High-Energy Astrophysics
Lecture 11: Cosmic rays

Robert Laing

Observed properties of cosmic rays

- Discovered 1912 by Victor Hess.

Observed properties of cosmic rays 2

- Mainly atomic nuclei.
- \(~2\%\) electrons and positrons
- Origin:
  - Solar flares
  - Outside solar system (low-energy particles deflected by the geomagnetic field)
- Elements generated by:
  - Primordial and stellar nucleosynthesis
  - Spallation in ISM

Observed properties of cosmic rays 3

- 79\% of nuclei are protons; 14\% He.
- Above 10 GeV, \(10^{-4}\) antiprotons/proton
- Slightly less p, He than in Solar System
  (acceleration process?)
- Li, Be, B and Sc, Ti, V, Cr, Mn overabundant, due to spallation of C, O and Fe, respectively. This allows us to estimate the typical path length for cosmic rays (50 kgm\(^{-2}\)), and hence to infer that they are confined in the Galaxy.

Cosmic-ray energy spectrum

Several Gev -
\(>100\) TeV
Galactic

\(10^{16} - 10^{18}\) eV
Probably galactic

\(>10^{18}\) eV
Extragalactic

Galactic or extragalactic origin?
Confinement volume for protons
- Typical path length 50 kgm$^{-3}$. ISM density in the disk 10$^6$ kgm$^{-3}$
- Hence typical timescale = $3 \times 10^6$ yr for $v = c$
  (longer if particles spend time in regions of lower density)
- Typical size scale 1 - 10 kpc (3 x 10$^3$ - 3 x 10$^4$ yr)
- Hence protons must be confined within the Galaxy.
- Halo of high-energy particles (cf. observed synchrotron radiation).

Confinement volume for electrons
- High-energy electrons will suffer inverse Compton losses off the CMB. Lifetime
  $t = 2.3 \times 10^{12}/\gamma$ years
- For example, $E = 100$ GeV corresponds to a distance of 3.6 Mpc if electrons travel in straight lines. But the electrons must diffuse from their sources (because of significant magnetic fields in the Galaxy); hence the sources must be at $<<$3.6 Mpc - i.e. within the Galaxy.

Chemical composition
- Mean path length inferred from differences in abundances is 50 kgm$^{-3}$.
- This corresponds to a distance of 10$^6$ Mpc in the intergalactic medium even if all of the observed density in the Universe is in baryons.
- Hence no danger of exceeding spallation limits if cosmic rays are extragalactic in origin.

Electron spectra of potential sources
- Both galactic (supernova remnant, GRB) and extragalactic (AGN) sources have synchrotron spectrum with frequency spectral index 0.5 - 0.75 (energy spectral index 2 - 2.5).
- These are similar to the observed cosmic-ray energy spectrum, so if we assume that electrons and nucleons are accelerated with the same spectrum, then either galactic or extragalactic sources could be responsible.

Cosmic-ray clocks
- Some of the species created in spallation reactions are radioactive, so their abundances can be used to date CR’s.
- Best case is $^{10}$Be (half-life $\tau = 3.9 \times 10^6$ yr; decays to $^{10}$B).
- We observe half-life $\gamma\tau$
- Infer mean particle density 2 x 10$^5$ m$^{-3}$ and escape times of 10$^7$ yr (hence CR’s spend most of their time in the Galactic halo).

Photo-pion and photo-pair production
- Arguments apply to extremely high-energy cosmic rays, in whose rest frame CMB photons have high energies.
- Threshold for photo-pion production = 200 MeV.
- Reactions:
  $\gamma + p \rightarrow n + \pi^+$
  $\gamma + p \rightarrow p + \pi^0 \rightarrow \gamma + \gamma + p$
  $\gamma + p \rightarrow p + n\pi$
- Average photon energy for CMB is $\epsilon_0 = 6 \times 10^{-4}$ eV.
- In particle frame $\epsilon = \gamma\epsilon_0 [1 + (v/c)\cos\theta] = \gamma\epsilon_0$
Photo-pion production 2

- Threshold for photo-pion production corresponds to \( \gamma = 3 \times 10^{11} \) (\( E = 3 \times 10^{20} \) eV).
- Better answer (by integrating over CMB spectrum) gives \( E = 5 \times 10^{19} \) eV.
- Corresponding propagation length is 3 Mpc (GZK cut-off).
- Therefore, we would expect a cut-off in the energy spectrum at around \( E = 3 \times 10^{20} \) eV unless the CR's come from closer than 30 Mpc or so.
- The cut-off is not observed.

Limits to the acceleration process

- For energies \( >10^{15} \) eV, the gyro-radius of a proton in the equipartition field of a supernova remnant becomes comparable with the size of the remnant.
- Therefore, Fermi acceleration at the SNR shock cannot work.
- Higher energies can be generated in extragalactic sources, but these must be close (to avoid the GZK cut-off).
- In that case, we would expect anisotropy in the arrival directions of UHECR’s (not observed), as there are few AGN within a 30 Mpc distance.
- .......

Deflection by magnetic fields?

- Gyro-radius for CR’s in typical galactic and extragalactic fields. Energy \( 3 \times 10^{20} \) eV.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Field</th>
<th>Gyro-radii</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galaxy</td>
<td>0.2nT</td>
<td>150 kpc</td>
</tr>
<tr>
<td></td>
<td>Z=1</td>
<td>Z=8</td>
</tr>
<tr>
<td>Extragalactic</td>
<td>&lt;10^{-10} T</td>
<td>&gt;300 Mpc &gt;40 Mpc</td>
</tr>
<tr>
<td></td>
<td>Z=26</td>
<td>Z=26</td>
</tr>
</tbody>
</table>

- If CR’s with energies \( >10^{20} \) eV, then they will point back accurately to their sources. Heavier nuclei will not.

A possible solution: SNR and GRB’s

- We need sources of UHE cosmic rays which are:
  - capable of accelerating the most energetic particles observed
  - within the GZK cut-off
  - not obviously associated with local AGN
- GRB’s are transient, so we do not observe their after-effects. Therefore UHECR’s could be produced by GRB’s in nearby galaxies (including the Milky Way).
- GRB’s are clearly capable of accelerating electrons to extremely high energies; presumably also protons.

GRB’s and SNR (continued)

- Local density of galaxies with some star-formation activity is consistent with the observed number of UHECRs; arrival directions would appear ~isotropic.
- Some contribution from local AGN also possible.
- Lower-energy CR’s (<10^{15} eV) from non-relativistic shocks in SNR.
- Test by observing gamma-ray and neutrino background.