The Enigma of Cosmic Rays – 2

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Part 1[1] of the article discussed the discovery and observed properties of cosmic ray particles. These energetic particles are produced during violent astronomical events. We discuss possible sources of cosmic rays detected on Earth in this article. Supernovae explosions of dying stars are believed to produce cosmic rays with low energy. The detection of ultra-high energy cosmic rays is however difficult to explain. On one hand, they must originate outside our Galaxy and on the other, the cosmic microwave background radiation pervading the universe makes it difficult for them to travel large distances in intergalactic space. So, they must be produced in the neighbourhood of our Galaxy, but are there enough energetic phenomena taking place in this region of the universe?

[1] The Enigma of Cosmic Rays – 1, *Resonance*, Vol.12, No.10, pp.6–17, 2007.

1. Where are Cosmic Rays Produced ?

It was suggested in 1960 by Bernard Peters of Tata Institute of Fundamental Research, Mumbai, that low energy cosmic rays originate in our Galaxy. One possible source is a cataclysmic event that destroys massive stars. They are called 'supernova' and these explosions can be very energetic. Shockwaves emanating from these explosions initially hit the surrounding gas with a speed exceeding 10^7 m/s before slowing down after $\sim 10^4$ years. One can ask if there is enough energy in these shockwaves to account for the total energy budget of cosmic rays. When one adds up the total energy density from the detected fluxes of cosmic rays at different energy ranges, one estimates a total energy flux of $\sim 3 \times 10^{-8}$ Watt per square meter. The total kinetic energy in a supernova

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shockwave is $\sim 10^{44}$ J, and from the estimated rate of supernova in our neighbourhood of the Galaxy (about one per century), the total power deposited by supernovae is $\sim 2 \times 10^{-7}$ Watt per square meter. In other words, supernovae need to use $\sim 15\%$ of their total kinetic energy into accelerating cosmic rays to account for the energy budget of cosmic rays in our Galaxy. This is quite feasible in the framework of shockwave acceleration of particles that we discussed in Part 1 of this series.

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These are not just theoretical estimates any longer. There are now hard evidences for particle acceleration in supernova shockwaves that have been obtained with modern X-ray telescopes. These telescopes have now detected emission of X-rays from highly accelerated particles on the rim of supernova remnants. An example is a remnant of a supernova named SN 1006 since it was surmised from observations that the explosion took place in year 1006, and it matched with the Chinese record of flaring of a star. These observations support the idea that cosmic rays detected on Earth are produced in energetic phenomena like supernovae. But theoretical calculations show that supernovae are not energetic enough to accelerate particles to energies $\geq 10^{16}$ eV. Cosmic rays more energetic than these must be produced elsewhere.

As discussed in Part 1, the spectrum of cosmic rays accelerated in shockwaves depend on the fractional energy gain ($\propto 1/t_a$) and fractional loss of particles per collision ($\propto 1/t_e$). It turns out that the ratio of these fractions is close to unity for shockwaves, and so one expects a cosmic ray spectrum close to E^{-2}. The observed cosmic ray spectrum ($E^{-2.7}$) is somewhat steeper than this, as some cosmic rays are thought to leak out of the Galaxy with higher energy particles leaking out faster than lower energy particles. So, the number of high energy cosmic rays is rendered smaller than expected from supernovae shock acceleration.

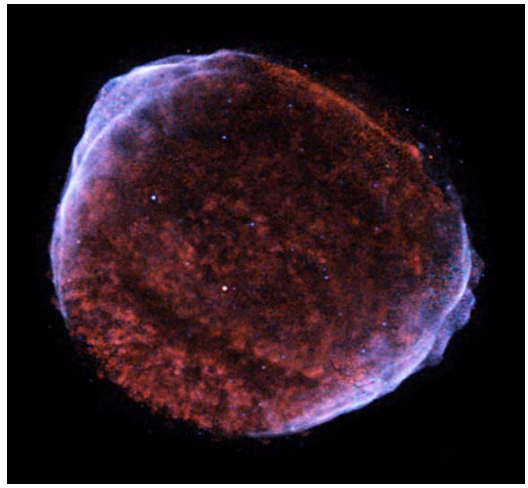

Figure 1. The supernova remnant SN 1006 as seen in X-rays by Chandra telescope. The colours are artificial (coded according to energy of X-ray photons). The 'blue' glow around the rim is believed to arise from cosmic ray particles accelerated by the supernova shockwave. The region inside the shock wave also shines in X-rays, but its spectrum is different from that of the X-rays from the 'blue' region. The observed spectrum of the 'blue' region shows that these X-rays are produced by energetic particles gyrating around compressed magnetic field lines, just as expected in the models of acceleration of particles in shockwaves.

(Courtesy: NASA)

The leakage of cosmic rays takes place on account of the magnetic field of our Galaxy. Charged particles generally spiral around magnetic field lines, with the spiraling radius (called the 'gyro radius') being larger for more energetic particles. For example, the typical strength of magnetic field in our Galaxy is a few micro Gauss (compared to about a Gauss on the Earth). For this strength, a 10^9 eV proton will gyrate around the magnetic field lines very tightly (gyro radius $\sim 3 \times 10^{10}$ m), whereas a 10^{20} eV proton will essentially travel straight (gyro radius $\sim 30,000$ light years). (As a matter of fact, this was the basis of the Bernard Peters' hypothesis mentioned earlier that low energy cosmic rays are produced inside our Galaxy.)

2. Ultra-High Energy Cosmic Rays

This estimate shows that the ultra-high energy cosmic rays cannot originate in our Galaxy and must come from elsewhere. The magnetic field in our Galaxy is not strong enough to hold them within our Galaxy, so they would easily escape if they are produced inside the Milky Way. Energy of these particles are comparable to bricks falling from a table, or that of a tennis ball being hurled at great speed, but packed into a subatomic particle!

The energy spectrum of cosmic rays too show some differences below and above a critical energy of $\sim 6 \times 10^{19}$ eV. This suggests that particles above this energy level constitute a different group of particles than those produced by the usual sources of our Galaxy that we have discussed in the first part of the article. So, they must be produced outside the galaxy.

Universe is pervaded by an electromagnetic radiation field, which is supposed to be a relic from the early, hot phase of the universe.

Can they be produced very far from our Galaxy and still reach us? Firstly, the intergalactic magnetic field – although very small, with $B \sim 10^{-9}$ Gauss – will change the direction of its trajectory to some extent, given the large distances involved in the intergalactic journey of a particle. So, the direction of arrival of an ultra-high energy cosmic ray may not really point towards its region of origin. If it were not so, one would have looked for in that direction for some extraordinary object capable of accelerating particles to very high energy.

Secondly, although gas inhabiting the intergalactic space is very tenuous – with densities as ridiculously low as $\sim 10^{-13}$ per cubic metre – it does contain a field of radiation. We know that the whole universe is pervaded by an electromagnetic radiation field, which is supposed to be a relic from the early, hot phase of the universe. This is called the cosmic microwave background radiation (CMBR).

3. Cosmic Microwave Background Radiation

When the universe was young, small, hot and dense, matter in it was in thermal equilibrium with radiation. We know from thermodynamics that in such a case, when matter and radiation interact strongly and keep one another in equilibrium – as much radiation is absorbed by matter as is emitted by them and the radiation acquires some special characteristics. This is called a blackbody radiation and it has a spectrum that is well studied, called the Planckian spectrum. The spectrum peaks at a certain wavelength which is determined only by the temperature of matter that the radiation is in equilibrium with. The spectrum drops at both lower and higher wavelengths. For example, the peak wavelength for a temperature of $\sim 5,000$ K is ~ 600 nm (nanometer) and for $T \sim 10$ K, it is $\sim 3 \times 10^5$ nm, or ~ 0.3 mm.

As the universe expanded and cooled, this radiation has also cooled down to a present day temperature of $\sim$ 2.7 K, and the radiation now peaks at a wavelength in the microwave region. This is why it is called cosmic microwave radiation. The mean energy of the photons is $\sim 7 \times 10^{-4}$ eV (1 eV$= 1.6 \times 10^{-19}$ J) and the number of the background radiation photons is $\sim 3.7 \times 10^8$ per cubic metre. It is these photons that pose a problem for ultra-high energy cosmic rays while travelling through the universe [1].

4. Greisen–Zatsepin–Kuzmin (GZK) Limit

When a very high energy nucleon collides with a microwave photon in the universe, there is a probability that the interaction will split the nucleon into smaller particles, like pions. The frequency of such interactions for a certain cosmic ray particle would be determined by the probability of interaction with microwave photons. Given the above mentioned number density of CMBR photons, and with the knowledge of the probability of the interactions, one finds that an ultra-high energy cosmic ray particle should have a collision of this type every few million light years. A conservative estimate would be to say that an ultra-high energy cosmic ray would *not* be able to travel further than a distance of ~ 150 million light years in the intergalactic space because of the obstacle of CMBR photons. It is as if they have to wade through a thick fluid of photons and soon lose their energy. This theoretical limit was calculated by Kenneth Greisen, George Zatsepin and Vadim Kuzmin in 1966 and is known as the GZK limit.

The result of rapid energy loss for protons (and other nuclei) is that they are not allowed to travel beyond a certain distance. Consider a proton with energy E that loses an amount of energy ΔE in an interaction with a background photon. Suppose the number density of photons is n, and the interaction cross-section is σ. Then the proton will not be able to go much beyond a length,

$$L_{GZK} \sim \frac{E}{\Delta E}\frac{1}{n\sigma}.$$

For example, if $\Delta E \sim E$, and $n \sim 400$ per cm^{-3} and $\sigma \sim 2 \times 10^{-28}$ cm^2, we get $L_{GZK} \sim 100$ million light years. Typically $\Delta E \lesssim E$, and we get L_{GZK} 150 million light years from more detailed calculations.

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The GZK limit essentially puts a bound on the possible distance at which the ultra-high energy cosmic rays that are detected on earth can originate. Clearly, one needs to look for possible sources of these particles within a distance of ~ 150 million light years. What should the characteristics of these sources be?

5. Sources of High Energy Cosmic Rays

When particles get accelerated by scattering off magnetic irregularities behind shockwaves, it can be shown that the maximum energy attained by particles is similar to the case of charged particles gaining energy across a potential gap. If a magnetic field of strength B moves with speed v through conducting matter, then from Lenz's law we can estimate the electric field generated by electromagnetic induction as $E \sim vB$. Over a length scale R, this produces an electromotive force $\sim ER \sim vRB$. And a charged particle (with charge q) can then attain a maximum energy $\sim qvRB$. So, we see that it helps to have a large magnetic field, and a large region, to accelerate particles to very high energies (v is of course limited by the speed of light). The source

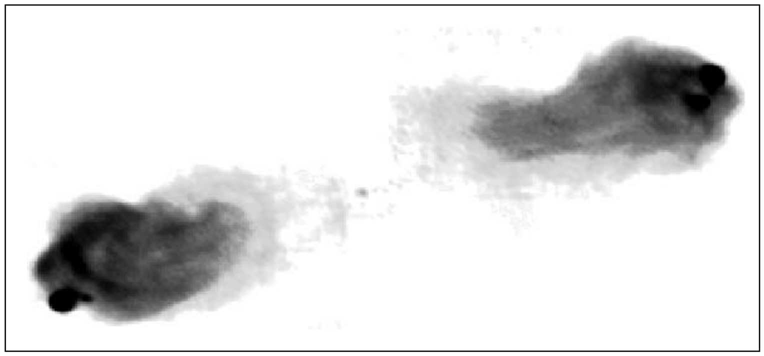

Figure 2. Cygnus-A is a radio galaxy, here imaged with radio waves of of 20cm wavelength. Two jets of highly energetic particles come out of the central galaxy and produce a region of strong magnetic field and accelerated particles when they interact with the intergalactic gas.

(Courtesy: National Radio Astronomical Observatory, USA)

of ultra-high energy cosmic rays must therefore be large and with strong magnetic fields.

There are some galaxies in the universe which produce enormous jets of energetic particles, which are spewed out of the galaxy into the intergalactic space. When they hit the intergalactic gas, they create an enormous shockwave encompassing a large region. These are called radio galaxies, since the high energy particles gyrate around the compressed magnetic field in the shocked regions, and emit photons of radio wavelengths. Radio astronomers have discovered many such radio galaxies, and the total power output of these galaxies is often as large as $\sim 10^{39}$ Watt!

The magnetic field in the compressed region (called the 'hotspot') is often of the order $\sim$ 10 nT (nano Tesla) and the size of the region is larger than 10^4 light years ($\sim 3 \times 10^{20}$ m). So, one gets a maximum energy of protons of order 100 J ($\sim 6 \times 10^{20}$ eV). This is what one would like to achieve to be able to explain the occurrence of ultra-high energy cosmic rays. The question is – are there some as powerful galaxies in our neighbourhood within about 150 million light years of our Galaxy.

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There are indeed a few powerful entities, like a galaxy named M87 that resides in Virgo cluster of galaxies. (It appeared to Messier as a hazy object in a catalogue he produced not to be mistaken for comets, and it was the 87th entry in his catalogue.) This cluster of galaxies is

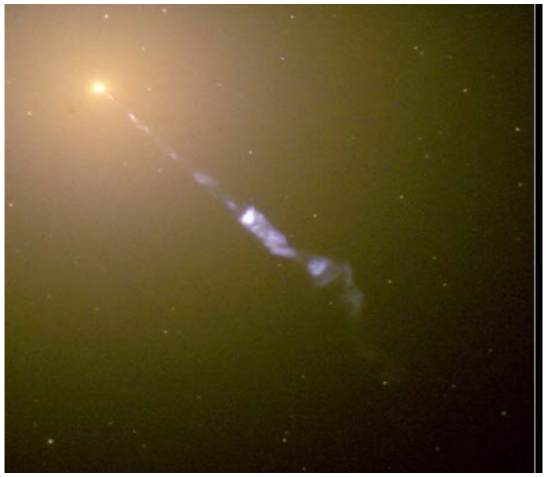

Figure 3. The galaxy M87 in virgo cluster of galaxies is at a distance ~50 million light years from us, and throws out jets of energetic particles.
(Courtesy: NASA)

about 60 million light years from Milky Way, and this galaxy in particular shows powerful jet coming out of it. But can one be really certain that this *is* at least one of the sources of ultra-high energy cosmic rays that bombard our Earth from time to time?

It is also possible that when clusters of galaxies collide, the resulting shockwave through the gas and the compressed magnetic field may produce some of these ultra-high energy cosmic rays. Observers have detected such collisions of galaxy clusters (each containing hundreds to a thousand galaxies, amounting to a large amount of hot gas and magnetic field) in visible wavelengths and in X-rays. But if these collisions were to give rise to ultra-high energy cosmic rays, they would need to take place within ~ 150 million light years from us.

Instead of accelerating slow particles to high energies during some energetic event, is it possible that there are sources of extremely high energetic particles, which have a much larger energy than that of cosmic rays, those that decay down slowly to lower energies and show up as cosmic rays?

6. Other Possibilities

There is yet another possibility that physicists have considered with regards to the origin of ultra-high energy cosmic rays. Instead of accelerating slow particles to high energies during some energetic event, is it possible that there are sources of extremely high energetic particles, which have a much larger energy than that of cosmic rays, those that decay down slowly to lower energies and show up as cosmic rays? In other words, The early universe was hot, and when it expanded and cooled, it may have gone through some 'phase transition' just as one finds in water cooling to form ice.

are ultra-high energy cosmic rays decay products of still higher energetic particles?

At first sight, the proposal might appear incredible, but there are reasons to believe that extremely high energetic particles are created from time to time in our universe, at places that contain what is called a 'topological defect'. The early universe was hot, and when it expanded and cooled, it may have gone through some 'phase transition' just as one finds in water cooling to form ice. The state after the phase transition may not be very uniform however, and one may end up with locations (or surfaces) which are at a different state than the surroundings. These are called defects and they may be highly energetic. They essentially contain the original, energetic state of matter in the early universe. These energetic entities may then produce particles with lower energies, and some of them may decay down to the typical energies comparable to that of ultra-high energy cosmic rays.

Physicists have studied this possibility in some detail and even estimated the energy spectrum of particles emanating from these defects. But it is not clear how abundant such hypothetical defects are in the universe, since they cannot be observed or detected easily. It is therefore difficult to compare the predictions with detected numbers of cosmic rays.

The puzzle posed by ultra-high energy cosmic rays is difficult to solve as the statistics of such energetic particles is very limited. At these energies, the particles are so rare that one of them strikes in about a century in an area of a square kilometre! To gather data for a large number of such energetic particles, one requires an array of detectors spread over a huge area.

7. Future Studies

A new detector system is now being built specifically for

Figure 4. A water tank detector in the Pierre Auger observatory in Argentina.
(Courtesy: http://www.auger.org)

this purpose in the Southern hemisphere. A grid of detectors covering an area of 3,000 square kilometers and with detectors spaced 1.5 km apart in a triangular pattern is under construction in the vast prairie region of west Argentina. It has been named Pierre Auger Cosmic Ray Observatory, after the French physicist Pierre Auger who, among other things, discovered air showers created by cosmic rays. It will consist of different types of detectors, for tracing the ultraviolet glow emitted by particles zooming through air, to detect them on ground and also by their interaction with water. The last type of detectors will consist of 1,600 water tanks, each containing 12,000 litres of water, completely dark inside, 1.5 km apart. When cosmic ray particles pass through them, they will emit a radiation which will be detected by sensitive instruments around the water tank.

This observatory is being built by physicists from about 15 countries, and it has begun to detect cosmic rays. One hopes that with its large area coverage, it will soon gather enough statistics to confront the rivaling hypotheses for the origin of ultra-high energy cosmic rays.

The most puzzling aspect of cosmic rays is that there does not appear to be any natural end or limit to the energy of cosmic rays. Energetic phenomena in nature usually have a characteristic limit up to which they can energize matter, but cosmic rays seem to carry energy without any apparent limit. Extremely energetic cosmic rays are rare in numbers, but they do exist, and therefore pose a challenge to physicists to explain their origin.

Suggested Reading

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[2] J Cronin, T Gaisser and S Swordy, Cosmic Rays at the Energy Frontier, *Scientific American*, January 1997.

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