

Astro 596/496 NPA

Lecture 40

Dec. 4, 2009

Announcements:

- Final Problem Set posted today

Last time: cosmic rays–acceleration and propagation

Q: propagation: affect on abundances–propagated vs source?

Q: loss mechanisms?

Q: acceleration mechanism? acceleration site(s)?

Cosmic-Ray Fossils: Lithium, Beryllium, and Boron

Lithium, Beryllium, and Boron:

Orphans of Nucleosynthesis

- LiBeB weakly bound → **destroyed** in stars
- ${}^6\text{LiBeB}$ **not made** in BBN

But LiBeB exist! must be made somewhere!

Hint: observed cosmic-rays highly enriched in LiBeB

www: cosmic-ray vs solar abundances

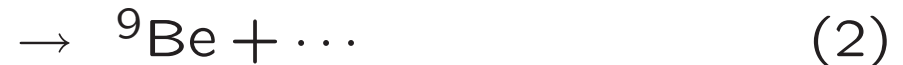
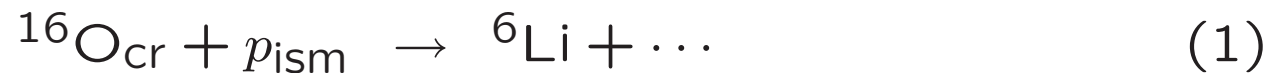
Q: why are CRs rich in LiBeB?

↳ *Q: how does this point to a LiBeB production mechanism?*

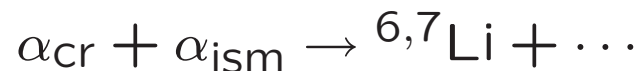
Lithium, Beryllium, and Boron: Cosmic-Ray Production

Observed cosmic rays high in LiBeB

- observed CRs have *propagated* from source in flight, *inevitably* interactions with interstellar gas, .eg. *spallation* makes all of LiBeB



fusion makes lithium isotopes only Q: *why?*



- after correcting for propagation, *no/tiny* LiBeB at source

ω But from nucleosynthesis point of view:
→ this is a *gauranteed* method of LiBeB production!

In more detail: note that LiBeB nuclides in CR have two fates

(1) escape

(2) energy loss, stopping

relative probability depends on kinematics

$\vec{O} + p \rightarrow$ **fast** LiBeB, $\sim 80\%$ escape

$\vec{p} + O \rightarrow$ **slow** LiBeB, $\sim 90\%$ stop

stopped LiBeB:

- accumulate in ISM
- guaranteed source of LiBeB nucleosynthesis
- spallation production dominated by $\vec{p}, \vec{\alpha} + C, N, O$

‡ *Q: but we haven't proven this explains solar LiBeB because...?*

Cosmic-Ray Nucleosynthesis

gauranteed to make but *some* LiBeB
...but do cosmic rays make *enough*?

consider $p + \text{O} \rightarrow \text{Be} + \dots$
production rate:

$$\dot{n}_{\text{Be}} \simeq n_{\text{O}} \sigma_{p\text{O} \rightarrow \text{Be}} \Phi_p$$

order-of-magnitude estimate:

$$\begin{aligned} \Rightarrow \left(\frac{\text{Be}}{\text{H}}\right)_{\text{cr}} &\sim \left(\frac{\text{O}}{\text{H}}\right)_{\odot} \sigma_{p\text{O} \rightarrow \text{Be}} \Phi_p \Delta t \\ &\sim \frac{1}{2} (\text{Be}/\text{H})_{\odot} \text{ (honest numbers!)} \end{aligned}$$

⇒ can produce **solar** Be (and B, ${}^6\text{Li}$)

cosmic-rays necessary and sufficient for LiBeB nuke!

Note:

${}^6\text{Li}$, ${}^9\text{Be}$, ${}^{10}\text{B}$ *only* made from CR

⇒ “CR dosimeters”:

- measure CR “radiation dose” in ISM
- record CR history!

Thus LiBeB nucleosynthesis:

- occurs in interstellar space
- shows that cosmic rays have always been in the Galaxy
- is powered ultimately by CR sources—supernovae?

Cosmic-Ray Fossils: Gamma-Rays

History

- early 1970's: Orbiting Solar Observatory (OSO-3)
discovery of high-energy > 100 MeV photons
www: OSO-3 sky, Kraushaar et al 1972
- mid 1970's: improved sensitivity resolution
www: SAS-2 sky, Fichtel et al
- 1990's: EGRET expt on Compton γ -Ray Observatory
www: EGRET sky
- 11 June 2007: *Fermi* Gamma-Ray Observatory launch

Lesson: MeV–GeV Gamma-ray astronomy is challenging!

- poor angular resolution

Fermi individual photons localized to $\sim 0.1^\circ - 3^\circ$
better for higher energies

- small photon counts

OSO-3: 627 photons total!

EGRET $\sim 10^6$ /yr \rightarrow cost \sim few \$/photon!

Fermi $\sim 10^8$ /yr \rightarrow pennies/photon – better value!

But still, a striking picture emerges

www: Fermi Gamma-Ray Sky > 100 MeV--year one

- ∞ Q: what the the main features of the gamma-ray sky?
- Q: what does this suggest about sources?

The Gamma-Ray Sky

Point Sources

- in Galactic plane, but cover entire sky
- many of these are *variable*
 - ⇒ at low latitudes, associated with pulsars
 - ⇒ at high latitudes, associated with active galaxies

Diffuse Emission

- most intense along Galactic plane
- rises smoothly to peak at Galactic center
- drops off at high Galactic latitude, but nonzero even at poles
- no obvious spheroidal component to Galactic emission

Diffuse Emission: Implications

- ★ *Galactic* sources for gammas, lie in plane
- ★ Galactic emission strongest near center
- ★ *extragalactic* emission exists
- ★ but no strong signal with Galactic halo-like morphology

Q: what might be sources of Galactic diffuse emission?

Q: extragalactic emission?

Diffuse Gamma-Ray Sources

Galactic Source Candidates

- photons from **cosmic-ray** propagation & interaction in ISM
How? What are mechanisms?
Hint: What are CR components, how can they interact?
concentrated in plane – where the targets are
a truly diffuse component
- photons from *unresolved* Galactic point sources
pulsars, microquasars, supernova remnants...
- photons from dark matter annihilation
...but should give spheroidal signal, not seen

Extragalactic Source Candidates

- unresolved point sources
galaxies like Milky Way
faint active galaxies
- truly diffuse emission
cosmic rays from structure formation

Gamma-Ray Production Mechanisms

- hadronic: pion production and decay
 $p_{\text{CR}} + p_{\text{ISM}} \rightarrow p + p + \pi^0$, then $\pi^0 \rightarrow \gamma\gamma$
in pion rest frame, $E_\gamma = m_\pi/2 \simeq 67.5$ MeV but real pions decay in flight Q : *resulting spectrum?*
- leptonic: bremsstrahlung = “breaking/deceleration radiation”
 $e_{\text{CR}} + Z_{\text{nuc}} \rightarrow e' + Z'$
 Z is ISM ion (mostly p)
spectrum: featureless for relativistic e
steeper than primary e spectrum
- leptonic: inverse Compton “upscattering”
 $e_{\text{CR}} + \gamma_{\text{bgnd}} \rightarrow e' + \gamma'$
who is γ_{bgnd} ?
 - ★ starlight (IR, optical)
 - ★ CMB (microwave)