Particle Acceleration and Astronomical Sources of Extremely High Energy Cosmic Rays

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Theoretical standpoints of particle acceleration processes are briefly reviewed, emphasizing the role of electric fields, both in direct and statistical acceleration mechanisms. Various astronomical source candidates for the origin of extremely high energy cosmic rays are also discussed.

KEYWORDS: particle acceleration, cosmic rays, collisionless shock, galaxies, gamma-ray bursts

§1. Introduction

The origin of cosmic rays is one of the long-standing unsolved problems in physics. The energy of cosmic rays ranges from below GeV up to above 10^{20}eV. In particular, the origin of extremely high energy cosmic rays (EHECR) above 10^{19}eV has recently attracted much attention.[1,2] Because of the interaction with microwave background radiation, cosmic ray protons above the Greisen-Zatsepin-Kuzmin (GZK) cutoff at $10^{19.7}$eV rapidly lose energy and a sharp cutoff is naturally expected at this energy,[3,4] while recent AGASA observations show that the cosmic ray spectrum extends smoothly well beyond 10^{20}eV.[5,6] Since EHECR cannot be confined in the Galactic diskCthey are believed to be extragalactic origin but come from within 50Mpc distance to avoid GZK cutoff. Although various ideas have been put forward, none is widely accepted.[7–9] In this article I will treat conventional bottom-up scenario in which some astrophysical sources accelerate protons above 10^{20}eV. I begin with the present status of the understanding of the cosmic ray acceleration at lower energies, noting that there remain several unsolved theoretical issues in particle acceleration the mechanisms of which should be common with EHECR.

Cosmic ray spectrum is well described by a power law shape with several break features. Below the knee at $10^{15.5}$eV, the spectral index is 2.7 and cosmic rays in this energy range are believed to be generated in supernova remnants (SNRs) in our Galaxy by the diffusive shock acceleration.[10–17] Although direct confirmation of cosmic ray acceleration in SNRs is possible through the γ-ray observations at GeV to PeV range,[18,19] definite confirmation is yet to be done at the present. Since observational upper limits are quite near the theoretical predictions, we expect that in near future it becomes possible to probe the cosmic ray spectrum at the source, which is confronted with theory of acceleration and propagation of galactic cosmic rays.

Above the knee, the spectrum steepens to an index of 3.1 and continues up to the ankle at $10^{18.5}$eV. Cosmic rays in this energy region are also believed to be produced in our Galaxy, since the gyro-radius of protons of $10^{18.5}$eV in the galactic magnetic field is the order of the thickness of the Galactic disk. Because the acceleration and propagation of cosmic rays primarily determined by rigidity, it is also expected that heavy nuclei are dominant in this energy region, which makes the confinement easier. Fly's Eye data suggest that the fraction of protons increases again as the energy approaches the ankle, which implies that extragalactic cosmic rays become dominant above the ankle.[20] Recent AGASA suggestion of the existence of anisotropies just below the ankle further supports the Galactic origin.[21] It should be noted that even in this energy region we have no widely accepted scenario of particle acceleration, although some ideas have been proposed such as the second stage acceleration by the ensemble of shock waves consisting of many SNRs in late stage evolution.[22]

Thus, around the ankle, cosmic ray origin changes from Galactic heavy particles to extragalactic protons, while the detailed feature of this transition is uncertain. Below the GZK cutoff $10^{19.7}$eV extragalactic cosmic rays come from basically the whole universe while above that they should come from within about 50Mpc from our Galaxy. Thus, a sharp roll over in the specrum at $10^{19.7}$eV is expected, while no such a feature is observed, which is the most puzzling problem in EHECR. From the standpoint of particle acceleration, this requires that at the sources particles are accelerated at least up to $10^{20.5}$eV with a very flat injection spectrum. General requirements for the sources of EHECR and several astronomical source candidates are discussed in section 3. In section 2, I discuss particle acceleration mechanisms in the general context, including diffusive shock acceleration.

§2. Particle Acceleration

2.1 Hillas diagram

The motion of a charged particle with an electric charge q in the electromagnetic field $\vec{E}$ and $\vec{B}$ is described

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by

$$\frac{d\vec{p}}{dt} = q(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}), \tag{2.1}$$

where $\vec{p}$ and $\vec{v}$ are the momentum and velocity of the particle. Because the energy of particle ϵ changes as

$$\frac{d\epsilon}{dt} = q\vec{v} \cdot \vec{E}, \tag{2.2}$$

particle acceleration occurs only when the electric field appears.

The famous Hillas diagram implies that the maximum energy realized in an object of a size R is limited by

$$\epsilon_{\max} = qBR \tag{2.3}$$

from the condition that the gyro-radius is smaller than the size;[23] particles must be confined within the object in order to be accelerated. Since most astronomical objects are known to have magnetic field and to have a large scale motion such as rotation, motional electric field is globally generated according to ideal magnetohydrodynamics as

$$\vec{E} = -\frac{\vec{V}}{c} \times \vec{B}, \tag{2.4}$$

where $\vec{V}$ is the velocity of the background plasma. Thus, the realistic maximum energy may be estimated as

$$\epsilon_{\max} = q\frac{V}{c}BR. \tag{2.5}$$

Although this estimate is quite simple, meaning that particles that are injected at positions with high electrostatic potentials gain energy when they reach those at low electrostatic potentials.

A natural question is which is pertinent for the estimate of $\epsilon_{\max}$ between eq. 2.3 and eq. 2.5. Below I argue that both are pertinent dependent on situations. It should be noted that electrostatic potential difference arises between different magnetic field lines and that individual magnetic field line is on an equi-potential surface. The particle energy does not change by the motion along the field line or by the $\vec{E} \times \vec{B}$ drift which means that the guiding center of the gyro-motion of the particle moves with the velocity $\vec{V}$. Thus, other ingredients are required for particle acceleration.

2.2 Direct acceleration

There are several possibilities to make use of the motional electric field and they are called direct acceleration mechanisms. For example, when the oppositely directed magnetic field lines are adjacent, reconnection of the field lines occur in a very thin region and non-motional global electric field appears there. The stength of the electric field may be estimated by replacing $\vec{V}$ by the Alfven velocity in the above equation. Secondly, when the magnetic field configuration is inhomogeneous, cross field drift motion occurs and if the direction of drift motion is the same as the electric field, particle acceleration arises. The cross field diffusion due to turbulent magnetic fields or any other causes make the same effects. These effects can certainly play an important role in particle acceleration, in particular, they do so when they are combined with shock acceleration as will be discussed below.

Another important example is a unipolar induction. When the astronomical body of a size R is surrounded by a vaccum, potential difference is generated between different positions on the surface of the body, which is called unipolar induction. Since the electric field is not necessarily perpendicular to the magnetic field in a vaccum, particle acceleration can occur in a surrounging vaccum. However, in realistic cases as rotation powered pulsars, the surrounding is filled with normal plasmas or copious electron-positron pairs and field aligned electric field tends to be shielded. The outcome is believed to be the generation of an outflow such as a relativistic pulsar wind as observed in the Crab nebula. The pulsar wind is shocked by the interaction with ejecta of supernova explosion and there particle acceleration occurs. The observed spectrum of the Crab nebula from radio to X- and γ-rays implies that the maximum energy of accelerated electrons is roughly the same order of the available potential difference on the surface of the neutron star.[24] This is not a mere coincidence but evidence that there exists a mechanism to fully make use of the available potential difference between the open field lines on the neutron star surface. Actual acceleration mechanism is not yet identified, but simple diffusive acceleration does not work in this highly relativistic perpendicular shock wave in the pulsar wind termination shock. The effects of internal structure of collisionless shock waves, as well as drift and cross field diffusion and possibly magnetic reconnection certainly play an important role for particle acceleration in the pulsar nebulae.

Although the pulsar wind consists of mainly electron-positron pairs, if it includes a fair amount of protons, there may be some relevance to the origin of cosmic rays above the knee. If we further consider extraordinary parameters such as the rotation period of 1 msec and the surface magnetic field of 10^{14}G, the electrostatic potential difference reaches the range of EHECR.

2.3 Diffusive shock acceleration

In contrast to direct acceleration, statistical acceleration (also called Fermi acceleration) makes use of fluctuating electric fields inside the plasmas. Although a conventional explanation of Fermi acceleration relies on the elastic collisions of particles with moving scattering agents such as magnetic mirrors and Alfven waves, in fact, particle energy changes by the action of the electric field associated with those scattering agents. Among various statistical mechanisms, diffusive shock acceleration has made a major success.[10–17] To illustrate the basic mechanism, note that astrophysical shock waves are collisionless and particles in the downstream region can traverse back to the upstream region when their velocity towards the shock front is larger than the downstream fluid velocity. In other words, collisionless shock may be formed by interactions of such reflected particles with incoming particles, although detailed mechanism is still an open problem. Thus, collisionless shocks necessarily involve complicated internal electromagnetic structure with a finite scale length and particle distribution function is not automatically determined by the thermal equilibrium. Rather, the dissipation mechanism of collisionless shocks can be particle acceleration itself.

In spite of this, simple version of diffusive shock acceleration assumes that the shock front formed by the background plasma is infinitesimally thin and that the global magnetic field direction is parallel to the shock normal, thus no motional electric field appears. In addition, the background plasma carries waves both in the upstream and in the downstream and the velocity of waves relative to the background plasma is neglected. High velocity particles are regarded as test particles moving in this background plasma flow, suffering from frequent pitch angle scattering through the wave-particle interaction. When the shock is non-relativistic, the velocity of high velocity particles is larger than the shock velocity and they cross the shock front back and forth repeatedly. Since the velocity field of the background plasma is a converging flow, i.e., the upstream and downstream plasmas are approaching each other, high velocity particles gain energy each time they cross and recross the front. At the same time those particles are tied with the background plasma through the scattering, they have a finite probabilty of escape from the shock front. The balance between acceleration and escape results in a power law spectrum of the accelerated particles with an index determined only by the compression ratio of the shock. In the strong shock limit for mono-atomic gas, the compression ratio is 4 and the power law index of 2 is realized.

This clean result is very encouraging in many points. It is consistent with the observed spectral index of 2.7 of cosmic rays below the knee when effects of rigidity dependent escape from the galactic disk is taken into account. It is consistent with the energy spectrum of relativistic electrons inferred from radio synchrotron spectra from SNRs. Although direct confirmation of proton acceleration is still on the way, X-ray and TeV γ-ray observations of SN1006 have shown that electrons are accelerated up to about 100TeV in this SNR.[25,26)]

The maximum energy of accelerated particles is determined by the balance bewteen acceleration and losses which are dependent on specific situations. For ions, in most cases it is determined by the lifetime of shocks and we obtain

$$\epsilon_{\max} = A m_{\mathrm{p}} c^2 \gamma_{\max} = \frac{3ZeBR}{20\xi}\frac{V_{\mathrm{s}}}{c}, \tag{2.6}$$

where

$$\xi = \frac{\lambda}{r_{\mathrm{g}}}, \tag{2.7}$$

the ratio of the mean free path for the pitch angle scattering λ to the gryo-radius r_{g}. Since λ is generally longer than r_{g}, ξ should be larger than 1. For typical supernova remnants, above equation predicts $\epsilon_{\max} \approx 10^{14}$eV for protons and electrons, which is smaller than the knee energy by a factor of 30. This difference remains one of the unsolved theoretical problems.

Since the above description is the most simplified, in reality various complications should be taken into account. For example, when the magnetic field direction is oblique to the shock normal, motional electric field appears and acceleration time scale can be shortened by a large factor through the gradient B drift effect at the shock front, although other factors may counterbalance this. Internal structure of shocks may also play an important role in injection and acceleration processes. Internal electric field may resonantly accelerate particles when the phase velocity matches the particle velocity. Accelerated particles should modify the shock structure significantly and accordingly the spectra of accelerated particles. Although any specific mechanism is not yet identified as a main contributor, there is likely a mechanism of accelerating protons up to the knee energy in SNRs.

The above consideration implies that the simple estimate eq. 2.6 of the maximum energy in diffusive shock acceleration is an order of magnitude smaller than the actual maximum energy, which is near the Hillas estimate given by eq. 2.5. This has a relevance to the consideration of EHECR,

Since the galactic disk can confine charged particles with much higher energy and since cosmic rays with such energies are really observed, there should be mechanisms to accelerate particles further. The maximum energy of the relevant mechanisms should be determined by eq. 2.3 rather than by eq. 2.5. A possible mechanism is the second stage acceleration,[22)] in which an ensemble of shock waves in the galactic disk act as the scattering agents. Since these shock waves, presumably SNRs in the late stage evolution, are expanding, the scattering is always head on and increases the particle energy. Thus, this second stage acceleration is different from the second order Fermi acceleration, although the acceleration agents are distributed in the disk. The resultant particle spectrum is determined by the balance between acceleration and escape from the disk. The maximum energy is determined by the reflectivity condition from shock waves, which is governed by eq. 2.3, where R and B are those of expanding shocks. Although they are not of the galactic disk, the difference is not so large. Since this type of acceleration make it possible to obtain highest particle energy, it may play an important role in the acceleration of EHECR.

§3. Astronomical Source Candidates of EHECR

3.1 General requirements

There are several requirements on the astrophysical sources of EHECR. First they must accelerate protons up to $10^{20.5}$eV, regarding that EHECRs are protons. Even if the source particles are helium or heavy nuclei, they disintegrate into protons through photo-disintegration interaction with cosmic background photons and the requirement on the acceleration is similar. Second, the sources should be within about 50Mpc to avoid the GZK cutoff. Third, the source spectrum of EHECR should be very flat, as flat as the power law index of 1.5, in order to reveal no sharp roll over at the GZK cutoff as discussed in the Introduction. Fourth, EHECR luminosity of the source L should satisfy

$$L \approx 10^{37}\frac{\mathrm{Mpc}^{-3}}{n}\mathrm{erg\ s}^{-1}, \tag{3.1}$$

where n is the number density of sources. Fifth, there should be at least more than several sources in this region from the observed isotropy of the arrival direction of EHECR. The angular deflection of EHECR depends on the strength and coherent length l of the intergalactic magnetic field as well as the energy of EHECR. The expected mean deflection angle is estimated by

$$\theta \approx \frac{10^{20}\mathrm{eV}}{\epsilon}\frac{B}{10^{-9}\mathrm{G}}\frac{\sqrt{ld}}{100\mathrm{Mpc}}, \tag{3.2}$$

where d is the distance to the source. For a reasonable choice of parameters, θ is at most a few degrees. Recent AGASA suggestion of the existence of EHECR clusters can put a stronger constraint on the source number if ultimately confirmed. It requires that θ is less than a few degrees and that the number density of sources is as large as normal galaxies. Here, I do not take it established but certainly it is an interesting possibility. A single source origin requires too high magnetic field, which seems to be unlikely.

3.2 Normal galaxies

Our Galaxy is known to accelerate cosmic rays up to $10^{18.5}$eV by some unkown mechanisms, probably making use of the ensemble of shock waves,[22)] with a luminosity of about 10^{37}erg s^{-1}. Note that this energy exceeds the limit given by eq. 2.5 and near the one given by eq. 2.3. We may assume that the acceleration to the limit given by eq. 2.3 is realized in other normal galaxies, too. If a few percent of normal galaxies have 10 times stronger magnetic field on 10 times larger scale than our Galaxy, they may produce EHECR.[9)] Since the confinement time becomes longer for such a case, very flat particle spectrum can be realized and most cosmic ray luminosity is expended in EHECR. If we take $n = 10^{-3}\mathrm{Mpc}^{-3}$, which corresponds to that of Seyfert galaxies, required luminosity $L \approx 10^{40}$erg s^{-1} seems to be reasonable. It is interesting to search for evidence for large scale strong magnetic field in nearby galaxies, although no such evidence has been yet reported. As was already noted, if the clustering events are firmly established, such galaxies are the most likely candidates of EHECR.

3.3 Radio galaxies

Radio galaxies have been much discussed in this decade as the most probable candidate for EHECR source.[27,28)] Among them FR-II galaxies exhibit hot spots at the ends of the jets, which are interpreted by the termination shock of relativistic jets. The size of the hot spots is about 1kpc and magnetic field strength is estimated as a few hundred micro Gauss, which leads to just $10^{20.5}$eV according to eqs. 2.3 and 2.5, taking $V = c$. The most difficult problem is that FR-II radio galaxies are too rare, none within the 50Mpc distance.

However, FR-I radio galaxies are more abundant including Cen A and M87. Although FR-I galaxies do not show hot spot structure, they also emanate relativistic jets which are decelerated by the entrainment of the interstellar gas without prominent hot spot formation. Particle acceleration in this circumstance is less well understood, but we surely know that electron acceleration does occur. Probably, diffusive shock acceleration and second stage acceleration similar to that in the galactic disk may play a role. Since the field strength and lobe size are similar to those of FR-II galaxies, we also expect acceleration of EHECR is possible in FR-I galaxies, too. Since the number density of FR-I galaxies is an order of $10^{-4.5}\mathrm{Mpc}^{-3}$, the required cosmic ray luminosity $L \approx 10^{41.5}$erg s^{-1} is very reasonable . At present the arrival direction of EHECR does not point to known FR-I galaxies, then some deflection during propagation is required. If FR-I galaxies are really producing EHECR, we will see enhancement around nearby sources, especially around Cen A, which can be confirmed by the southern observing facilities. It is to be noted that relativistic jets in radio galaxies may consist of mainly electron-positron pairs. If so, hot spots of FR-II radio galaxies do not produce EHECR, while FR-I radio galaxies can do so since entrainment of the interstellar gas changes the composition of jets to baryon dominated during the propagation of jets.

3.4 Active galactic nuclei

Since the active galactic nuclei reveal various kinds of non-thermal activities, they are also much discussed as the source candidates. However, bright galactic nuclei are not the prime candidates for EHECR because high energy density of photons prevents protons from being accelerated up to the highest energy.[29)] Even when the brightness temperature at millimeter wavelengths is as modest as 10^{10}K, protons with energy above GZK cutoff can traverse at most 10^{-2}pc in the nuclei. Quiet galactic nuclei are not likely candidates, too, because magnetic field is expected to be small for a low accretion rate.

3.5 Clusters of galaxies

Clusters of galaxies have a hot intracluster gas with magnetic field of the order of 0.1μG and a spatial extent of a few Mpc. Thus, EHECR can be confined in clusters of galaxies. But, since the expected velocity field due to accretion shock or merging events is an order of 10^3km s^{-1}, the acceleration time becomes longer than the GZK interaction time. Thus, clusters of galaxies are not likely candidates.

3.6 Gamma-ray bursts

Since the gamma-ray bursts involve a relativistically expanding plasma with the bulk Lorentz factor of 100 to 1000,[30)] we should take into this factor. Taking the typical total energy of 10^{51}erg and bulk Lorentz factor of 300, and assuming that magnetic energy accounts for 0.1% of the rest mass energy, eqs. 2.3 and 2.5 with $V = c$ give $\epsilon_{\max} = 10^{21}$eV in the comoving frame. It is more than enough to produce EHECR, considering that the energy in the observer frame is further boosted by the bulk Lorentz factor of 300. But, since the internal shocks are presumably to occur at $R \approx 10^{13}$cm and synchrotron cooling and photo-pion production seem to limit proton acceleration to much lower energy. For external shocks which occur at around 10^{16}cm, these constraints are relaxed and acceleration of EHECR is possible.

The occurrence rate of gamma-ray bursts is about 1 event per day for the whole universe. The rate of occurrence in the nearby universe is uncertain because of the evolution effect. We may roughly estimate as $10^{-14}\mathrm{s}^{-1}\mathrm{Mpc}^{-3}$ if the evolution is neglected. Thus, each gamma-ray burst is required to produce 10^{51}erg EHECR, which is very reasonable. But if we consider the evolution effect, the requiremd luminosity is orders of magnitude larger.[31] Even if the gamma-ray bursts are assumed to produce such an amount of EHECR, the bump feature at GZK cutoff whould be much more prominent due to a larger contribution from remote universe, which is difficult to reconcile with observed spectrum.

Although the gamma-ray bursts are transient events, the arrival time distribution is broadened by deflection by the intergalactic magnetic field as

$$\Delta t \approx 3\times 10^8\mathrm{years}(\frac{10^{20}\mathrm{eV}}{\epsilon}\frac{B}{10^{-9}\mathrm{G}})^2\frac{ld^2}{(100\mathrm{Mpc})^3}. \quad (3.3)$$

Thus, $\Delta t > 10^4$years is expected unless the intergalactic magnetic field is too weak. One particular feature is that higher energy cosmic rays should arrive first, followed by lower energy particles from a single gamma-ray burst. No such feature has yet been reported among clustering events. If evolution is neglected, the total number of gamma-ray bursts contributing to the single epoch observation is about $300(\Delta t/10^4\mathrm{years})$ which is large enough for $\Delta t > 10^4$years. From the point of view of acceleration theory, diffusive shock acceleration in ultra-relativistic shock is considered to produce a power law spectrum with an index of 2.2 according to recent work,[31,32] which is too steep to explain the observed spectrum of EHECR.

§4. Conclusions

I have briefly reviewed particle acceleration mechanisms from a general point of view. Diffusive shock acceleration mechanism gives basically correct view on cosmic ray acceleration but it is not yet complete. Missing ingredients are related to various kinds of electric field structures associated with collisionless shock formation and if combined with these effects, maximum energy is expected to increase up to the Hillas limit. It is also noted that the second stage acceleration, which is supposed to work for galactic cosmic rays between the knee and ankle in our Galaxy, may play a major role in the production of EHECR in other normal galaxies and FR-I radio galaxies. I also briefly commented on other astrophysical candidates such as radio galaxies and gamma-ray bursts. At the present stage, FR-I radio galaxies may be the prime candidates and some normal galaxies such as Seyfert galaxies must be seriously considered when the clustering events are further confirmed. If these objects are producing EHECR, particle acceleration of EHECR needs some second stage mechanism in addition to diffusive shock acceleration. Although gamma-ray bursts, FR-II galaxies, active galactic nuclei and clusters of galaxies have been much discussed, they have difficulties to explain EHECR.

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