Chapter 1

HISTORICAL PERSPECTIVE ON THE COSMIC RAY RESEARCH

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The existence of cosmic rays was discovered in the early 1910s, but their exact nature was not uncovered immediately. However, we soon acknowledged their importance, and our existence itself may even have owed to cosmic rays. This problem on the origin of life has not yet been resolved, but it seems certain that cosmic rays have played some role in the formation of the present universe. In reviewing the historical development of cosmic ray research, let us consider the natural phenomena related to cosmic rays, which are one of the important elements of nature.

1.1 The History of Cosmic Ray Research

When we think of the term "cosmic ray research", it seems, in general, that there are two distinct meanings of it. Truly speaking, the main objective in the research had been considered to be the research on the cosmic rays themselves in the early history of cosmic ray physics, whereas nowadays various astrophysical phenomena are being investigated by referring to the knowledge obtained from cosmic ray research in recent history. Since, in the modern research in this field, such astrophysical phenomena cover many wide fields in high-energy astrophysics, it is not easy to summarise the current research related to cosmic ray physics in a simple picture. Even with respect to the research on cosmic rays themselves, it is also difficult to give a simple outline of the research, since the definition of "cosmic rays" was somewhat ambiguous in early history. However, it should be noted that the structure of the cosmic ray research is rather complicated since this research covers a wide range of fields in both physics and astrophysics. In this respect, from the history of the research over the last 80 years, the main themes which have remained for some decades will be extracted, though rough it may be and these themes will then be reviewed with reference to the historical development of cosmic ray research.

From the point of view mentioned above, five main eras can be defined as shown in Table 1.1.1. Since the decades defined in this table should be thought of as very rough, the readers should not refer to them strictly, but will understand their meaning while studying the whole of this book.

The main reason why the eras in Table 1.1.1 are divided about every 20 years is that these eras may correspond to the thirty-year periodicity in scientific research as
Table 1.1.1. Historical development of the cosmic ray research.

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described below. According to this periodicity, the subject of the research is usually studied for about 30 years and classified as follows; the first 10 years is the developing period, the second 10 years the prime period and then finally comes the declining period. Although, in chemical research, this period is about half the above length and also sometimes this period is said to become shorter as history goes on, a length of about 20 years is considered to apply for cosmic ray research. Since such periodicity is highly dependent on our subjective view, both the length of the above periods and the names of these periods should also be considered subjective.

1.2 Early History

During the last quarter of the 19th century, physics was considered to be a fully developed discipline. Many contemporaries considered that basic physics research had nothing further to accomplish. Although a new branch of physics named "statistical mechanics" was just being born around that time, it seems this had not been accepted immediately as the science which would introduce the new concept associated with light quanta. But, the discovery of X-rays in 1895 had made revolutionized physics. Afterwards, radioactivity, the existence of electrons, protons and other active nuclei were discovered consecutively.

Since X-rays and radioactivity are both able to ionize gases, the existence of electrons was found from the search for the origin of the ionization of gases. In nature, it was then discovered that the atmospheric gas was also in an ionized state. Elster, Geitel and Wilson (C.T.R.), who had been studying this ionization, inferred that the cause of the atmospheric ionization might be due to some unknown radioactivity. This ionization could even be produced inside a box shielded from radioactivity by a thick wall, and furthermore occurred even if this box was buried deep underground. Thus it was concluded that this "unknown" radioactivity must have had a strong penetrating power. Wilson predicted, in his paper published in 1900, that this radioactive emission might have been generated in the upper atmosphere or beyond.

The main source responsible for atmospheric ionization near ground level is identified with the radioactivity in the earth. The most penetrative radioactivity
emanating from the ground are the well-known gamma-rays. In fact, in comparison with ground level observations, ionization decreased when the ionization detector was located at the top of the Eiffel Tower, but the degree of this decrease was smaller than that which was expected from the atmospheric absorption of gamma-rays. For this reason, it was thought that some kind of radiation came from the upper atmosphere. This radiation was eventually found from observations at balloon altitude and furthermore this intensity seemed to increase at a level higher than 1 km from the ground when the decrease of the atmospheric pressure was corrected inside the detector.

1.3 Decades Searching for Future Projects

From 1911 to 1913, Hess (of Austria) made a series of the balloon experiments using the ionization chamber. In so doing, the effect of the pressure decrease was eliminated by making the chamber airtight. According to his experimental results, the ionization degree had a tendency to increase with altitude above 1 km in height. Based on this, he inferred that some radioactive rays must have come down from the sky, or perhaps from somewhere beyond the upper atmosphere. For these experiments, Hess was later given the Nobel prize for physics in 1936. These rays were then, named as “Höhenstrahlung” from the sky.

These rays which could penetrate wholly through the earth’s atmosphere were first identified as gamma-rays. Although gamma-rays emitted from radioactive substances were not so penetrating, it seemed that their penetrating power would become higher with their energy. Some experiments were made to detect the excess ionization due to gamma-rays coming from particular celestial objects, although nothing was found to show possible evidence of their existence. During the First World War, no research was done on these rays from the sky.

The cosmic ray research was began again after the war, but the nature of these rays from the sky was still not understood. However, the observations by Clay (in 1921) on the latitude effect of the cosmic ray intensity on the earth had partly shown their nature for the first time. By assuming that cosmic rays were positively charged, he interpreted his observed results on the basis of the effects due to their interaction with the geomagnetic field. Thus it became clear that the primary cosmic rays before entering into the earth’s atmosphere mainly consisted of positively charged particles, perhaps protons.

In the same year, based on cloud chamber observations on the ground, Skobelzyn found that there existed charged particles with high penetrating power in cosmic rays. The coincidence method was then developed by Bothe and Kolhörster to detect charged particles by using two GM counter tubes. Their experiments also indicated that most cosmic rays were positively charged.

Thus it became clear that cosmic rays mainly consist of charged particles. Since the charged particles known by that time were electrons, protons and α-particles, it was possible to distinguish if cosmic rays mainly consisted of protons or electrons by measuring the charges of cosmic rays. When cosmic rays mainly consisted of
positively charged particles, they had to come from the west because of the geomagnetic effect on them. This situation must be reversed when cosmic rays are mainly negatively charged.

In 1930, Rossi developed the coincidence method with higher accuracy by the combination of electronic tubes, and made experiments to detect the east-west effect on the cosmic ray incidence. The theory developed by Störmer, of the geomagnetic effect on the motion of charged particles, was first considered to explain the origin of aurorae, but it became clear later that this theory could be applied to the investigation of the motion of cosmic rays in the geomagnetic field. According to the Störmer theory, the momentum of a cosmic ray particle has a lower limit to arrive at a given geomagnetic latitude on the ground, and this limit for a positive charge is higher for incidence from the east than from the west. Furthermore, Fermi and Rossi had shown that the intensity of cosmic ray particles having momenta higher than this lower limit is the same everywhere, so that this intensity on the earth is, of course, the same as that in the far distant space. Based on their calculation of the orbital motion of cosmic ray particles, Lemaitre and Vallarta had further shown that the lower limit just mentioned could become somewhat lower in some special cases. Referring to those theoretical results, Johnson and Rossi independently made the experiment for the east-west effect with cosmic ray incidence on the ground and finally proved that incident cosmic rays are mostly positively charged.

1.4 The Age of Elementary Particle Physics

The coincidence method by combination of three counters was further devised by Rossi to study the secondary processes produced by incident cosmic ray particles. As indicated in Fig. 1.4.1, these counters were arranged in a triangular form and lead boards were piled up between the counters. The coincidence frequency first increased with the thickness of lead boards, but then gradually began decreased when this thickness went beyond some limit as seen in this figure. This curve, which shows the

![Fig. 1.4.1. Rossi curve.](image-url)
relation of this frequency with the thickness of lead, is now called the Rossi curve. It was thought that this phenomenon was caused by the multiple production of secondary particles from cosmic rays incident into lead. In order to see what really happened in the lead sheets, Occhialini, who was a collaborator with Rossi, went to England to make some cooperative experiments on this phenomenon with Blackett by using the Wilson cloud chamber technique. In order that the paths of secondary particles are captured in this chamber, the internal pressure had to be reduced while ions produced by those particles were still contained, since the super-cooled state in the chamber is favorable for such ions to become nuclei which cause condensation. The Wilson chamber was powered up after it was connected with the coincidence apparatus and was then always expanded to take photographic pictures whenever this apparatus recorded a coincidence of secondary particles. As a result of those experiments, Blackett and Occhialini found that many secondary particles were emitted as showers. This was the discovery of the phenomena of cosmic ray showers.

Furthermore, Blackett and Occhialini were both interested in the anomalous absorption phenomena of $\gamma$-rays. At that time, it was known that the measurements of the absorption and the scattering of $\gamma$-rays with matter coincided well with the prediction from the Klein-Nishina formula. This meant, of course, that the interaction of $\gamma$-rays with matter was mainly produced by the Compton scattering. In cases where the $\gamma$-ray energy became high enough, however, the absorption was higher than that predicted from the Klein-Nishina formula. This was the phenomenon known as the “anomalous absorption”.

During those years, Anderson had been making experiments with the Wilson chamber to look for the product due to the interaction as mentioned above. His experimental procedure was similar to that of Blackett and Occhialini, but, in order to study the relation of the anomalous absorption with the radiation energy, he tried to make use of cosmic rays instead of using $\gamma$-rays from radioactive substances since the energy of cosmic rays was much higher than that of such $\gamma$-rays. He further applied magnetic fields to the Wilson chamber to measure the energy of electrons scattered through the Compton effect and then found some strange phenomena in the paths of particles, which showed paths oppositely curved from the path of the electron. This was the discovery of positrons in 1933.

Around this time, Blackett and Occhialini proposed a hypothesis that this anomalous absorption might be produced by positrons predicted earlier by Dirac. According to him, with respect to the negative energy state resulting from his equations of relativistic electrons, whenever an electron in the negative energy state jumps into the positive energy state, it is observed as the usual electron and then the hole generated in the negative energy state behaves as a positron. However, his theory was not accepted by most contemporary physicists, since it seemed that the positrons which appeared in his theory were never found in the nature. Consequently, such scientists as Blackett, Occhialini, Persico and Racah had to be considered as a minority who had positively evaluated the Dirac theory. Later, Blackett and Occhialini released evidence from their experiments of the creation of positron-electron pairs by means of radioactive $\gamma$-rays. Furthermore, they discovered many
positrons in the cosmic ray shower phenomena and then concluded these phenomena were associated with the creation of both electrons and positrons.

Based on their interpretation on the relation of the production of positrons with the creation of positron-electron pairs, Nishina and Tomonaga calculated quantum-mechanically the probability of this production. More quantitative results were later obtained by Nishina, Tomonaga and Sakata. While their calculations were appropriate to the pair-creation from radioactive $\gamma$-rays with relatively low energy, the theory of the pair-creation applicable to high energies was proposed by Bethe and Heitler in 1934. They also advanced the bremsstrahlung theory of $\gamma$-rays emitted from electrons deflected by the electric fields of nuclei. The theoretical formula from their theory is now called the Bethe-Heitler formula and is often applied to the study of the secondary cosmic ray phenomena.

As regards the energy-loss mechanism of charged particles moving in matter, there is the theory by Bohr which was proposed just before the birth of the atomic model. Since, in an atom, electrons are orbiting under the action of the positive charges of the central nucleus, a particle impinging into such atomic state usually makes these electrons fluctuate by its own electric field and so loses its energy while passing through those atoms. Thus, the energy-loss rate per atom is always proportional to the number of electrons of the atom. On the other hand, the experimental results by Rutherford showed that this rate was proportional to the atomic number of this atom. In this way, it became clear that the atomic number denotes the number of electrons in the atom under consideration. This was the foundation of the atomic model.

According to the theory of energy-loss by Bohr, the energy-loss rate is strongly dependent on the speed of impinging particles, but hardly depends on their mass. This rate becomes smaller with the increase of particle speed and approaches the small value of 2 MeV/g-cm$^2$. In consequence, it seems that any particle as high energy as cosmic rays loses hardly any of its own energy while passing through matter.

Since every cosmic ray particle has passed through an atmosphere of thickness more than 1 kg/cm$^2$, its mean energy loss must have been several GeV (1 GeV = $10^6$ eV). Since the energy lost by a cosmic ray particle by its passage through lead with a thickness of several cm is 100 MeV at most, the rate of the intensity decrease of cosmic rays resulting from the passage of this thick lead is estimated to be several percent. However, this rate actually measured reached 20 to 30 percent. Furthermore, the experimental results on the absorption of cosmic rays by several different matters, the atomic number of which differ from each other, indicated that this absorption is not always proportional to the atomic number $Z$, but consists of two distinct components. One is proportional to $Z$, whereas the other depends on $Z^2$. This also means that there exists an anomalous absorption of charged particles.

In 1930, using quantum mechanics, Bethe calculated the energy loss for the collision of cosmic ray particles with hydrogen atoms, but the results obtained by him were substantially equivalent to those deduced from the classical theory by Bohr. The results for the cases of atoms with many electrons, calculated by Bloch in 1933, were the same as those obtained by Bohr except for a difference which appeared in the
logarithmic term. Even if the relativistic effect was taken into account, the energy-loss rate only increased logarithmically with particle energy. Hence, this effect did not make the theoretical results change drastically. However, because of these theoretical investigations, the energy-loss mechanism was established quantum-mechanically and it was also found that the particle energy was almost equally expended in both the excitation and the ionization of atoms. The formula for this mechanism is now called the Bethe-Bloch formula of ionization loss.

On the other hand, the Bethe-Heitler formula showed that a high-energy electron always loses most of its energy due to bremsstrahlung. This mechanism is called the radiation loss and its loss rate is proportional to both $Z^2$ and the energy of the impinging electron. This energy-loss rate is shown in Fig. 1.4.2 as a function of the logarithmic ratio of $P/mc$, where $P$, $m$ and $c$ are, respectively, the particle momentum and mass and the speed of light.

Since the results shown in Fig. 1.4.2 are concerned with lead, the curve for bremsstrahlung comes in the far right of the figure for air consisting of atoms with small $Z$. The critical energy, for which both the ionization and the radiation losses become equal, is about 7 MeV for lead and about 90 MeV for air. In an energy range less than the above critical energy, the ionization is most important, while the radiation loss is the main one for an energy higher than the critical energy.

As has been described above, the problems related to the absorption of electrons and the generation of positrons was finally resolved, but two other important problems were left open. These were respectively related to the existence of the hard component penetrating through lead of thickness 10 cm and the shower phenomena. The hard component only loses energy through the ionization loss and so produces no shower phenomena. According to the theory of the electromagnetic interaction, the probability of the occurrence of shower phenomena must be very small, since the factor $\alpha (=1/137)$ must be multiplied with this probability for each process of $\gamma$-ray emission or electron-positron pair creation. In addition, it was known that these phenomena usually occurred when electrons or $\gamma$-rays with energy higher than about 100 MeV hit the lead. Actually speaking, on the other hand, the energy of the hard component was almost always higher than 100 MeV. In consequence, it was assumed

![Fig. 1.4.2. Energy-loss rates of charged particles in lead slab.](image)
that the theory of the electromagnetic interaction could not be applied to such high-energy phenomena. By connecting this threshold of the energy with the mysterious value $mc^2/\alpha = 137 \times mc^2 = 70$ MeV, the applicability of quantum electrodynamics was often suspected for these problems.

Williams and Weizäcker, however, showed that bremsstrahlung was not identified as a high-energy phenomenon. In fact, for instance, with respect to the system consisting of a nucleus and an electron, the nucleus is thought of as moving extremely fast when viewed from the coordinate system in which the electron is at rest. The electron could be forced to move by the action of the electric field from the nucleus and consequently would emit light quanta by the dipole radiation mechanism similar to that from a radio antenna. These quanta are thus to be identified as $\gamma$-rays when the coordinate system is transformed back to that for the moving electron. In other words, the bremsstrahlung mechanism belongs to one of the low-energy phenomena.

Williams thought that the hard component consisted of protons. Certainly, the bremsstrahlung from protons did not occur unless their energy was not as high as shown in Fig. 1.4.2, since the probability of this radiation was inversely proportional to the square of their mass. His idea, however, was denied by the results of the measurement of the charge of the hard component.

Around this time, the meson theory by Yukawa had already been proposed, but he never thought that these mesons were identified with the hard component, though they were predicted to be observed in cosmic rays. His theory had not been remarked by cosmic ray researchers abroad, either. In the meantime, Anderson and Neddermyer had been investigating the energy loss processes by cosmic rays using the Wilson chamber containing a lead board inside. They found in 1936 that many particles were produced from this lead board and then reached a conclusion that one particle among them had a mass between that of an electron and a proton. However, they did not publish their result because of the strong opposition against the introduction of a new particle. When he became aware of their results, Yukawa intuitively considered that this particle had to be the same as the meson predicted by him and immediately started a series of theoretical studies on the possible behavior of the meson. In 1937, Neddermyer and Anderson obtained clear evidence of the path associated with the meson in their pictures. Nishina, Takeuchi and Ichimiya and Street and Stevenson had also taken the paths similar to those obtained by Neddermyer and Anderson. Reviewing these results, Yukawa concluded that the particle paths appearing in those pictures were produced from the mesons predicted by him.

According to the Yukawa theory, the mesons exchanged between nucleons produce the nuclear $\beta$-decays through the decay of mesons into electrons and neutrinos. Bhabha thus pointed out that these mesons naturally decay by this interaction, and Yukawa estimated the half-life of the mesons to be about $10^8$ sec with the collaboration of Sakata and Taketani. By analyzing the observation that the cosmic ray intensity decreases as the atmospheric temperature increases, Blackett interpreted this result on the basis of the variation of the atmospheric height where most mesons are produced, and then estimated the half-life of the meson decay to be
about $10^{-6}$ sec.

The problems related to the shower phenomena were finally resolved in 1937, since Bhabha and Heitler and Carlson and Oppenheimer both formulated the theory of the cascade showers. As a result, the shower phenomena were no longer mysterious, but were well understood in the frame of the theory of the electromagnetic interaction.

Taking into account the ideas on the mesons and the shower phenomena, Euler and Heisenberg proposed a synthetic theory to explain the cosmic ray phenomena in the atmosphere. According to this theory, the primary cosmic rays were attributed to the positrons which were assumed to produce the cascade shower after entering into the atmosphere. Hence the maximum of the cosmic ray intensity is produced in the upper portion of the atmosphere. Since the high-energy $\gamma$-rays were accompanied by the cascade showers, they could produce mesons after colliding with the atmospheric constituents. Although most mesons could reach the ground without losing much of the energy, a part of them would decay and produce the soft component with electrons knocked out from their collision with the atmospheric nuclei.

The behavior of cosmic rays seemed to have been well interpreted as mentioned above, but a new problem was born later concerning the nature of the mesons. In the Yukawa theory, the mesons had two important roles as regards the nuclear interaction and the $\beta$-decay, so that the mesons had to strongly interact with atomic nuclei and to decay with an appropriate half-life. The scattering cross-section of the mesons with nuclei was estimated to be about $10^{-26}$ cm$^2$ and their life was then predicted to be of the order of $10^{-8}$ sec based on the improved theory. However, the experimental results indicated that this scattering cross-section and the life were respectively $<10^{-28}$ cm$^2$ and $<10^{-6}$ sec. This discrepancy between theory and experiment was finally successfully resolved by the two meson theory first proposed by Sakata, Tanikawa and Inoue.

Though there have been several different ideas on the two meson theory, the most important of them was that the mesons identified with the hard component were different from the Yukawa mesons which are responsible for the nuclear force. According to the two meson theory, the Yukawa mesons are produced by the strong interaction in the high atmosphere and then decay to cosmic ray mesons with a short life time. Since the latter do not interact so strongly with nucleons, they do not contribute to the nuclear interactions.

In fact, Lattes, Occhialini and Powell, in 1947, found the event in the photographic emulsions which indicated that a meson decayed into another meson. The former was defined as the pi-meson ($\pi$), while the latter was named as the mu-meson ($\mu$). This meant that the pi- and mu-mesons were, respectively, identified with the Yukawa meson and the hard component of cosmic rays. Futhermore, in 1940, based on their study of the nuclear force, Sakata and Tanikawa showed that neutral mesons decayed into two $\gamma$-ray photons with a very short life time. Later in 1943, Taketani showed that these $\gamma$-ray photons could produce the cascade showers and seemed responsible for about half of the soft component in the upper atmosphere. In 1941, Schein and his associates found that the primary cosmic rays mainly
consisted of protons. Actually, pi-mesons are produced due to the collision of these protons with atmospheric nuclei, so that charged pi-mesons decay into mu-mesons, while neutral pi-mesons decay into two γ-ray photons which produce the atmospheric component of cosmic rays. The behavior of cosmic rays in the atmosphere, as mentioned above, has mostly been verified by Japanese workers in the years from 1948 to 1950.

A new particle was also discovered in 1947 by Rochester and Butler, because they found strange paths of some unknown particles in pictures from a Wilson chamber. These particles were named V-particles from the pattern of their decay and their mass was also estimated to be much heavier than pi-mesons. While Leprince-Ringuet took pictures of the paths of particles with mass about 1000 times that of an electron in 1944, it was conjectured that they might have been those of protons.

In order to confirm the nature of V-particles, researchers from England, U.S.A. and France took many pictures of them in Wilson chambers located on the tops of high mountains. These particles were also found in the photographic emulsions. From this experiment, it became clear that V-particles were generated by the strong interaction with nuclei and tended to decay in several different modes, since they consisted of hyperons heavier than nucleons and heavy mesons with a mass between that of nucleons and mesons. In particular, the mass of the heavy mesons now called K-mesons was about 970 times that of an electron, and were also thought of as a variety of particles which decayed into several different modes.

Since the half-life of V-particles is of the order of $10^{-8}$ to $10^{-10}$ sec, their decay occurs due to the weak interaction. However, they are produced by the strong interaction. This situation is similar to that of the two meson theory, but could not be said to be the same as the latter, for the hyperon and the heavy meson could decay into nucleons and π-mesons, respectively, with a short life time through the strong interaction. According to the idea proposed by Nambu, Nishijima and Yamaguchi, the reason why they never decay so quickly is that their decay is prohibited energetically since two V-particles interact strongly in making them paired. Furthermore, they considered that the particles produced from the decay of hyperons would make a V-shaped pattern. The pair creation of V-particles was actually seen in accelerator experiments in 1953. Based on these results, Nakano and Nishijima and Gell-Mann had independently introduced a new quantum number denoted by “Strangeness”, which is conserved in the processes of the strong interaction, but can vary in those of the weak interaction associated with the decay.

From these investigations, the nature of V-particles was finally understood, and later they came to be called “strange particles”. However, there has remained the problem of whether those heavy mesons associated with a series of decaying processes were identifiable with a single particle. In order to clarify this question, the experiments to track from the generation to the decay of V-particles was done in an international cooperation by sending large-area photographic emulsions aloft on-board balloons. The data from these experiments were collected in 1955, but, based on the experiment on the production of many heavy mesons by accelerators, at almost same time, the cross section for the production of V-particles was shown to be the
same event independent of the decaying patterns. It was also shown that their mass was independent of these patterns. In other words, it had become clear that the heavy mesons consisted of $K^±$ mesons with positive charge, their anti-particles $K^−$, and neutral kaons, $K^0$. The mass of charged kaons $K^±$ is slightly different from that of $K^0$ particles, but all of these are a variety of "single" particle as is seen in the $\pi$-meson group ($\pi^±$, $\pi^0$). However, still strange was that they had two distinctive decaying processes with different parities (2 pion- and 3 pion-decays).

To interpret these processes, Sakata and Gell-Mann had tried to build interesting models in which $K$-mesons and heavy hyperons were composite particles consisting of nucleons and $\Lambda$-particles as kinds of hyperons. It was assumed that the difference of parities could be explained by considering the difference between their couplings. Around that time, a hypothesis that the parity was not conserved in the weak interaction was put forward by Lee and Yang. This non-conservability had been experimentally confirmed by $\beta$-decays, $\pi$-$\mu$-$e$ decays and others. The models by Sakata and Gell-Mann were later developed into the composite models of elementary particles and became the foundation of contemporary particle physics.

After the experimental proof of the existence of $K$-mesons using cosmic rays in 1955, the main stream of experimental research on elementary particles moved into that done by means of particle accelerators rather than cosmic rays. As a result, the main theme of cosmic ray research as related to particle physics became the ultrahigh energy interaction of particles. As the upper limit of the particle energy which could be attained by accelerators increased, the ideas and the models proposed from cosmic ray research were consecutively confirmed on a quantitative basis.

1.5 The Age of Cosmic Physics

Since the year 1948 when $\pi$-mesons were artificially produced by accelerators, the main subject of cosmic ray research has shifted gradually to the problems related to astrophysics. As the origin of cosmic rays is cosmical as shown by the name itself, several pioneering works have been done on this origin to date since the early days of cosmic ray research. In the neighborhood of the earth, the geomagnetic effect of cosmic rays was first investigated as described in Section 1.3. From the research on this effect, it became clear that cosmic rays were distributed almost isotropically in the space beyond the region in which this effect had an influence. Although the variability of cosmic rays as related to solar and sidereal time was pursued in order to find a possible anisotropy of cosmic rays in outer space, no definite result has been obtained because of the difficulty of separating the effect of the atmospheric perturbation from this variability.

It was discovered in 1937 that the cosmic ray intensity on the ground varied with disturbances in the earth’s environs such as geomagnetic storms. This intensity is usually decreased most during the main phase of these storms. This phenomenon was later named the Forbush decrease to commemorate Scott Forbush who discovered it. Chapman and Ferraro then proposed a model of the geomagnetic storm, according to which the main phase of the storm was thought to be produced by the ring current
flowing in the geomagnetic equatorial plane. Since this current would produce a
magnetic moment in this plane, whose direction would be the same as that of the
earth's magnetism, it had been estimated that the magnetic field originating from this
moment played a role of a magnetic barrier to the influxing cosmic rays. This meant
that the lower limit of the cosmic ray energy invading to the earth had to become
higher.

Such an interpretation as mentioned above had long been accepted, but it was
shown by the Japanese workers in 1948 that this interpretation could never be
accepted as the cause of the Forbush decrease. Really speaking, during the
geomagnetic storm, the cosmic ray intensity, in fact, had to be increased by the
Chapman-Ferraro model, since the magnetic intensity becomes weaker within the
ring current in the equatorial plane, while this intensity becomes stronger outside this
current. To eliminate this difficulty, Nagashima showed in 1953 that the Forbush
decrease could be explained by assuming an electric field generated symmetrically
beyond the earth's orbit with respect to the sun. Although the origin of this field was
questioned, it was shown in 1970s that the behavior of cosmic rays being pushed
backward from the sun by the action of the solar wind was equivalent to that of this
field proposed by Nagashima.

Before the year 1950, it had been believed that the space occupied by the solar
system was a vacuum and that the corpuscular streams occasionally emitted from the
sun disturbed the geomagnetic field. Since the idea proposed by Alfvén became
gradually accepted after the early 1950s, however, the view that those streams
transport the solar magnetic field became popular and so magnetized plasmas usually
fill the interplanetary space. Based on this idea, in 1955, Morrison tried to explain the
time variation of the cosmic ray intensity on the earth by taking into account the
scattering of cosmic rays by the interplanetary magnetic field. According to him, the
intensity of this field was to be well correlated with solar activity, and the influx of
cosmic rays into the inner solar system was interrupted by the outward passage of the
magnetized plasmas ejected from the sun, which was also responsible for the
g geomagnetic storms. Thus, the plasma density had to show a tendency to decrease
with distance from the sun, so the diurnal change of the cosmic ray intensity was to be
induced by the change of the relative position of the sun as seen from the earth. Since
the solar activity varies with an eleven-year period, the cosmic ray intensity also
changes with this period.

The secular variation of the cosmic ray intensity has been made gradually clear
from the collection of observational records over many years. By analyzing those
records obtained with ionization chambers since 1937, Forbush found the existence of
the eleven-year variation in the cosmic ray intensity. On the basis of their observed
data on neutrons which are more sensitive to the variability in the low-energy primary
cosmic ray flux, Simpson et al. found that the amplitude of the time variation of this
flux was energy-dependent, and became larger as the cosmic ray energy decreased. By
making balloon experiments at different latitudes to observe the cosmic ray flux,
Neher et al. also found that this amplitude was larger for the observations on cosmic
rays of lower-energy. Since the scattering of cosmic rays by the interplanetary
magnetic field becomes weaker in the case where the characteristic length of this field is short compared with the curvature radii of cosmic rays being deflected by this field, the results as mentioned above, deduced from the observational records, suggest that the intensity and the characteristic length of this field are about 10 micro-gauss and 0.1 AU, respectively.

A concrete idea on the structure of the interplanetary magnetic field was further given by the investigation of the propagation of high-energy particles associated with solar flares. Although cosmic ray increases observed immediately after solar flares had been recorded several times since 1942, synthetic knowledge on the propagation of so-called solar cosmic rays was obtained from the observation of the cosmic rays generated in the solar flare of February 23, 1956. From the study of this event, it became clear that there existed two different components of solar cosmic rays; one component quickly reached the earth several minutes after the onset of the flare, whereas the other gradually arrived isotropically at the earth after about an hour. Based on these results, Meyer, Parker and Simpson and Gold et al. concluded that the magnetic field extending in the inner solar system between the sun and the earth's orbit was smoothly aligned, but that beyond this orbit it was highly turbulent. According to them, cosmic rays produced in solar flares initially tend to propagate under the guidance of such an aligned field and are then scattered randomly by a turbulent field to fill up the interplanetary space. Since the former was formed as a result of the mechanism by which the magnetic field on the sun was transported by the solar wind plasma, the field configuration was deduced to be spiral because of the solar rotation. In consequence, the magnetic lines of force crossing the position of the earth had to be connected with the western portion of the solar disk. Thus, solar cosmic rays could directly arrived at the earth in the cases where the solar flares occur on the west side of the sun. A slow increase of solar cosmic rays is, however, observed when parent flares occur on the east side of the sun.

As a result of the extension of the energy range of cosmic rays observed on and near the earth, the electromagnetic nature of interplanetary space became quantitatively well understood. Furthermore, observations of the energetic particles from the planet Jupiter and direct soundings of the interplanetary magnetic fields by means of spacecraft were later made. These studies were then united as interplanetary plasma physics.

Now, let us consider the discovery of the earth's radiation belts as brought about by cosmic ray research. The rocket-observations of cosmic rays began after World War II. As a result of these observations, van Allen discovered a large increase in the counting rate of energetic particles during quiet times over the auroral zone. Though such an increase was doubted to be a result of a malfunction of the particle counter since this increase was beyond that which might have been expected, the real reason for the increase was finally found in 1957 as a result of rocket observations. Namely, van Allen et al. and Vernov et al. both discovered the existence of radiation, the intensity of which was several orders of magnitude higher than that of the background cosmic rays. This radiation was found to surround the earth, and mainly consisted of both protons of energy less than 1 GeV and electrons of energy less than 1 MeV. These
particles were distributed in a doughnut-shaped area that is located at several earth's radii above the upper atmosphere. This area was then called the radiation belts.

In order to explain the origin of these belts, Singer proposed the neutron albedo theory, which assumed that these protons and electrons originated from the decay of the neutrons produced as a result of the interaction of cosmic rays with the atmospheric gases. This theory was also thought to explain the origin of most protons in the inner radiation belt, but its weakness was associated with the existence of electrons with energy higher than that expected from the neutron decays and with the radial distribution from the earth of protons with relatively higher energy. Later work, however, has clarified that, after being captured by the earth's magnetic field, the solar wind plasmas approach deep into the magnetosphere by being accelerated, and then become the components within the radiation belts. It should be here remarked that there exists a large radiation belt around the planet Jupiter, which is identified as the Jovian radio emissions and the source of interplanetary energetic electrons.

As we have discussed the cosmic rays in the solar system, let us consider hereafter the origin and the propagation of cosmic rays in the Galaxy. Although several ideas have been put forward on the origin of cosmic rays even in the era considered in Sections 1.4 and 1.5, we will start with the research in the age of cosmic physics, since these ideas have been discussed in my book entitled "Cosmic Rays" (published in 1972, in Japanese).

Following the discovery of protons in the primary cosmic rays by Schein et al. in 1941, the search for the components other than protons was made. By making balloon-borne experiments using Wilson chambers and photographic emulsions, Freier et al. and Bradt and Peters discovered the existence of $\alpha$ particles and some other heavier nuclei. The search for cosmic electrons and $\gamma$-rays was also made by some research groups, but only an upper limit of these electrons could be found, which was at most $1/100$ that of protons.

Bradt and Peters further searched for the chemical composition of cosmic rays and found that it was very similar to the cosmic universal abundances of the chemical elements. From this result, they concluded that the acceleration processes of cosmic rays were not so violent as to destroy the nuclei composing cosmic rays. Since they, however, found that the abundances of the elements Li, Be and B were by a factor of $10^6$ higher than those seen in the universal abundances, they considered the possibility that these elements were produced by the interaction of the primary cosmic rays with the atmospheric constituents and then estimated only the upper limit for the abundances of the elements contained in the primary cosmic rays. In the meantime, based on his own experiments, Fowler emphasized the existence of these light elements in the primary cosmic rays.

As an acceleration mechanism taking place slowly without the destruction of heavy nuclei, Fermi proposed the so-called Fermi mechanism in 1949. The main scheme of this mechanism is as follows; turbulent magnetic fields are moving at random in interstellar space, since they are transported with the plasma there as predicted by the "frozen-in" principle of Alfvén, and hence they always scatter cosmic
ray particles whenever they interact. These particles thus gain some amount of kinetic energy for head-on collisions, whereas they lose some energy for overtaking collisions. Since the former process usually occurs more frequently than the latter one, it follows that cosmic ray particles gradually gain energy stochastically. Regarding the Fermi mechanism, therefore, the rate of the energy gain is proportional to the square of the mean speed of the turbulent magnetic fields. Due to the scattering mentioned above, cosmic rays gradually gain energy and become isotropic whilst stored within the Galactic space. However, this process does not proceed indefinitely, because the accelerated particles are often destroyed or lose their energy through collisions with the ambient plasmas. As a result, an equilibrium state of the energy distribution of these particles is finally reached, which is expressed as a power law for the particle energy. This agrees well with the observed energy spectrum of cosmic rays.

The Fermi theory of the origin of cosmic rays has been considered as epoch-making, because the problem of their origin became a subject of scientific research, though it had no physical foundation before this theory appeared. Consequently, this theory has become a leading one in the search for the origin of cosmic rays. However, the details of the acceleration mechanism have been modified many times since 1949.

In order to explain the energy spectrum of cosmic rays, the mean speed of the turbulent magnetic fields had to be \( \sim 100 \text{ km/sec} \). Since the observed speed in interstellar space was usually an order of magnitude less than the above value, Unsöld asserted that cosmic rays in the Galaxy must have been accelerated in the stellar atmospheres like solar cosmic rays. Meanwhile, Fan criticized the result of the Fermi theory regarding the life of cosmic rays which is eventually determined by the collision processes of cosmic rays with interstellar plasmas, because the chemical compositions derived from his theory do not coincide with the observed results, indicating that this composition is independent of the particle energy. According to his theory, the abundances of heavier nuclei had to decrease with particle energy. Hayakawa remarked that the observed fluxes of electrons and \( \gamma \)-rays which might have been produced from the decay of mesons yielded from the collisions, as mentioned above, had to be higher than the upper limit observed so far. Based on this result, he estimated the fluxes of electrons and \( \gamma \)-rays reaching the earth’s neighborhood by assuming that the life of cosmic rays is not determined by the interstellar acceleration, but by their escape from the Galaxy.

A hypothesis of the supernova origin of cosmic rays was put forward from both east and west in 1955, but the “central dogma” differed completely between the two. The east opinion was that which had been put forward by Hayakawa. Based on the assumption that the nuclei Li, Be and B were originally existent in the primary cosmic rays, since they must have yielded from the collisions of the primary nuclei such as C, N and O with the interstellar gas, he proposed that cosmic rays must have passed through a gas of several grams/cm\(^2\) during their propagation. The chemical composition of cosmic rays at their source, as estimated by considering the idea just mentioned, necessarily became overabundant with respect to heavy nuclei. In other words, the source composition of cosmic rays had to be different from the chemical composition of the universe, i.e., the universal abundances. Since heavy nuclei are
synthesized deep in the stellar interior during stellar evolution, they should be released into outer space in association with the supernova explosion which occurs during the last phase of this evolution. These heavy nuclei are efficiently accelerated by this explosion and form cosmic rays.

In the meantime, in 1953, Shklovsky, from the west, pointed out that the light and radio emissions from the Crab nebula (a supernova remnant) were generated from the synchrotron mechanism which resulted from the spiralling motion of high-energy electrons in strong magnetic fields. This meant that these electrons were being continuously accelerated together with nuclear components in and near the supernova. On the basis of this idea, Ginzburg constructed a model in which cosmic rays were initially accelerated inside supernova remnants and later diffused outward to fill interstellar space. Furthermore, he was also successful in explaining the galactic radio emission by the existence of those electrons ambient in this space.

The supernova origin theory of cosmic rays has become eminent, as described above, but some criticisms against it were put forward as shown in the following. Even if electrons would have been accelerated efficiently, it might be impossible for the nuclear components to be accelerated together in the same way with electrons. In other arguments, particles to be accelerated were not identified as those which had been released from the supernova explosion, and the interstellar gas might have been partly accelerated by the shock waves formed by the explosion. According to this mechanism, the overabundances of heavy nuclei in cosmic rays could be necessarily derived.

In the 1970s, evidence of the change of the composition of cosmic rays associated with the acceleration processes was found successively. Generally speaking, the metallic elements are overabundant in this composition when compared with the universal abundances. Since these elements are relatively easily ionized because their first ionization potentials are usually low, the efficiency of their acceleration is necessarily higher than that for any other non-metallic elements whenever they are accelerated electromagnetically. Cassé has shown a correlation between the over-abundances of heavy elements in cosmic rays and their potentials.

It has also been found that the overabundances of heavy nuclei are significant in the chemical composition of solar cosmic rays. This tendency becomes clearer as the energy of these cosmic rays decreases. This result seems to definitely show that the acceleration mechanism works more efficiently for heavy nuclei. Such a mechanism may be plasma turbulence, ion-cyclotron heating or radiation pressure.

Recent observations of the chemical composition of cosmic rays, however, have shown the excess of heavier isotopes for such elements as Ne, Mg and Si in comparison with those seen in the universal abundances. Since these nuclei are produced by the reaction $^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}$ and the successive neutron capture, where $\alpha$ and $\gamma$ are respectively $^4\text{He}$ nuclei and gamma-rays, they seem to have originated from the carbon-burning proceeding in the stars which have helium-cores. Because this series of processes is causally related to the supernova explosions, it is considered that the supernova origin theory of cosmic rays still survives.
1.6 Present Status of Cosmic Ray Research

As described in the last section, there still remains the fundamental question on the origin of cosmic rays even after the 1970's. Likewise, even now, there remain several important problems on the interactions among elementary particles, though it may appear that the age of elementary particle physics has already gone. In spite of this situation, it seems that the present era is no longer thought of as one in which cosmic ray research itself can be done independently of other research in physics and astrophysics. At the present moment, it should be considered that cosmic rays have become an element in various fields of scientific research. Consequently, cosmic rays should be considered as offering a useful means for investigating those fields. In other words, researches on cosmic rays themselves would never produce any interesting results.

A research that could be investigated by using cosmic rays, for instance, is the experimental research on the proton decay, which has been predicted from the grand unified theory. While using the apparatus to measure cosmic rays, scientists, who have also worked on cosmic rays, are now trying to detect this decay. This clearly indicates that this topic is truly related to the natural sciences by itself and so is not confined to the realm of cosmic ray physics. Even so, a full knowledge of the various aspects of cosmic rays must be learned by those engaged in this research, because cosmic rays are the main source of the background radiations which are the obstacles of many measurements. It may be emphasized that the technique to detect the proton decay mainly adopts that which has been developed in cosmic ray research in the past.

As another example, let us consider the nuclear dating techniques of absolute ages related to geological and archaeological problems. One of these was developed by Libby in 1948, which was initiated by the application of the $\beta$-decay of carbon isotopes $^{14}$C. As is well known, these isotopes are produced from the reaction $^{14}$N ($n, p$) $^{14}$C, in which neutrons are produced from the collision of cosmic rays with atmospheric constituents. Recently, such measuring techniques as thermoluminescence and electron-spin resonance are used to study the secular change of the cosmic ray intensity on the ground. A knowledge of cosmic rays is, of course, very important in these techniques, but the subjects are essentially far from that of cosmic ray research.

As understood from these two examples above, it is impossible to talk about nature without considering the existence of cosmic rays, since cosmic rays existed in nature even in ancient times. Because the results from the cosmic ray research are now taken for granted in the research in many fields of science, they are hardly ever recognized in the current research in those fields. Let us consider two such fields which have developed recently.

a) $\gamma$-ray astronomy

It may be said that $\gamma$-ray astronomy began in 1952 with the theoretical estimation of the $\gamma$-ray flux near the earth being attributed to the $\gamma$-decay of neutral mesons resulting from the cosmic ray collisions with the interstellar gas. Later optimistic
results on this flux were obtained, but several experiments done on the basis of these results did not give us any conclusive data on the flux. Definite results on cosmic $\gamma$-rays were first obtained by the observations made on-board the satellite OSO-3 and the observed flux was of the order of that which was initially estimated.

In the 1970's, two satellites, SAS-2 and COS-B, which observed $\gamma$-rays, brought about results of high quality. The investigation of these results was the birth of $\gamma$-ray astronomy, and it may be said that a new branch of astronomy had been born in cosmic ray research. The following results have been found through the investigation of galactic $\gamma$-rays.

(1) First, nearly thirty discrete $\gamma$-sources have already been found. Since all of them are located in or near the galactic plane, except for the quasar 3C 273, they seem to be of galactic origin. Among them, $\gamma$-ray emissions from the Crab and the Vela pulsars are synchronized with the periods of other emissions such as radio waves and X-rays, but all other sources have not been identified with any stellar objects as yet.

(2) The galactic longitude distribution of $\gamma$-ray intensity shows an increase between 330° and 30° longitude. The extension of this longitude distribution is narrower than that which is estimated from the distribution of hydrogen atoms. When the molecular hydrogens are taken into account there, it follows that the observed intensity of $\gamma$-rays should be proportional to the density of the interstellar matter. This result suggests that cosmic rays are distributed in the Galaxy in proportion with the space density of the interstellar matter.

(3) As regards the galactic latitude distribution of $\gamma$-ray emission, there exists a component which extends up to high latitude regions, in addition to the sharp peaks of $\gamma$-ray flux as expected from the galactic distribution of the interstellar matter. The distribution of this component is similar to that of the galactic radio emissions.

(4) No maximum expected from the decay of neutral pi-mesons has been observed in the energy distribution of $\gamma$-ray emissions. In other words, the energy spectrum of this emission is smoothly extended to an energy higher than 100 MeV. This seems to indicate the importance of the bremsstrahlung of energetic electrons and the inverse-Compton effect due to the collisions of such electrons with stellar visible radiation and the background microwave radio photons.

(5) There clearly exist two components of the $\gamma$-ray emissions; one of intergalactic origin and one of cosmological origin related to the evolution of the Universe.

As is understood from the considerations mentioned above, $\gamma$-ray emissions can be applied to astronomical observations together with those of other wavelength regions. Thus, these emissions are able to enrich our knowledge of stellar objects as compared with observations in other wavelength regions. Since $\gamma$-ray astronomy has just recently been born, rapid progress is expected in this field in the near future. The main reason why the observed numbers of the $\gamma$-ray sources are not so numerous even now, and that most of them have still not been identified with known celestial objects, seems highly dependent on the low angular resolving power of the measuring equipment, which is now only of the order of about 0.5 degrees at most.

Among the energy ranges of $\gamma$-ray observations, the observations in the energy range from 0.3 to 30 MeV are the most delayed at the present moment. The angular
resolution is worse by an order of magnitude compared with that for the higher energy range as mentioned earlier. Another problem is the effect of radio activity on the observing equipment due to bombardment by energetic particles and other radiation. However, with respect to the gamma-ray lines at 0.51 MeV originating from electron-positron annihilation, their intense emissions are now thought to be very important to the future research in astrophysics.

The phenomena defined as $\gamma$-ray bursts were observed for the first time in 1973. They are characterized by an increase in the $\gamma$-ray intensity of energy $0.1 \sim 1$ MeV of duration from 0.1 to 10 seconds, and are usually observed about 10 times a year. Though most of them are generated in the Galaxy, the source of the burst whose directivity has been determined most exactly seems to be located somewhere in the Large Magellanic Cloud. Many theories on the origin of these bursts have been proposed, but none seems successful in explaining their characteristics.

Even now, $\gamma$-ray astronomy is in a state of infancy and so many observed results are still open to future research.

b) Interstellar matter

It was pointed out in 1960 that the heating of the interstellar hydrogen clouds by low energy cosmic rays played an important role in maintaining their temperature at about 100 K. This heating was thought favorable for the understanding of many properties of these clouds, but no evidence has yet been obtained to show a cosmic ray intensity sufficient to raise their temperature to the above mentioned value. With the progress made in the research on interstellar molecules, it became clear that this intensity was two orders of magnitude smaller than that deduced for the required heating.

When hydrogens are ionized by the bombardment of cosmic rays, the following reactions usually proceed consecutively: $\text{H}^+ + \text{D} = \text{D}^+ + \text{H}$, $\text{D}^+ + \text{H}_2 \rightarrow \text{HD} + \text{H}^+$. Since such molecules as HD, containing heavy hydrogens, have been detected radio-spectroscopically, the production rate of ionized hydrogens, and hence the cosmic ray intensity, could be estimated based on the observed concentration of these molecules. This intensity is not contradictory to the result which is deduced from the observed intensity corrected for the effect of the solar wind. Therefore, it is necessary to look for some other cause of the heating of the interstellar hydrogen clouds.

Even if the cosmic ray intensity there is of this order of magnitude, cosmic rays may fully contribute to the formation of various interstellar molecules. Hydrogen molecules, which are the main components of molecular clouds, are ionized by cosmic ray particles to become $\text{H}_2^+$ ions. These ions may consecutively produce various molecules of higher molecular weight through the reactions such as $\text{H}_2^+ + \text{CO} \rightarrow \text{HCO}^+ + \text{H}$.

The formation of interstellar molecules is triggered by the reaction of cosmic rays to the interstellar gases, but the main tools for this research are all found in molecular chemistry. Most of the problems related to cosmic ray research itself have already been resolved, but it must be emphasized here that the research on the molecular chemistry of interstellar gases has to consider the role played by cosmic rays.

Three-quarters of a century has already passed since cosmic ray research started
in the early 1910s. During these years, the research into cosmic ray physics has made many important contributions to those of elementary particles and cosmic physics, through which the vigour of the research has been refreshed. It can thus be said that cosmic ray research has maintained its vital force for a long time compared to many other fields. However, it seems very difficult to predict that there will be another period so prosperous for cosmic ray research in the near future, because many of the subjects related to cosmic research have now grown beyond the realm observed in the past history of cosmic ray physics. In other words, these subjects usually contain cosmic ray research as one of the many branches in the research of the universe. This tendency may be considered rather healthy for the research connected with cosmic ray physics. If cosmic ray physics were only to pursue the subject properly related to cosmic rays themselves, there does exist no bright future in this field of physics. But, cosmic ray research can survive vitally if this research itself continues to extend into the research fields adjacent to cosmic ray physics.