Physics of high-energy cosmic rays
Lecture 1: Origin of cosmic rays
Lecture 2: Propagation and interactions of cosmic rays
Lecture 3: Experiments and results

References:
Cosmic Rays and Particle Physics, Thomas K. Gaisser, Cambridge University Press, 1990

Jyväskylä, 25-29, August 2008
Tiina Suomijärvi
Institut de Physique Nucléaire
Université Paris XI-Orsay, IN2P3/CNRS
France
tiina@ipno.in2p3.fr
Physics of high-energy cosmic rays
Lecture 1: Origin of cosmic rays

Tiina Suomijärvi
Institut de Physique Nucléaire
Université Paris XI-Orsay, IN2P3/CNRS
France
Contents

Why to study cosmic rays?
Dimensions and time-scales
Historical perspective
Some characteristics of cosmic rays
Contents of the Universe
Origin of cosmic rays: Cosmic accelerators?
Origin of cosmic rays: Something exotic?
Conclusions
Why to study cosmic rays?

✓ Cosmic rays span over an enormous range of energies, up to $10^{20}$ eV.
✓ They are abundant and serve an important role in the energy balance of galaxy. Their energy density 1 eV cm$^{-3}$ is comparable to that contained in the galactic magnetic field or in the cosmic microwave background.
✓ They can be evidence of powerful astrophysical accelerators (supernovae, active galactic nuclei…) and can be used to study these accelerators.
Why to study cosmic rays…

✓ They propagate through universe and can give information on properties of cosmic environment (magnetic fields, matter densities…)
✓ Their chemical composition, modulated by propagation, reflects the nucleosynthetic processes occurring at their origin and can also be used to measure age of astrophysical objects
✓ They can be used to study the validity of physical laws in extreme conditions (violation of Lorentz invariance?)
✓ They can be messengers of « new physics » or yet unknown particles
The unit of distance in astronomy is called the parallax-second, or parsec. It is defined to be the distance at which the mean radius of the Earth’s orbit about the sun subtends an angle of one second of arc.

\[ 1 \text{ pc} = 3.08 \times 10^{16} \text{ m} = 3.26 \text{ light years} \]

\[ 1 \text{ erg} = 10^{-7} \text{ J} \]
Historical perspective
Great triumphs of 19th century

Unification of electricity and magnetism
Maxwell 1864

20 years later experiments of Hertz confirmed that the light is a form of electromagnetic radiation
Experiments in electricity and magnetism

Conduction of electricity through gases:
Good vacuum tubes and high voltages between the positive and negative electrodes

1879: Crookes tube
Discovery of cathode rays

1897: Thomson measured the charge to mass ratio of cathode rays by deflection the radiation by crossed electric and magnetic fields: Discovery of the first sub-atomic particle, electron
New discoveries

1895 Röntgen discovered X-rays: Photographic plates left close to Crookes tubes were darkened

Search for other sources of X-ray emission

1896 Becquerel discovered natural radioactivity by studying uranium samples

1898-1900 Rutherford, P. et M. Curie and Villard understood that there were several types of radioactivity: $\alpha$, $\beta$, $\gamma$
Discovery of Cosmic Rays (CR)
Early experiments in radioactivity used electroscope

- When electroscope is charged, the leaves (A) are pushed apart
- The ionisation of the gas inside discharge the electroscope and the leaves move towards each other
- The rate at which the leaves came together measured the amount of ionisation

Spontaneous discharge of the electroscope!

- 1901 Wilson observes that the discharge is identical on the ground and in a tunnel
- Rutherford shows that this is due to the natural radioactivity
Eiffel Tower and the science

1910 Father Théodore Wulf (jesuite, amatory physicists) conducted experiments on top of the Eiffel tower.

Radiation intensity decreases with height but less than expected.

80 mètres : flux/2

300 meters : flux/15
1912 and 1913: Hess and Kolhörster made manned balloon flights to measure the ionisation of the atmosphere with increasing altitude.

**Average ionisation increase with increasing altitude**

« The result of these observations seems to be explained in the easiest way by assuming that an extremely penetrating radiation enters the atmosphere from above » (V. Hess)

Victor Hess, 1912
17,000 feet
1929 Geiger-Müller detector was invented
Fast response time allow to count individual cosmic rays and also
to determine precisely their arrival time.

1929 Bothe and Kolhörster performed the first coincidence (to about
0.01 s !) experiment by using two counters one placed above the other
and introducing thick absorber between the two.

Coincident events indicated that the cosmic rays were charged, very
penetrating particle (gamma rays were stopped in the absorber).
Extensive air showers

Measurements in the Alps
1938: Pierre Auger and P. Ehrenfest, Jr

Two particle detectors positioned high in the Alps signaled arrival of particles at exactly the same time
Explanation: particles are generated in air-showers
E > 10^{15} \text{ eV}
Cosmic rays and the discovery of elementary particles

Invention of cloud chamber

C.T.R. Wilson

Fast expansion of gas in order to decrease temperature and over saturate the gas
Condensation of drops on the ions produced by particles
Ionisation tracks

α tracks from radium

β

α

β
The beginning of Particle Physics!

- Positron $\Rightarrow$ antimatter!
- Muon
- Pions: $\pi^0$, $\pi^+$, $\pi^-$
- Kaons (K)
- Lambda ($\Lambda$)
- Xi ($\Xi$)
- Sigma ($\Sigma$)
Some characteristics of cosmic rays
Cosmic ray spectrum

Very steep spectra!
Low energy CR

10 MeV/n
1 GeV/n

solar attenuation
Solar modulation

- Flux variation in coincidence with solar cycles

Sun spot activity

CR intensity
1 particle per m\(^2\)-second
- Knee (1 per m\(^2\)-year)
- Ankle (1 per km\(^2\)-year)

\[ J(E) \propto E^{-\gamma} \]
\[ \gamma \approx 2.7 - 3.0 \]

All-particle CR energy spectrum

direct measurements galactic CRs

diffusion losses of galactic CRs?

air shower measurements extragalactic CRs?
Cosmic ray composition

- Composition (at ~GeV):
  - 85% H (p)
  - 12% He (α)
  - 1% heavier nuclei
  - 2% e± (≥90% e⁻)
  - 10⁻⁵-10⁻⁴ antiprotons.
Angular distribution

Isotropique!

Non rectilinear propagation!

- Galactic magnetic field: $\sim 3 \, \mu G$ (3.10$^{-10}$ T)
- Gyroradius:

  - $10^{15}$ eV: Supernova remnant
  - $10^{18}$ eV: Disk + Galactic halo
  - $10^{21}$ eV: $\gg$ galaxy

  $1$ pc  $1$ kpc  $1$ Mpc

$B = 3 \, \mu G$
Contents of the Universe
Large scale distribution of matter and radiation in the Universe

- Measurements of the cosmic microwave background (CMB): evidence for the overall isotropy of the Universe
- Discovered by Penzias and Wilson 1965
- CMB is the cooled remnant of the early phase of the Universe
Distribution of visible matter

The Wilkinson Microwave Anisotropy Probe (WMAP) team has made the first detailed full-sky map of the oldest light in the universe.

Sky distribution of approximately 30000 galaxies from CfA Catalog.

- The most striking features about the CMB is its uniformity.
- Only with very sensitive instruments can detect fluctuations.
- By studying these fluctuations, one can learn about the origin of galaxies and large scale structures and measure the basic parameters of the Big Bang theory.

The distribution of galaxies is highly irregular, with huge holes, filaments and clusters occurring in the local Universe.
The Virgo cluster

• The Virgo Cluster with its some 2000 member galaxies dominates our intergalactic neighborhood.
• It represents the physical center of our Local Supercluster and influences all the galaxies and galaxy groups by the gravitational attraction of its enormous mass.
• The center of the Virgo cluster is about 15–20 Mpc from our galaxy.

The Virgo Cluster of Galaxies, and is centered on the giant elliptical galaxy M87. The two bright galaxies on the right (west) are (right-to-left) M84 and M86; starting from these two, a chain of galaxies ("Markarian’s chain") stretches well to the upper (northern) middle of our image (and beyond, well to M88 which is slightly outside above the sky area photographed our image).
Hubble law

Hubble 1929: the Universe of galaxies is in a state of uniform expansion.
All galaxies are receding from our galaxy, the further away a galaxy is from us, the greater its velocity of recession $v$:

$$v = H_0 r,$$

$r$ is the distance of the galaxy
$H_0$ is the Hubble constant

The velocity is measured from the shift of the spectral lines in the galaxy’s spectrum to longer wavelengths $\Rightarrow$ redshift

The current value of the Hubble constant is still debated, values near the high and low ends of 50 and 100 km s$^{-1}$/Mpc.
The galaxies

Galaxies are the basic building blocks of the Universe. Basic distinction is between spiral and elliptical galaxies.

Spiral galaxy: The Milky Way is the galaxy which is the home of our Solar System together with at least 200 billion other stars (more recent estimates have given numbers around 400 billion) and their planets, and thousands of clusters and nebulae.

Elliptical galaxy: The giant elliptical galaxy M87, also called Virgo A, is one of the most remarkable objects in the sky. It is perhaps the dominant galaxy in the Virgo Cluster of galaxies. M87's diameter corresponds to a linear extension of 120,000 light years, more than the diameter of our Milky Way's disk. It fills a much larger volume, and thus contains much more stars (and mass) than our galaxy, certainly several trillion ($10^{12}$) solar masses.
Funny galaxies

The ‘Cartwheel’

The ‘Antennae’
Galaxies with active nuclei

- The first class of galaxies with active nuclei was discovered by Seyfert (1940): Seyfert galaxies.
  - Spiral galaxies but possess star like nuclei
  - Strong and broad emission lines

- The next class of galaxies with active nuclei discovered was the radio galaxies.
  - Sources of vast fluxes of high energy particles and magnetic fields

- The first quasars were discovered early 1960
  - Look like star but has a luminosity much greater than galaxies.

- Radio quiet quasars, blazars, were discovered in 1965

- BL Lacertae er BL-Lac objects are the most extreme examples of active galactic nuclei.
  - Similar to quasars but luminosity vary rapidly (days): compact objects.
  - Optical spectra featureless and radiation strongly polarized.
Model for generating energy in AGNs

If the matter fell directly into the black hole on a purely radial orbit, then no energy would be liberated at all.
However, it is most unlikely that the matter falls straight in, because it must acquire some angular momentum, or rotation.
The matter can collapse along the axis of rotation and forms an accretion disc about the axis of rotation.

When the jet is directed towards us the luminosity increases.

The brightest observed steady sources:
\[ L_\gamma = 10^{42} \div 10^{47} \text{ erg/s} \]
Supernovae

• Supernova occur at the end of a star's lifetime, when its nuclear fuel is exhausted and it is no longer supported by the release of nuclear energy.
• If the star is particularly massive, then its core will collapse and a huge amount of energy is released.
• This will cause a blast wave that ejects the star's envelope into interstellar space.
• The result of the collapse may be a rapidly rotating neutron star that can be observed many years later as a radio pulsar.

Supernovae are rare events in our galaxy. There are many remnants of Supernovae explosions in our galaxy, that are seen as X-ray shell like structures caused by the shock wave propagating out into the interstellar medium.
A famous remnant is the Crab Nebula which exploded in 1054: pulsar which rotates 30 times a second and emits a rotating beam of X-rays (like a lighthouse).
Neutron stars may appear in supernova remnants, as isolated objects, or in binary systems. When a neutron star is in a binary system, astronomers are able to measure its mass. For binary systems containing an unknown object, this information helps distinguish whether the object is a neutron star or a black hole, since black holes are more massive than neutron stars.
Radio pulsars were discovered in 1967. Pulsars are isolated, rotating, magnetised neutron stars. They have jets of particles moving almost at the speed of light streaming out above their magnetic poles.

**Crab Nebula**: example of a neutron star formed during a supernova explosion. Figures show the diffuse emission of the Crab Nebula surrounding the bright pulsar in both the "on" and "off" states, i.e. when the magnetic pole is "in" and "out" of the line-of-sight from Earth. The period is 33 ms.
The pulses detected separately for the first time

One second time markers

First observation of pulses from CP 1919
28 November 1967

Mullard Radio Astronomy Observatory
Gamma-ray bursts are short-lived bursts of gamma-ray photons. At least some of them are associated with a special type of supernovae, the explosions marking the deaths of especially massive stars.

Lasting anywhere from a few milliseconds to several minutes, gamma-ray bursts (GRBs) shine hundreds of times brighter than a typical supernova. GRBs are detected roughly once per day from wholly random directions of the sky.

GRBs were discovered in the late 1960s by U.S. military satellites which were on the look out for Soviet nuclear testing in violation of the atmospheric nuclear test ban treaty.
The interstellar medium

The region between the stars in a galaxy have very low densities (they constitute a vacuum far better than can be produced artificially on the surface of the Earth), but are filled with gas, dust, and charged particles.

Approximately 99% of the mass of the interstellar medium is in the form of gas with the remainder primarily in dust. The total mass of the gas and dust in the interstellar medium is about 15% of the total mass of visible matter in the Milky Way.

Of the gas in the Milky Way, 90% by mass is hydrogen. The gas appears primarily in two forms

1. Cold clouds of atomic or molecular hydrogen
2. Hot ionized hydrogen near hot young stars

The clouds of cold molecular and atomic hydrogen represent the raw material from which stars can be formed in the disk of the galaxy if they become gravitationally unstable and collapse.

Interstellar dust grains are typically a fraction of a micron across (approximately the wavelength of blue light), irregularly shaped, and composed of carbon and/or silicates. These dust clouds are visible if they absorb the light coming through them.
Example: Orion Nebula

The Orion Nebula is relatively nearby, about 1500 light years away in the same spiral arm of the galaxy as our own Sun.
The Pleiades Cluster is a young cluster of predominantly blue stars that is visible to the naked eye. There is still some dust left from the nebula in which they formed, and light reflecting from that dust causes the blue haze around each star of the cluster.
Magnetic fields

The Milky Way galaxy contains an ordered, large-scale magnetic field of the value of about 3 µGauss (Earth's field at ground level is about 1 Gauss.)

Observation methods: analysis of starlight polarization, modeling pulsar or Faraday rotation, Zeeman splitting of atomic or molecular lines, radio synchrotron emission of electrons

A spiral galaxy like the Milky Way has three basic components to its visible matter which include the disk (containing the spiral arms), the halo, and the nucleus or central bulge. Because of the varying density in the galaxy's components, the magnetic field has a range of values.

Magnetic field derived from galaxy simulation overlaid on the galaxy NGC 4151. The blue 'ribbons' are components of a vertical magnetic field while the green arrows depict both the axisymmetric and bisymmetric magnetic fields observed in galaxies of this morphological type.

Estimations for extra-galactic magnetic field varies from 1 nGauss to 100 nGauss

The strongest, naturally-occurring, fields are found on a new kind of neutron star called a magnetar. These fields can exceed $10^{15}$ Gauss.
Dark matter

The basic principle for observations is that if we measure velocities in some region, then there has to be enough mass there for gravity to stop all the objects flying apart. Velocity measurements \(\rightarrow\) the amount of inferred mass is much more than can be explained by the luminous stuff \(\rightarrow\) Dark Matter

Precise measurements of the cosmic microwave background \(\rightarrow\) dark matter makes up about 25% of the energy budget of the Universe; visible matter in the form of stars, gas, and dust only contributes about 4%.

The leading candidate for this "dark matter" is the \textit{neutralino}, the lightest supersymmetric particle. On astrophysical scales, collisions of neutralinos with ordinary matter are believed to slow them down. The scattered neutralinos, whose velocity is degraded after each collision, may then be gravitationally trapped by objects such as the Sun, Earth, and the black hole at the center of the Milky Way galaxy, where they can accumulate over cosmic time scales.
Origin of cosmic rays: Cosmic accelerators?
Origin of cosmic rays

- The origin of CR is one of the major unsolved astrophysical problems.
- Their origin is most likely to be associated with the most energetic processes in the Universe.
- There is a large number of models for cosmic ray acceleration. The acceleration mechanism is not completely understood yet.
- In top-down scenarios energetic cosmic rays can also be produced by decay of massif particles which can be related to early Universe.
General principles of acceleration

The acceleration mechanisms may be classified as dynamic, hydrodynamic and electromagnetic.

**Dynamic:** Acceleration takes place through the collision of particles with clouds.

**Hydrodynamic:** Acceleration of whole layers of plasma to high velocities.

**Electromagnetic:** Particles accelerated by electric fields (magnetospheres of neutron stars).

Acceleration of particles in electric and magnetic field:
\[
\frac{d}{dt} (\gamma mv) = e(E + v \times B)
\]

Static electric fields difficult to maintain due to the very high conductivity of ionised gases. Acceleration mechanism can only be associated with non-stationary electric fields. Static magnetic fields don’t do any work but if the magnetic field is time-varying work is done by induced electric field.

Recent years: most effort to study particle acceleration in strong shock waves.
Cyclotron mechanism

- Even normal stars can accelerate charged particles up to GeV range.
- This acceleration can occur in time-dependent magnetic fields.
- These magnetic sites appear as star spots or sunspots: B typically 1000 Gauss.
- Particles from the Sun with energies up to 100 GeV has been observed.
Fermi mechanism of 2nd order (more generally Fermi mechanism) describes the interaction of CR with magnetic clouds.

When a particle is reflected off a magnetic mirror coming towards it, in a head-on collision, it gains energy.

When a particle is reflected off a magnetic mirror going away from it, in an overtaking collision, it loses energy.

Net energy gain, on average (stochastic process)
Schema of Fermi mechanism

**Case 1**

\[ \Delta E_1 = \frac{1}{2}m(v+u)^2 - \frac{1}{2}mv^2 = \frac{1}{2}m(2uv + u^2) \]

**Case 2**

\[ \Delta E_2 = \frac{1}{2}m(v-u)^2 - \frac{1}{2}mv^2 = \frac{1}{2}m(-2uv + u^2) \]

On the average, net energy gain is:

\[ \Delta E = \Delta E_1 + \Delta E_2 = mu^2 \]

\[ \Delta E/E = 2u^2/v^2 \]
Characteristics

Yields a power law spectrum (OK)

However:

Since the cloud velocity is low compared to particle velocities \((u \ll v \approx c)\), the energy gain per collision \(\approx u^2\) is very small
=> acceleration requires a long time (about \(10^8\) years!)

CR particles loose some of their gained energy between two collisions => requires a minimum injection energy above which particles can only be effectively accelerated.
Shock acceleration

Suggested in early 70, under development

Example: The ejected envelope of a supernova represents a shock front with respect to interstellar medium.

A particle of velocity $v$ colliding with the shock front and being reflected gains the energy:

$$\Delta E = \frac{1}{2}m(v+(u_1 - u_2))^2 - \frac{1}{2}mv^2$$

$$= \frac{1}{2}m(2v+(u_1 - u_2)+(u_1 - u_2)^2)$$
Shock acceleration

Since the linear terms dominate ($v \gg u_1, u_2, u_1 > u_2$):

$$\frac{\Delta E}{E} \approx \frac{2(u_1 - u_2)}{v}$$

A more general, relativistic treatment including also variable angles yield:

$$\frac{\Delta E}{E} = \frac{3}{4}\frac{(u_1 - u_2)}{c},$$

particle velocity $\approx c$

More efficient than 2nd order Fermi acceleration.
Astrophysical shocks

- Supernovae eject supersonic material
  - SN 1006
  - Tycho

- + gamma-ray bursts (relativistic fireballs)
- Stellar mass black holes emit plasma blobs

\[ \sim 10^{51} \text{ erg} \]
Maximum energy?

Energy losses
- Friction with ambient medium
- Synchrotron, IC
- Pair production
- photo-π

Escape
- Keep the particle in the accelerator
- Diffusion, gyroradius

Destruction
- Photo-disintegration

Confine the particle within the site:

\[ r_g = \frac{E}{ZeBc} < L \quad \rightarrow \quad E \lesssim Ze \times Bc \times L \]
Maximum energy: Example

For energies of $10^{20}$ eV a chock of 1 Mpc needed!
A candidate for acceleration up to extreme energies
Pulsars as cosmic accelerators

Spinning magnetized neutron stars (pulsars) are remnants of supernova explosions. They shrink under gravitational collapse to a size about 20 km! Their densities are comparable to nuclear densities!

Gravitational collapse conserve angular momentum => short rotational periods (milliseconds)!

The gravitational collapse amplifies the magnetic field (magnetic flux is conserved):

\[ B_{\text{star}} = 1000 \text{ Gauss} \Rightarrow B_{\text{pulsar}} \approx 10^{12} \text{ Gauss} = 10^8 \text{ Tesla} \]

For a 30 ms pulsar \( v_{\text{rot}} = 4 \times 10^6 \text{ m/s} \)

\[ \mathbf{E} = \mathbf{v} \times \mathbf{B} \text{ with } v \perp \mathbf{B} \Rightarrow E \approx vB = 10^{15} \text{ V/m} \]

A single charged particle can gain 1 PeV per meter!

However, it is not at all obvious how pulsars manage in detail to transform the rotational energy into acceleration of particles.
Production of particles and radiation by cosmic accelerators

- Acceleration of charges particles
- Production of gammas and neutrinos in the radiation and gas around the accelerator
Acceleration power

$E_{\text{max}} \sim \beta_s \cdot z \cdot B \cdot L$

- GRB
- Neutron Stars
- White dwarfs
- Active Galactic Nuclei
- LHC
- Interplanetary Space
- SNR
- Galact.
- Galactic Clusters
- Jets from radio galaxies
- IGM

Magnetic Field Strength (Gauss)

Size

$1 \text{ km}$ $10^6 \text{ km}$ $1 \text{ AU}$ $1 \text{ pc}$ $1 \text{ kpc}$ $1 \text{ Mpc}$
Origin of cosmic rays: Something exotic?
Exotic Particles? Other Sources?

Decay of topological defects:
super heavy relic particles from Big-Bang

\[ X\text{-particles} \quad (m \approx 10^{21}-10^{25} \text{ eV}) \]

\[ W, Z \text{ bosons} \]

\[ \gamma, \nu, p \ldots \]

Long living X-particles

Clustering in galactic halo, Dark Matter candidate

\[ Z^0 \rightarrow p, n, \gamma, \pi, \nu \]

\[ \text{UHE } \nu \rightarrow \text{Zevatron} \text{ Z-burst model} \]

i.e.: proof of evidence for neutrino background radiation
Conclusions

Cosmic ray Physics started 1912 when Victor Hess discovered that mysterious radiation is coming from space.

Today, the origin of cosmic rays is one of the most important question in modern astrophysics.

There are astrophysical objects that can probably accelerate cosmic rays. However, it is unclear how they can accelerate up to energies of $10^{20}$ eV!

Another possibility would be that some of these cosmic rays are decay products of yet unknown particle.