The Enigma of Cosmic Rays – 1

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Cosmic rays are energetic particles that zoom through space and occasionally enter our atmosphere. They are believed to be produced by violent astronomical events in and outside our Galaxy. Study of these particles provides a glimpse into the fascinating world of high energy physics.

We are being constantly bombarded on Earth by highly energetic particles coming from space. They are collectively called 'cosmic rays'. They constitute a large fraction of the total radiation exposure of human beings on earth. As a matter of fact, had it not been for the protective layers of our atmosphere, cosmic rays would have posed a considerable hazard for us (and something that future space travellers may well have to worry about).

Figure 1. Victor Hess aboard his balloon in 1912.

Cosmic rays were identified as particles coming from outer space soon after the discovery of radioactivity, when physicists had stumbled into a puzzling phenomenon. Radioactive materials emit particles that temporarily ionize air, and the resulting electric charges are detected by instruments like electroscopes. However, physicists noticed that electroscopes discharged, although slowly, even in the absence of radioactive matter, and they could not explain this residual discharge through leakage of any sort. They guessed that there was some sort of a background 'radiation' of particles.

An Austrian physicist Victor Hess planned in 1912 to study the source of this background by measuring the radiation level at different heights above ground, with electroscopes aboard a balloon. He wanted to determine whether this background radiation was in some way caused by radiation sources in the Earth. Hess went

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up to 17,500 feet in the balloon without oxygen tanks, and to everyone's surprise, he found that the radiation level *increased* with altitude. He interpreted that the source of radiation was not in the Earth, but in the cosmos (see *Box* 1). He called the radiation 'cosmic radiation', which later changed to 'cosmic rays'. Victor Hess was awarded the Nobel prize in physics in 1936 for this discovery.

Box 1. Discovery

C T R Wilson in England, who had invented the cloud chamber to detect energetic particles, noticed as early as 1902 that even in a well-shielded ionization chamber, a certain electrical leakage always occurred due to production of ions in the chamber. Radioactive substances and X-rays would have been stopped by the shields around the chamber. So, Wilson thought that some source of residual ionization existed that penetrated even thick material. He even suspected that the radiation was probably cosmic in nature.

He had set up an experiment at a place called Peebles in Scotland in a Caledonian railway tunnel and found that the discharge rate inside and outside the tunnel was the same. He concluded that: "There is thus no evidence of any falling off of the rate of production of ions in the vessel, although there were many feet of rock overhead. It is unlikely, therefore, that the ionization is due to radiation which has traversed our atmosphere ..."

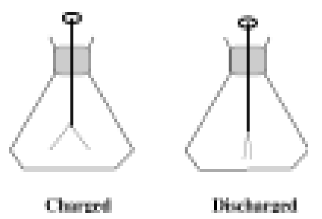

Figure A. An electroscope.

In 1912 (on 7th August), Victor Hess went up in a balloon along with two companions from Aussig in northern Bohemia. It was the seventh in his series of flights to seek the source of the strange radiation. The orange and black balloon, named Böhmen ('Bohemia' in German), was twelve stories tall, and was helped on its ascent by members of the Austraian Aeroclub. It had a lifting power of about two tons. One companion, Captain Hoffory, took care of the flight details, and another, W Wolf, observed the weather. Hess had listed himself as an 'observer of atmospheric electricity'.

They took off soon after six o'clock in the morning, after the helpers disconnected hoses from hydrogen tanks that they had carried in a wagon to the meadow by the river Elbe, from where they had decided to launch the balloon. An hour after the lift-off they reached a height of 1,600 meters and then to 3,600 meters in the next two hours. They were helped by a gentle breeze and the warming of the gas by the morning sun. They reached their maximum height of 5,350 meters sometime before 11 am, and Captain Hoffory began to release gas to start their slow descent.

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During the six hour long flight, Hess had noted the readings of three electroscopes he had carried to measure the intensity of radiation. He had three ionization chambers and relevant equipment – each chamber had a volume of two litres and was made of a sealed and thick walled metal cylinder that had a glass window to observe the electroscope leaves with the help of a microscope. Hess recorded the readings on all three instruments in rotation, along with barometric pressure reading that indicated the altitude, as called out by Wolf. Hess realized that the ionization at an altitude of 1 km dropped to 10 units compared to 12 units on the ground. But the reading went up to 12 units at an altitude of 2 km, climbing to 15 units at 3.5 km and then reaching 27 units at 5 km, double the level of ionization compared to what they found on the ground. On their way down, Hess took readings for another two hours, and confirmed the data he had obtained on his ascent. They landed soon after noon, in a village about 50 km east of Berlin, having travelled a distance of 200 kilometers in six hours.

When Hess plotted the data, there was no doubt that the radiation level increased with the altitude of the balloon. He wrote in a paper that he published later that year in *Physikalische Zeitschrift*: “The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above.”

Further balloon flights were made during the next two years by Werner Kohlhörster that reached heights beyond 9 kilometers. Even at that height, Kohlhörster found that the ionization continued to increase rapidly, but not every one was convinced by the data of Hess and Kohlhörster, and there ensued a debate in the scientific circles that continued for a dozen years.

A historically important event took place the day Kohlhörster went up on his balloon to reach a height of 9,300 meters: Archduke Francis Ferdi-nand, heir to the throne of Austria-Hungary, was assassinated in Sarajevo, and soon the whole of Europe plunged into World War 1. Further research for the strange ‘cosmic’ radiation had to wait until the political turmoil was resolved.

1. What are Cosmic Rays?

Cosmic rays are essentially elementary particles and nuclei that are accelerated to very high energy in space and which then enter our atmosphere. Their energies span a large range, from 10^9 eV to 10^{20} eV. Recall that one electron volt (eV) is the amount of kinetic energy gained by an electron in passing through a potential difference of one volt (in vacuum), and is roughly 1.6×10^{-19} J. Compare the energy of a typical cosmic ray to the typical kinetic energy of a molecule in our atmosphere, which is ~ 0.025 eV – cosmic rays are at least a billion times more energetic than this.

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The most puzzling aspect of cosmic rays is that some of these particles possess a tremendous amount of energy. Their kinetic energy per particle can be as large as 10^{20} eV$\sim$ 10 J, which is approximately the kinetic energy of a coconut weighing 1/2 kg falling to the ground from a 2 meter tall tree! Imagine all that energy being carried by a tiny sub-atomic particle. It is also roughly the energy used by a 40W light bulb in one third of a second.

The existence of very energetic cosmic rays is therefore a puzzling phenomenon, and one must explain how particles can be accelerated to such high energies in space. One must also explain the distribution of cosmic ray energies, which means the number of particles in different energy ranges. For example, when one considers gas in thermal equilibrium, one expects the number of particles in a certain energy range to behave in a predictable way – most particles would have energy close to the 'mean' energy (of order kT where $k = 1.38 \times 10^{-23}$ J per degrees Kelvin is the Boltzmann constant, and T is the matter temperature) and some particles would have smaller or larger energy than this typical energy. In other words, the distribution has a 'peak' at an energy close to $\sim kT$, and the number of particles with smaller and higher en-

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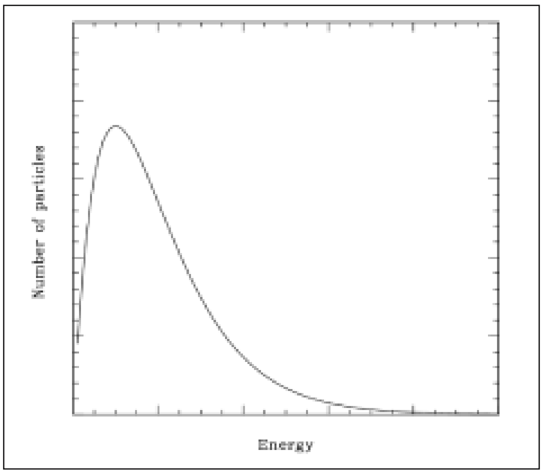

Figure 2. Maxwell–Boltzmann distribution of particles with respect to their energies in a gas of a given temperature.

ergy than this is small. This is the Maxwell–Boltzmann distribution of energy expected among gas particles in thermal equilibrium (*Figure* 2).

Observations of cosmic rays show that their energies are distributed in a peculiar way. There does not seem to be any 'mean' energy, nor is there any peak in the distribution of energy among particles. Instead, the number of particles with energy E seems to be proportional to E^{-p}, so that there are many particles with very small energies, energies, and few particles with very high energies (*Figure* 3). At the smallest energy ranges, there are

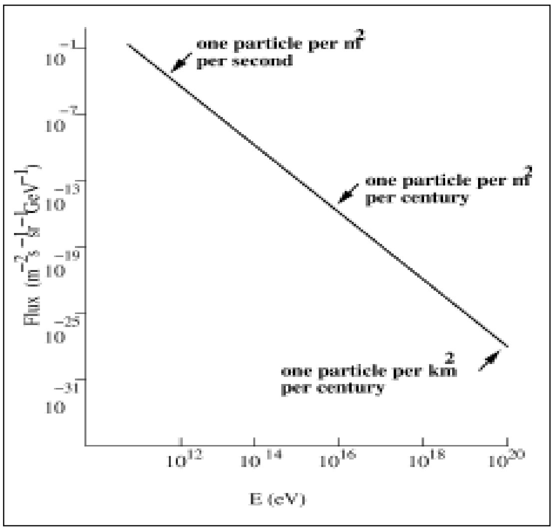

Figure 3. Energy spectrum of cosmic rays. The x-axis shows energy in eV, and the y-axis plots the flux of particles carrying this energy (in the units of number per second per square meter per steradian, per 10^9 eV.)

plentiful cosmic rays, of many thousand particles hitting the atmosphere per square meter per second, whereas the highest energy cosmic rays are very rare – with less than one hitting a square kilometer of Earth's surface each century! This 'power-law' distribution of energy (since the distribution is proportional to some 'power' $-p$ of energy E) also cries out for an explanation.

As far as the composition of cosmic rays are concerned, most of them appear to be protons, but many heavy atomic nuclei[1] are also present, extending all the way up to uranium nuclei. In numbers, about half of all cosmic rays (in the energy range of 10^{12}–10^{15} eV) are protons, about 25% are helium nuclei, $\sim$ 13% are carbon-nitrogen-oxygen nuclei, and about a percent are electrons. A small fraction of cosmic rays are photons (with very high energy, which have gamma rays).

2. Detection of Cosmic Rays

It is difficult to detect the lowest energy cosmic rays on the surface of the Earth as they get absorbed in the upper atmosphere. They can be only detected by high altitude balloons or satellites.

When a high energy cosmic ray hits the upper atmosphere, it creates a jet of particles which travel approximately in the same direction (with a small deflection due to collision with air molecules). The particles in this jet can themselves create more particles when they hit other molecules in the air. This 'cascade' of particles is called an 'air shower', and it grows until particles in the shower have lost their energy and have been absorbed in the atmosphere. (*Figure* 4.) The initial cosmic ray particle, which triggers the showers is called the primary particle, and the particles created in the air shower are called the secondary particles. Numerous secondary particles are created every time a cosmic ray hits our atmosphere.

A high energy cosmic ray can generate a shower with

[1] See the Reflections article, on p.87, by Bernard Peters, one of the discoverers of heavy nuclei in cosmic rays.

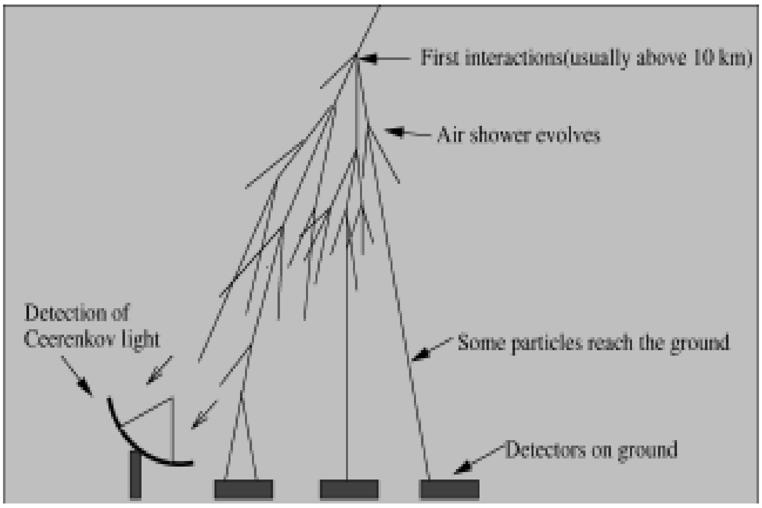

Figure 4. Air showers created by primary cosmic rays. Several types of detectors exist to estimate the energy and direction of arrival of the primary cosmic ray particle by studying the air shower.

a million particles in it. The secondary particles emit flashes of blue light known as Cerenkov radiation that can be detected by using optical telescopes. These observed flashes can then be interpreted based on models of air showers, and the energy and the direction of the primary cosmic ray can be determined.

Very high energy cosmic rays can create showers with billions of secondary particles which are energetic enough to reach the ground that can be detected by particle detectors. Often these detectors are arranged in the form of a grid or an array on the ground so that a single shower can be detected at several points. From the number of particles hitting a certain detector in this grid, and the time of detection, one can reconstruct the air shower and one can estimate the energy and direction of the primary cosmic ray.

3. Age of Cosmic Rays

A high energy cosmic ray can generate a shower with a million particles in it.

Among the nuclei detected as cosmic rays, a few are radioactive, and the measurement of their abundance with respect to nuclei of other elements in cosmic rays provides a way of measuring the ‘age’ of cosmic rays. By ‘age’, we mean the average time period spent between their origin in the cosmos and detection on Earth. One such radioactive nuclei is an isotope of Beryllium with atomic number 10; it has a half-life time of ~ 1.5 million years. Comparison of its abundance with other elements shows that cosmic rays on an average spend $\sim (2\text{–}3) \times 10^7$ years in the interstellar space before beign detected on Earth.

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There is another way of estimating this 'age'. Cosmic rays show an extra abundance of light element nuclei, such as that of lithium, boron and beryllium (with respect to the abundance of hydrogen nuclei) compared to the abundance in solar neighbourhood. This phenomenon is explained in the following way: Cosmic rays travel through the interstellar gas and when they collide with a heavy nucleus (like carbon, nitrogen or oxygen), they split it into lighter nuclei, thereby increasing the abundance of light elements in cosmic rays. Clearly, the extra abundance is determined by the collision rate, and therefore depends on two factors: density of interstellar gas and the travel time of cosmic rays through it (or their 'age'). This estimate also shows that cosmic rays spend about 20 million years in their interstellar journey around the Galaxy.

Recall that in the presence of magnetic field, charged particles spiral around the field lines (*Box* 2). The interstellar space is permeated by tangled magnetic field lines, and cosmic ray particles travel through the interstellar gas in a complicated zigzag fashion, being guided by the magnetic field lines. This means that the direction of arrival of cosmic rays on Earth does not necessarily point towards their origin in space – all memory of the direction of their source with respect to Earth is lost during the journey through the interstellar space. It therefore becomes difficult to pinpoint their origin by simply finding out the direction of their arrival.

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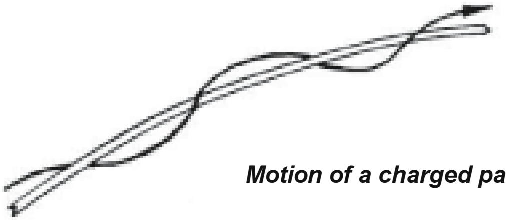
Box 2. Magnetic Mirrors

Consider a charged particle moving in a uniform magnetic field, where the electric field is zero. Suppose the magnetic field is described by $\mathbf{B} = B\hat{\mathbf{z}}$, so that the field is zero in x and y directions, and is non-zero only in the z direction. The law of motion of the particle is given by (in the non-relativistic case):

$$m\frac{d\mathbf{v}}{dt} = q\mathbf{v} \times \mathbf{B}$$

Note that the force is perpendicular to velocity, and so there is no net work done $(\mathbf{F} \cdot \mathbf{v})$ on the particle by the magnetic field. So, the energy of the particle does not change, and the kinetic energy in particular ($(1/2)mv^2$) is a constant. In other words, the magnitude of velocity does not change.

The equation also shows that the acceleration is perpendicular to velocity. The velocity of the particle can be divided into two components : $\mathbf{v}_\perp$ perpendicular to the magnetic field and $\mathbf{v}_\|$ that is parallel to the magnetic field. Clearly, the magnitude and direction of $\mathbf{v}_\|$ is not changed, and only the direction of $\mathbf{v}_\perp$ changes.



Motion of a charged particle in magnetic field.

Therefore, the motion is helical as shown in the figure (generalized to a case when the magnetic field changes its direction). The radius (gyro radius) of the helix is $r = \frac{mv}{|q|B}$, which can be derived by equating the acceleration mentioned above with centrifugal acceleration.

The total energy of the particle is given by $E = \mu B + mv^2/2$, where μ is the permeability. Now consider the case that B is not uniform. It can be shown, in the case where the change in B is not drastic, that the quantity ${\mathbf{v}_\perp}^2/B$ is a constant. This means that when B increases, the parallel component of velocity decreases, and it may so happen that it can drop to zero and the direction of velocity may reverse. The charged particle will then 'reflect' off in the opposite direction from the region of large B. This is called a magnetic mirror.

4. Origin of Cosmic Rays

What sort of cosmic phenomenon can accelerate particles to very high energies? Flares on the surface of the sun – in which hot gas is flung by magnetic fields to large distances off the surface, and during which gas particles can get accelerated – can produce ions with energy of a few billion eV, and which are often missed by ground-based detectors on Earth as these ions are shunted by the magnetic field around the Earth to the polar regions (to create aurora in the sky there).

Figure 5. Enrico Fermi depicted in a stamp issued by USA.

But there are other phenomena in space more energetic than solar flares. When massive stars use up their nuclear fuel, they explode in a spectacular manner, ripping themselves apart in a gigantic explosion called 'supernova'. These stellar material (which once made up the progenitor star) travel in space with initial speeds of order 10,000 km per second. They are eventually slowed down as they sweep up the surrounding gas (space between stars is not completely empty!), and compressing the gas to large density and high temperature. The compression of gas also leads to compression of magnetic field embedded in this gas.

In 1949, Enrico Fermi suggested that charged particles reflected by moving interstellar magnetic fields can explain the cosmic ray phenomenon. A particle hit by a moving cloud will either gain or lose energy, depending on whether the magnetic 'mirror' (see *Box* 2) is approaching or receding from it. Fermi argued that the probability of a head-on collision is greater than a collision in which a cloud recedes from a colliding particle (a 'tailgate' collision). So, particles would on an average be accelerated. But it can be shown that in this case, for a relativistic particle moving with speed c close to that of light reflecting off a heavy cloud moving with speed v, the fractional energy gain by the particle is of order $(v/c)^2$, which can be very small, since the typical speed of interstellar clouds is $\sim 10^3$ m/s, so that $v/c < 10^4$, and the fractional energy gain becomes too inefficient. (It would take, typically, as many collisions as $\sim (v/c)^{-2}$ for the particle to gain significant amount of energy. With a typical distance of $\sim 10^{16}$ m between interstellar clouds, it would mean waiting for a dura-

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tion $\sim (L/v)(v/c)^{-2}$, or more than ten billion years, or the age of the universe, for particles to get significantly accelerated!)

When a shockwave moves through a fluid, particles ahead which are moving with a small speed, are suddenly enveloped by the shockwave and start moving with a high speed.

In 1970s, physicists found a way to accelerate particles with a higher efficiency than this. Energetic events often push gas in space with a speed larger than the sound speed, and it leads to what is called a 'shock wave' travelling through space. A 'shock front' is essentially a location where gas parameters, like its speed and density, change drastically and abruptly. When a shockwave moves through a fluid, particles ahead which are moving with a small speed, are suddenly enveloped by the shockwave and start moving with a high speed. Magnetic field lines disrupted by such a shockwave will still act as 'mirrors' and scatter these highly energetic particles which may travel back and forth across the shockfront many times and keep gaining energy. It can be shown that in the case of a shockwave moving with speed v, a relativistically moving particle can gain a fractional energy of $\sim v/c$. Firstly, this fraction is greater than the previous case, and secondly, shockwave speeds can be as large as 10^7 m/s in some cases. This mechanism can then accelerate particles to very high energies in a short time.

It can be shown that in the case of a shockwave moving with speed *v*, a relativistically moving particle can gain a fractional energy of ~ *v/c*.

Interestingly, Fermi had noted that this 'stochastic' acceleration mechanism can also produce a power-law energy distribution among particles, just as observed for cosmic rays. Consider the case when particles are steadily injected into some acceleration region, and they gain energy at a rate that is proportional to their energy ($dE/dt = E/t_a$). At the same time, suppose that the particles escape from in a time scale t_e ($dn/dt = -n/t_e$). In other words, the probability per unit time of escape is $1/t_e$. Then in a steady state, the number of particles in the energy range $E, E + dE$ is given by (see *Box* 3),

$$n(E)dE \propto E^{-(1+t_a/t_e)}dE \, . \qquad (1)$$

Box 3.

If particles gain energy according to the equation,

$$\frac{dE}{dt} = \frac{E}{t_a} \tag{1}$$

then this equation can be solved to give,

$$E(t) \propto \exp(t/t_a)\,. \tag{2}$$

At the same time, if particles are lost according to,

$$\frac{dn}{dt} = -\frac{n}{t_e} \tag{3}$$

then we also have for the evolution in the number of particles,

$$n(t) \propto \exp(-t/t_e) \propto E^{-[t_a/t_e]}\,. \tag{4}$$

The number of particle with energy in the range $E, E + dE$ in a steady state will then be,

$$n(E)dE = n(t)\left(\frac{dt}{dE}\right)dE \propto \frac{1}{E}\exp(-t/t_e)\,dE \propto E^{\left[-1-t_a/t_e\right]}\,dE\,. \tag{5}$$

Equivalently, the number of particles with energy more than E is obtained by integrating this distribution, and is given by $n(> E) \propto E^{-t_a/t_e}$.

As an analogy with a game of chance, consider some gamblers who continually join a game so that they can either increase their winnings by a small fraction f with probability $(1 - p)$ or lose everything with probability $p(\ll 1)$. In that case, the number of gamblers that win more than some amount w before inevitably losing is proportional to $w^{-p/f}$. In the cosmic rays, w corresponds to the energy, f is proportional to $1/t_a$, and $p \propto 1/t_e$.

Therefore, the energy spectrum of cosmic ray depends on two important parameters: the time scale of acceleration and that of escape. We will discuss in the next article of the series the cosmic events that can produce cosmic rays detected on Earth.

Suggested Reading

[1] J Cronin, T Gaisser and S Swordy, 'Cosmic rays at the energy frontier', ***Scientific American*****, January 1997**

[2] J Cronin, 'Cosmic rays : the most energetic particles in the universe', ***Reviews of Modern Physics*****, Vol.71, p.165, 1999.**

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