries
e.g.., ^{10}Be ($\tau = 1.5$ Myr)
ep "clock" → CR age $t \sim 2 \times 10^7$ yr
higher than naive τ_{esc}
interpretation: $\langle n \rangle \sim 1/3\ \langle n \rangle_{\mathrm{ISM}}$
$\Rightarrow$ CR spend part of lives in low-density Galactic halo

Acceleration

How does nature accelerate particles?

Hint: in solar system, see low-E particle accel.:
- in coronal mass ejections
- in planetary bowshocks
- at the solar wind termination shock

$\Rightarrow$ at *magnetized, collisionless shocks*

Magnetized

- charged particles spiral around field lines
  speed $v_{\|}$ along (parallel to) field $\ll$ total speed v

$\Rightarrow$ charged particles carried ("entrained")
in flow between scatterings

Shocks

- discontinuities in gas flows
- deceleration: supersonic → subsonic
- ordered pre-shock ("upstream") flow converted to
  disordered, turbulent post-shock downstream flow

$\Rightarrow$ downstream magnetic field tangled → scattering centers

Collisionless

charged particles scatter off magnetic inhomogeneities,
but don't collide with (and lose energy to) gas particles

Q: how would such shocks lead to acceleration?

Diffusive Shock Acceleration

basic idea: 1st-order Fermi mechanism:

- incoming (upstream) particles encounter shock
- scatter collisionlessly:
  bounce between slower downstream and faster upstream flows
  with some probability of escape (advection) downstream
- like ball between convering walls: energy gain each cycle

net effect: power law spectrum!

`www: simulation of diffusively accelerated particle trajectory`

In general:
astrophysical shocks are collisionless and magnetized, so
astrophysical shocks accelerate particles
stronger shocks → more powerful/higher-E acceleration

Q: candidates for cosmic-ray acceleration in Milky Way?

Cosmic Ray Accelerator Candidates

Leading candidate for CR acceleration:
shock acceleration in supernova blast waves

- strong shocks
- large energy reservoir
- long-lasting

`www:` e `(and ion?) acceleration to TeV in SN 1006`

The Energetics & Origin of Cosmic Rays

Local: energy densities

$\epsilon_{\rm CR} \sim \epsilon_{\rm therm,ISM}(= n_{\rm ISM}kT) \sim \epsilon_{\rm mag}(= B^2/8\pi) \sim \epsilon_{\rm CMB} \sim 1 \text{ eV cm}^{-3}$

Q: why is CMB energy density comparable to the rest?
Q: why is mag energy comparable to CR?

Global: cosmic ray sources and escape
if steady state, $L_{\rm accel} = L_{\rm esc}$, but

$$\begin{aligned} L_{\rm esc} &= \frac{N_{\rm CR}}{\tau_{\rm esc}} \\ &= \frac{E_{\rm CR} n_{\rm CR} V_{\rm CR}}{\Lambda/\rho_{\rm ism} v} \\ &= \frac{E_{\rm CR} \Phi_{\rm CR} M_{\rm gas}}{\Lambda} \sim 10^{41} \text{ erg/s} \sim 0.3 \text{ foe/century} \end{aligned}$$

If SN rate is ~ 3/century, then need $\sim 10\%$ of E into particles