Astroparticle Physics
Lecture 8: Sources of cosmic rays

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Lecture 8: From cosmic-ray spectrum to cosmic ray sources

Cygnus A
Cosmic ray spectrum

Lower cut-off due to solar wind

Break in spectrum: $3 \times 10^{15} \text{ eV}$
aka “The Knee”: $E^{-2.7} \rightarrow E^{-3.0}$

Break in spectrum: $3 \times 10^{18} \text{ eV}$
aka “The Ankle”: $E^{-3.0} \rightarrow E^{-2.7}$

Greisen, Zatsepin & Kuzmin (GZK)-
cut-off: $4 \times 10^{19} \text{ eV}$?
Solar modulation at low cosmic ray energies

- Solar wind keeps low energy cosmic rays outside the Heliosphere
- Solar wind is variable (22yr solar cycle):
  - Low energy cosmic ray spectrum (cut-off) variable
- Voyager spacecrafts now probe the end of Heliosphere
- Total energy density in cosmic rays determined by low energy cut-off
  - solar wind modulation adds to uncertainty about cosmic ray energy density

http://www.srl.caltech.edu/ACE/ACENews/ACENews155.html
Cosmic Ray Spectrum: high energies

Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV)

Scaled flux $E^{2.5} J(E)$ (m$^{-2}$ sec$^{-1}$ sr$^{-1}$ eV$^{-1.5}$)

Energy (eV/particle)

- ATIC
- PROTON
- RUNJOB
- KASCADE (QGSJET 01)
- KASCADE (SIBYLL 2.1)
- KASCADE-Grande (prel.)
- HiRes-MIA
- HiRes I
- HiRes II
- Tibet ASg (SIBYLL 2.1)
- Auger SD 2008

HERA ($\gamma$-p)
RHIC (p-p)
Tevatron (p-p)
LHC (p-p)
Change of composition around the knee

- KASCADE and other experiments:
  - all elements seems to have their own “knee”
  - Knee seems to be charge/rigidity dependent $E_{knee} \propto Z$
    - Knee is maximum proton energy of a source class (supernova remnants)
    - Heavier elements extent to higher energies

Fig. 20. Energy spectra for four elemental groups and the all-particle spectrum as measured by the KASCADE experiment [79] (symbols) compared to the spectra of the poly-gonato model (lines).
Diffusion of cosmic rays

• Lecture 6, transport of cosmic rays:

\[
\frac{\partial N_i}{\partial t} = D \nabla^2 N_i(E) + \frac{\partial}{\partial E} [b(E)N_i(E)] + Q_i(E) - \frac{N_i}{\tau_i} + \sum_{j>i} \frac{P_{ij}}{\tau_j} N_j
\]

• For high energy cosmic rays diffusion term important
• Primitive idea about diffusion, random walk due scattering on “clouds”
More modern idea: scattering centers are magnetic field irregularities (tangled magnetic fields/Alfvén waves)
Note: Galactic magnetic field has also a structured component
• Diffusion coefficient likely anisotropic: different along magnetic field than perpendicular to magnetic field
• Typical magnetic field strength in Galaxy: 5 μG
Diffusion coefficient

- Diffusion coefficient:
  \[ D = \frac{1}{3} \lambda_{\text{mfp}} v \]

- Diffusion coefficient is energy dependent: mean free path increases with energy
- For tangled magnetic fields, mean free path \( \approx \) gyro-radius
  \[ r_g = \frac{p_\perp}{e c Z B} \approx \frac{E}{e Z B} \approx 0.28 Z^{-1} \left( \frac{E}{10^{15} \text{eV}} \right) \left( \frac{B}{5 \mu \text{G}} \right)^{-1} \text{ pc} \]

- Expression for diffusion coefficient (cgs):
  \[ D = \eta \frac{1}{3} c \frac{E}{e Z B} \approx 6.7 \times 10^{27} \eta Z^{-1} \left( \frac{E}{10^{15} \text{eV}} \right) \left( \frac{B}{5 \mu \text{G}} \right)^{-1} \text{ cm}^2 \text{s}^{-1} \]

- \( \eta \) is fudge factor
- \( \eta = 1 \) : Bohm-diffusion (smallest diffusion coefficient possible)
- Diffusion coefficient energy dependence is function of turbulence spectrum of magnetic fields
Estimating diffusion coefficient

• Approximate

\[
\frac{\partial N_i}{\partial t} = D \nabla^2 N_i(E) + \frac{\partial}{\partial E} \left[b(E)N_i(E)\right] + Q_i(E) - \frac{N_i}{\tau_i} + \sum_{i>j} \frac{P_{ij}}{\tau_j} N_j
\]

• With (steady state \(dN/dt=0\))

\[
D \nabla^2 N_i(E) \approx \frac{N_i}{\tau_i}
\]

• Further approximation

\[
D \frac{N_i}{L^2} \approx \frac{N_i}{\tau_i}
\]

• Using typical escape time \((10^7\text{yr})\) and Galactic scale height \(300\text{pc}\):

\[
D \approx \frac{L^2}{\tau_i} \approx \frac{(300\text{pc})^2}{10^7\text{yr}} \approx 3 \times 10^{27}\text{cm}^2\text{s}
\]

• This corresponds to mfp of 0.1 pc, energies \(\sim 1\ \text{GeV}\), and \(\eta=4\times10^5\)
• Locally there may be large variations in diffusion coefficient due to local turbulence!
Diffusion coefficient in star forming region
Large Magellanic Cloud

CHARACTERIZING COSMIC-RAY PROPAGATION IN MASSIVE STAR-FORMING REGIONS: THE CASE OF 30 DORADUS AND THE LARGE MAGELLANIC CLOUD

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ABSTRACT

Using infrared, radio, and γ-ray data, we investigate the propagation characteristics of cosmic-ray (CR) electrons and nuclei in the 30 Doradus (30 Dor) star-forming region in the Large Magellanic Cloud (LMC) using a phenomenological model based on the radio–far-infrared correlation within galaxies. Employing a correlation analysis, we derive an average propagation length of \( \sim 100 - 140 \) pc for \( \sim 3 \) GeV CR electrons resident in 30 Dor from consideration of the radio and infrared data. Assuming that the observed γ-ray emission towards 30 Dor is associated with the star-forming region, and applying the same methodology to the infrared and γ-ray data, we estimate a \( \sim 20 \) GeV propagation length of \( 200 - 320 \) pc for the CR nuclei. This is approximately twice as large as for \( \sim 3 \) GeV CR electrons, corresponding to a spatial diffusion coefficient that is \( \sim 4 \) times higher, scaling as \((R/GV)^{0.7}\) with \( \delta \approx 0.7 - 0.8 \) depending on the smearing kernel used in the correlation analysis. This value is in agreement with the results found by extending the correlation analysis to include \( \sim 70 \) GeV CR nuclei traced by the \( 3 - 10 \) GeV γ-ray data (\( \delta \approx 0.66 \pm 0.23 \)). Using the mean age of the stellar populations in 30 Dor and the results from our correlation analysis, we estimate a diffusion coefficient

\[
D_R \approx 0.9 - 1.0 \times 10^{27} (R/GV)^{0.7} \text{ cm}^2\text{s}^{-1}
\]

We compare the values of the CR electron propagation length and surface brightness for 30 Dor and the LMC as a whole with those of entire disk galaxies. We find that the trend of decreasing average CR propagation distance with increasing disk-averaged star formation activity holds for the LMC, and extends down to single star-forming regions, at least for the case of 30 Dor.

Subject headings: cosmic rays – galaxies: individual (LMC) – γ rays: galaxies – HII regions – infrared: galaxies – radio continuum: galaxies – stars: formation
Energy density in cosmic rays in Galaxy and cosmic-ray energy production rate

- From cosmic ray spectrum:
  - energy density \( \approx 1 \text{ eV/cm}^3 \)
  - comparable to gas energy density/pressure and magnetic field energy density!
- Assumes that local cosmic ray spectrum is typical for Galaxy
- Energy production factor:
  - \( Q = \text{Energy density} \times \frac{\text{Volume}}{\tau_{\text{esc}}} \)
  - Volume \( = \pi L R^2 \approx 5 \times 10^{66} \text{ cm}^3 \)
  - \( \tau_{\text{esc}} \approx 10^7 \text{ yr} \)
  - \( Q = 3 \times 10^{40} \text{ erg/s} \)
- NB higher than derived in lecture 6!!
Where is the change from Galactic to extra-galactic cosmic rays?

- In order for cosmic rays to remain for some time in Galaxy:
  - Gyroradius needs to be smaller than Galactic scale height
- For $L=300$, we find $E \approx 2 \times 10^{18}$ eV
- This suggest that the “ankle” defines change from Galactic to extra-galactic
Hillas Diagram: what are the sources of cosmic rays?

Hillas diagram generalizes notion that in order to accelerate particles you need to confine them to source:
- Gyroradius needs to be 0.1x size of object
- Either large scale objects (IGM shocks) with low magnetic field
- Or small objects with large fields (neutron stars)
- Hillas diagram does not tell whether acceleration occurs
Some potential sources of cosmic rays

- Supernova remnant
- Cygnus A
- Active galaxy
- Pulsar/magnetar
- Large scale shock in cluster
Origin of Galactic cosmic rays

• Supernovae and their remnants
• Pulsars/neutron stars
• Stellar winds
• Combined effects of SNe/winds in star forming regions

• Two constraints:
  • Is total power provide enough
  • Are they capable of accelerating up to $3 \times 10^{15}$ eV?

http://apod.nasa.gov/apod/ap051107.html
Baade and Zwicky

Walther Baade

Frits Zwicky

In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the “gravitational packing” energy in a cold neutron star may become very large, and, under certain circumstances, may far exceed the ordinary nuclear packing fractions. A neutron star would therefore represent the most stable configuration of matter as such. The consequences of this hypothesis will be developed in another place, where also will be mentioned some observations that tend to support the idea of stellar bodies made up mainly of neutrons.
Why supernovae/supernova remnants prime candidate

- Previously derived:
  - \( Q = 3 \times 10^{40} \text{ erg/s} \)

- Supernova power:
  - \( 10^{51} \text{ erg kinetic energy/supernova} \)
  - 2-3 supernovae per century - where have they been? 😞
  - Total power \( Q = 3 \times 10^{51} \text{ erg/100 yr} = 6 \times 10^{41} \text{ erg/s} \)
  - Efficiency for cosmic-ray acceleration needed: 5-10%

- Later lecture:
  - Is energy used in supernova or remnant phase
  - Can particles be accelerated up to, or beyond \( 3 \times 10^{15} \text{ eV} \)?
What about other Galactic sources?

• There are about $10^{11}$ stars in the Milky Way.
• Solar wind “luminosity”:
  • $\sim 750 \text{ km/s}, 3 \times 10^{-14} M_{\text{sun}}/\text{yr}$: mechanical power=$10^{28}$ erg/s
  • Total power from sun-like stars: $10^{39}$ erg/s → not sufficient

• Winds from massive stars:
  • $v_{w}=500-2000 \text{ km/s}$, mass loss rate=$10^{-8}-10^{-4}$ $M_{\text{sun}}/\text{yr}$
  • Power: up to $10^{38}$ erg/s
  • But very few stars
  • Some synchrotron/gamma-ray sources: may contribute
What about other Galactic sources?  
**Pulsars/magnetars**

- Neutron stars/pulsars:
- Have the right spot in Hillas diagram (even for $10^{20}$ eV!)
- Birth rate $\approx$ supernova rate
- Energy of pulsars: rotation
  \[
  E_{\text{rot}} = \frac{1}{2} I \Omega^2 = 4 \times 10^{52} I_{45} \left( \frac{P}{1 \text{ms}} \right)^{-2}
  \]
  - Initial spin most pulsars: $P>20$ ms
  - Hence: if $P<5$ ms, pulsar power $>\text{SN power}$, but for $P=20$ ms 400x less
  - Pulsars wind: thought to consist mostly of electrons/positrons

- Magnetars:
  - Highest magnetic fields $10^{14}$-$10^{15}$ G
  - Display energetic bursts ($<10^{48}$ erg)
  - 1 theory origin of magnetic fields: high initial spin ($P=1$ ms)!
  - May drive (some) gamma-ray bursts!

- Fang, Kotera, Olinto, 2012: hypothesis that rare fraction of rapid pulsars origin of ultra-high energy cosmic rays (extragalactic)
Extra-galactic cosmic rays: origin particles $>10^{18}$ eV?
Extra-galactic losses: GZK effect

• In intergalactic space energy losses for very high energy cosmic rays is low
• However, cosmic rays may interact with the ubiquitous CMB photons!

\[ \gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0 \]
\[ \gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+ \]

• Threshold energy, and \( q = \text{momentum photon} = y k T_{\text{CMB}} / c \approx y 2.35 \times 10^{-3} \text{ eV} \),
• \( E_{\text{cms}} = (m_{\text{pion}} + m_p) c^2 = 1073 \text{ MeV} \)

\[ s = E_{\text{cms}}^2 = (E + q)^2 - (p c + q c)^2 = (mc^2)^2 + 2qc(E - |p|c \cos \theta) \]
\[ (1073)^2 = (938)^2 + 2 \times 10^{-9}E(1 - \cos \theta) \rightarrow E \approx 1.35 \times 10^{20} / (1 - \cos \theta) \text{ eV} \]

• The cross-section near threshold is \( 2 \times 10^{-28} \text{ cm}^2 \)
• CMB density \( 411 \text{ cm}^{-3} \)
• Hence typical mean free path = \( 1 / (2 \times 10^{-28} \times 411) = 1.2 \times 10^{25} \text{ cm} \approx 4 \text{ Mpc} \)
• Effect already present at lower energies, since enough photons with \( y = 5 \)
• Around \( 5 \times 10^{19} \text{ eV} \): \( \text{mfp} \approx 100 \text{ Mpc} \)

One does not expect to see cosmic rays above \( 10^{20} \text{ eV}! \)
This effect is named after the people predicting this:
the Greisen, Zatsepin, Kuzmin (GZK) effect.
GZK effect measured by Pierre Auger Observatory

The largest uncertainties are given by the absolute fluorescence yield (14%), the absolute calibration of the FD (9.5%) and the reconstruction method (10%). The uncertainty due to the dependence of the fluorescence spectrum on pressure (1%), humidity (5%) and temperature (5%) is taken into account as well as the wavelength dependent response of the FD, the aerosol phase function, invisible energy and others, which are well below 4%. The individual systematic uncertainties in determining $E_{SD}$ coming from the FD sum up to 22%. Therefore all spectra are affected by the 22% uncertainty in the FD energy scale. This common uncertainty does not affect the relative comparison of our spectra. The systematic uncertainty in the hybrid-only spectrum is dominated by uncertainties in the calculation of the exposure. The systematic uncertainty in the SD spectrum has two contributions: the calculation of the exposure (3%) and the statistical uncertainty in the calibration of $S_{1000}$ with the FD energy ($\leq 10\%$). The energy spectrum derived from hybrid data has been combined with the one obtained from surface detector data using a maximum likelihood method. Since the surface detector energy estimator is calibrated with hybrid events, the two spectra have the same systematic uncertainty in the energy scale (22%). On the other hand, the normalization uncertainties are independent. They are taken as 6% for the SD and 10% ($6\%$) for the hybrid flux at $10^{18}$ eV ($10^{19}$ eV). These normalization uncertainties are used as additional constraints in the combination. This combination procedure is used to derive the scale parameters $k_{SD} = 1.01$ and $k_{FD} = 0.99$ which have to be applied to the individual spectra in order to match them. We find that the different spectra are in excellent agreement with normalization factors smaller than 3%. The combined spectrum is shown in Fig. 5.

The characteristic features of the combined spectrum have been quantified in two ways. For the first method, shown as a dotted line in Fig. 5, three power laws with free breaks between them have been used. For the second approach, two power laws in the ankle region and a smoothly changing function at higher energies have been adopted. Therefore we fitted the combined Auger spectrum to the following equation:

$$J(E,E_{\text{ankle}}) = E^{\gamma_1} / C_0^{\gamma_1} \exp \left( \frac{\log E}{\log E_{\text{c}}} \right)^{W_c}$$

where $\gamma_1$ and $\gamma_2$ are the spectral indices before and after the break respectively, $E_{\text{ankle}}$ is the position of the break, and the second term in the second equation is a flux suppression term where $E_{\text{c}}$ is the energy at which the flux is suppressed 50% compared to a pure power-law, and $W_c$ determines the sharpness of the cut-off. The derived parameters are in Table 1 with statistical uncertainties.

See [4] for more details.
Origin of highest energy cosmic rays: location on the sky (Pierre Auger Observatory)

- Around $5 \times 10^{19}$ eV: cosmic ray sources within 200 Mpc
- Gyroradius $5 \times 10^{19}$ eV: $r_g \approx 54 \ (B/10^{-9} G)^{-1}$ Mpc
- In Galaxy little deflection: $r_g \approx 11 \ Z(B/5 \mu G)^{-1}$ kpc
- We don’t know intergalactic magnetic field
- But good chance that highest energy cosmic rays roughly point back to sources!!
- 2007: Early evidence for non-isotropic distribution above $6 \times 10^{19}$ eV:
  - correlation with galaxies (=AGN?)
- 2010: Correlation not as strong as claimed earlier
Summary

• Features in cosmic ray spectrum hint at origin of cosmic rays:
  • Knee ($3 \times 10^{15}$ eV): highest energy protons Galactic sources
  • Ankle ($3 \times 10^{18}$ eV): change from Galactic to extra-galactic CRs
  • Cut-off ($5 \times 10^{19}$ eV): GZK cut-off, interactions with CMB, provides wind on origin (within 100-200 Mpc)

• Source of cosmic rays:
  • Galactic: supernova (remnants) most likely sources
    - energy constraints OK
    - maximum energy (future lectures)
  Additional (?) contributions:
    - pulsars (but only electrons/positrons?), generally not energetic enough
    - stellar winds (only subset of massive stars)

• Extra-galactic
  - Pierre Auger Observatory provide evidence for anisotropy/correlation with galaxy distribution
  - Newer results less conclusive

• Next lecture: shock acceleration mechanism