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 $\rightarrow$ destroyed in stars
- ^{6}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

$$
\begin{aligned}
{}^{16}\mathrm{O}_{\mathrm{cr}} + p_{\mathrm{ism}} &\rightarrow {}^{6}\mathrm{Li} + \cdots && (1) \\
&\rightarrow {}^{9}\mathrm{Be} + \cdots && (2) \\
&\rightarrow {}^{10,11}\mathrm{B} + \cdots && (3)
\end{aligned}
$$

  fusion makes lithium isotopes only *Q: why?*

$$\alpha_{\mathrm{cr}} + \alpha_{\mathrm{ism}} \rightarrow {}^{6,7}\mathrm{Li} + \cdots$$

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

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

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

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

stopped LiBeB:

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

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 $p + \mathrm{O} \rightarrow \mathrm{Be} + \cdots$
production rate:

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

order-of-magnitude estimate:

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

$\Rightarrow$ can produce solar Be (and B, ^{6}Li)
cosmic-rays necessary and sufficient for LiBeB nuke!

Note:

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

$\Rightarrow$ "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*
  - $\Rightarrow$ at low latitudes, associated with pulsars
  - $\Rightarrow$ 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
  $p_{\rm CR} + p_{\rm ISM} \rightarrow p + p + \pi^0$, 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"
  $e_{\rm CR} + Z_{\rm nuc} \rightarrow e' + Z'$
  Z is ISM ion (mostly p)
  spectrum: featureless for relativistic e
  steeper than primary e spectrum

- leptonic: inverse Compton "upscattering"
  $e_{\rm CR} + \gamma_{\rm bgnd} \rightarrow e' + \gamma'$
  who is $\gamma_{\rm bgnd}$?
  ⋆ starlight (IR, optical)
  ⋆ CMB (microwave)