Chapter 2

RESEARCH FIELDS IN COSMIC RAY ASTROPHYSICS

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2.1 Introduction

Cosmic rays were discovered as a byproduct of research on radioactivity in the early 1910s. Before the end of the 1920s, it had been made clear, based on studies of the geomagnetic effect, that cosmic rays consisted of various nuclei and electrons arriving at the earth from outer space. The research on radioactivity opened up new fields of research on the structure of matter, in particular, the structure of atoms and of atomic nuclei. Since no accelerator was available during those years, cosmic rays were considered as the most important source of obtaining information relating to research on nuclear structure and elementary particles, since cosmic rays were the only energy source available to investigate the structure of matter through the elementary particles produced from cosmic ray interactions with atmospheric nuclei. Indeed, it could be said that research on nuclear structure and elementary particles in the years up to the middle of the 1940s could never have been conceived without the utilization of cosmic rays. In other words, during those years information on high-energy phenomena related to the search for the fundamental structure of matter became available from research on the interactions of cosmic rays with atmospheric nuclei. The fact that high-energy and ultra-high-energy phenomena due to cosmic ray interactions with atmospheric nuclei are still one of the most important fields in cosmic ray research even today may be considered to be based on the long history of these fields.

Since the early 1940s, cosmic ray research has changed radically because of the research and development of accelerators to artificially produce high energy particles comparable to those observed in cosmic rays. For instance, particles of energy up to several 100 GeV can be produced by accelerators and are being used to investigate experimentally the high-energy nuclear interactions. Since the efficiency and the accuracy of research in high-energy physics are very high, the research on nuclear interactions by cosmic rays has been gradually replaced by experimental work using accelerators. In consequence, the research on these interactions by cosmic rays necessarily needs to shift to nuclear interactions with cosmic rays of energy higher than those being currently used in accelerator work. This is the current situation in cosmic ray research in the field of high-energy physics.
Extensive air showers are being extensively investigated with this sort of research related to high-energy physics. In order to understand the development of these showers, it is necessary to study the chemical composition of high-energy cosmic rays, since they are mostly responsible for the production of these showers. Furthermore, the “astrophysical” neutrinos are now being investigated to understand the high-energy phenomena in galactic space, since they seem to be generated during supernova explosions. It may therefore be said that, at present, cosmic ray research with the aim of understanding high-energy interactions has to consider various problems related to high-energy astrophysics.

Other areas of cosmic ray research include the investigation of the behavior of cosmic ray particles before they enter the atmosphere. Since the late 1920s, during which the charges of these particles had been found to be mainly positive, the investigations of the origin of cosmic rays and the modulation of the cosmic ray intensity during geomagnetic disturbances began with those on the geomagnetic effect and the east-west effects on cosmic rays. In particular, routine observations of cosmic ray muons, which are a secondary component produced from their interactions with the atmospheric nuclei, began in the middle of the 1930s, and then the modulation mechanism on the muon intensity began by taking into account various geophysical phenomena.

In the late 1940s, the existence of nuclei other than protons was directly detected for the first time. Later on, the investigations were extended to the chemical composition and energy spectra of cosmic rays. During the last two years of the 1940s, the first theories on the origin of cosmic rays were put forward by several scientists, such as Fermi, Alfvén, Teller and Unsöld, on the basis of the reliable observed results on their composition and energy spectra. Thus the physical quantities relating to cosmic rays became clear by the observations made during these years.

Since then, it has been recognized that research on cosmic rays plays a key role in the investigations of many problems related to astrophysics. The problems on the origin and the propagation of cosmic rays in the Galaxy and their secular variation had first been pursued in relation to the non-thermal radio emissions from the interstellar space, one of the high-energy phenomena in the Galaxy. Important aspects in the progress of research on the origin of cosmic rays in the 1950s were the discovery of the differences in chemical compositions as related to the stellar population and the identification of supernova remnants as non-thermal radio sources.

Rapid progress in astrophysical research has been made in the fields of X-ray and γ-ray astronomy since the early 1960s. The discovery of new objects such as pulsars and black holes had, furthermore, brought progress in research on the origin of cosmic rays, in particular, on the physical state of the birth place of cosmic rays. At present, most fields of cosmic ray research are aimed at understanding the properties and the behavior of cosmic rays before they enter the atmosphere. Taking into account these current trends, the research fields in cosmic ray astrophysics will be reviewed in this chapter.
2.2 Perspective on Cosmic Ray Research

The research fields in cosmic ray astrophysics are conventionally divided into several different categories, each of which occupies some characteristic scale-length and time in the universe. Since the research on the interactions of cosmic rays with atmospheric nuclei does not belong to any of the above categories, the topics related to these interactions will be considered separately in Section 2.6. The categories aforementioned are schematically shown in Fig. 2.2.1 with respect to both time and scale-length of space. Among these categories, the largest one is associated with cosmology, as shown in this figure, but cosmic ray research related to galactic space will be here considered first.
2.2.1 *In galactic and extragalactic space*

It is thought that our Galaxy, commonly termed the Milky Way as viewed from earth, is similar to the Andromeda galaxy with respect to both structure and size. The structure of the Galaxy was first deduced from the distribution of the stars in galactic space, but its detail was made clear in the late 1950s based on radio astronomical observations of the 21-cm radio waves (1420 MHz) emitted from the ambient hydrogen atoms in interstellar space⁹ (Fig. 2.2.2). As a result, several arms were discovered in the Galaxy. The sun is located in the so-called Orion arm of the Galaxy.

Recent observational results using γ-rays and infra-red rays have introduced much new knowledge about the physical state of the regions in the direction towards the galactic center, and made clear the relations among the distributions of various objects such as supernovae, pulsars, H II regions and the stars of O and B types⁹ (Fig. 2.2.3). Since it is now thought that most cosmic rays are produced through some acceleration processes from the matter ejected in association with supernova explosions, it is estimated that an enormous amount of cosmic rays are to be found in the circular-ring area far from the galactic center by about 5 kpc (1pc=3.26 light years (1.y.), 15000 l.y.).⁹ At present, almost all of the observed continuums of γ-ray

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![Diagram](image_url)

**Fig. 2.2.2.** The distribution of the hydrogen atoms (H I) in the Galaxy (the spiral structure found from the observations on the 21-cm radio emissions).⁹
emissions can be explained as being produced by the bremsstrahlung from high-energy electrons. This strongly suggests that the distribution of cosmic rays is neither uniform nor isotropic throughout the Galaxy.

As shown in Fig. 2.2.4, in the galactic space around the sun, the remnants of supernovae are found in the galactic spiral arms, where many of the H II regions are observed.\(^5\) It seems, therefore, that some fraction of cosmic rays produced from these supernovae will arrive at the solar system. The energy density of cosmic rays as a whole, observed in the vicinity of the earth, is about 1 eV/cm\(^3\) and is almost equal to those of the magnetic field, turbulence and light in interstellar space. This observed energy balance indicates that a quasi-equilibrium state is now attained among these quantities in interstellar space.\(^5\) This fact suggests that, since their birth, cosmic rays must exist for a long time to reach such equilibrium in galactic space.

It is known that there exists a galactic magnetic field, and that its intensity near the sun is about $5 \times 10^{-6}$ gauss.\(^6\) If we assume that a magnetic field of this intensity is, on the average, spherically distributed throughout the Galaxy, the maximum energy of a cosmic ray particle to be confined by this magnetic field inside the Galaxy is estimated to be about $10^{20}$ eV. This amount of energy is reduced by roughly two orders
of magnitude in the case where the structure of the Galaxy is very flat like the Andromeda galaxy as shown in Fig. 2.2.5. The cosmic ray particles of energy higher than $10^{18}$ eV or $10^{20}$ eV are not confined within the Galaxy for a long time and eventually escape into extragalactic space. If we were to detect cosmic rays of energy higher than $10^{20}$ eV on the earth, they should, therefore, have been extragalactic in origin. Since such ultrahigh energy cosmic rays are on occasion observed on the earth as those which produce extensive air showers, it seems that a component of extragalactic origin is contained in the cosmic ray particles as observed on the earth.  

As mentioned above, cosmic rays arriving at the earth are a composite of both the component generated in the Galaxy and one of extragalactic origin.

2.2.2 *In the solar system and its neighborhood*

A supersonic plasma called the solar wind continuously flows out from the sun with a mean speed of 450 km/sec. This solar wind carries with it coronal magnetic fields into interplanetary space. Therefore, the space pervaded by the solar wind is filled by such plasma and magnetic fields. Since the sun rotates with a period of about 27 days, it seems that the pattern of the magnetic fields in interplanetary space from the sun to the earth's orbit should be as schematically shown in Fig. 2.2.6 when viewed
from above the north pole of the sun. Space vehicles exploring the extraterrestrial medium have indeed found the pattern of the interplanetary magnetic field as shown in Fig. 2.2.6. However, the speed of the solar wind is not uniform in interplanetary space, since high-speed particles, up to 650 km/sec, can flow from coronal holes where the temperature is relatively lower. Thus, the plasma and magnetic field intensity are rather irregularly distributed in interplanetary space.

The sun moves with a proper speed of about 20 km/sec in galactic space, accompanied by the solar wind. It therefore seems that the space in which the solar wind is observed is not expected to be spherically symmetric. Since the development of coronal holes varies significantly with the phase of the eleven-year solar activity cycle, the size and the configuration of this space will also change significantly throughout this cycle. Furthermore, the polarity of the solar "general" magnetic field, which is formed over the polar region of the sun, usually reverses during the maximum phase of the solar activity cycle. Since the period of such reverses is also about eleven years, the physical state of interplanetary space will be modulated by this behavior of the general magnetic field.

Although the interplanetary space where the solar wind is flowing is forced to vary with such changes of solar activity and solar magnetic field, the global
configuration of this space is as shown in Fig. 2.2.7. Because of the proper motion of the sun, the outer boundary of this space facing the front side of the sun is bluntly spherical, while on the rear side of the sun a long magnetic tail is formed.

The space in which the solar wind flow is dominant, as shown in Fig. 2.2.7, is called the heliosphere. It is known from direct observations by spacecraft such as Pioneers 10 and 11 and Voyagers 1 and 2, that this heliosphere is extended at least beyond the orbit of Saturn (about 10 AU). It is theoretically estimated that the edge of the heliosphere is located at a distance between 30 AU to 100 AU from the sun, depending on the physical quantities of the solar wind. Since the configuration of the heliosphere varies with the physical quantities in it throughout the solar activity cycle, cosmic rays of galactic and extragalactic origin will be modulated depending on the changes in the physical state of this sphere. This sphere is, therefore, modulated with a period of about eleven years, but it may be also said that its physical state changes with a period of about twenty-two years, since the period of the variation of the polarity of the solar general magnetic field is about twenty-two years. 9)

As expected from the foregoing considerations, there should exist two distinct periods of about eleven and twenty-two years on the modulation of cosmic rays coming into the inner solar system. In fact, the existence of these two periods has been
made clear observationally as described in Subsection 2.5.2. In the heliosphere, the modulation effect on cosmic rays is observed on such a short time scale as mentioned earlier in this section (see Fig. 2.2.1).

2.2.3 *The sun and the stars*

It is now thought that, in the Galaxy, there exist about $4 \times 10^{11}$ stars. Among them, more than half seem to be similar to the sun. The relationship of surface temperature with absolute brightness of stars within a hundred light years of the sun is shown in Fig. 2.2.8. The representation shown in this figure is now called the Hertzsprung-Russell diagram, or the H.R. diagram. There is a clear relationship as shown in Fig. 2.2.9, between the absolute brightness and the mass of the stars. It is seen that, with an increase of mass, both the surface temperature and the absolute brightness of the stars become higher simultaneously. The stars are often classified in the series O, B, A ... in accordance with their surface temperature, i.e., the color of the stars. Based on this classification, Table 2.2.1 summarizes some characteristics of stars regarding their surface temperatures, spectral properties and mean lives.\(^{10}\) It is clear that the lives of massive stars such as O and B types are much shorter than those of stars of G type like the sun.

From the results shown in Figs. 2.2.3 and 2.2.8, many stars classified as types O, B and A are observed in the Galaxy. Since their lives are much shorter than that of the sun, they must be still very young as compared to the sun. It is thus concluded that stars are being born even now in the Galaxy. Furthermore, this means that some stars are now approaching the final stages of their evolution just before the death. Supernovae are the explosions of stars as their death. The remnant of the supernova which occurred in the dawn of July 4th of 1054 A.D. is still today observed as the Crab nebula\(^{11}\) (Fig. 2.2.10). On the basis of research on the evolution of stars, it has been
Fig. 2.2.8. The H-R diagram for the stars near the sun.

Fig. 2.2.9. The mass-luminosity relation on the stars near the sun.
Table 2.2.1. Types of the stars and their lives.\(^{(10)}\)

<table>
<thead>
<tr>
<th>Spectral Type</th>
<th>Effective Surface Temperature ((^\circ) K)</th>
<th>Mass*</th>
<th>Brightness*</th>
<th>Life (Evolving Time in the Unit of Year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O 7.5</td>
<td>38 000</td>
<td>25</td>
<td>80 000</td>
<td>2(\times)10(^{6})</td>
</tr>
<tr>
<td>B 0</td>
<td>33 000</td>
<td>16</td>
<td>10 000</td>
<td>1(\times)10(^{7})</td>
</tr>
<tr>
<td>B 5</td>
<td>17 000</td>
<td>6</td>
<td>600</td>
<td>7(\times)10(^{7})</td>
</tr>
<tr>
<td>A 0</td>
<td>9 500</td>
<td>3</td>
<td>60</td>
<td>3(\times)10(^{8})</td>
</tr>
<tr>
<td>F 0</td>
<td>6 900</td>
<td>1.5</td>
<td>6</td>
<td>1.7(\times)10(^{9})</td>
</tr>
<tr>
<td>G 0</td>
<td>5 800</td>
<td>1</td>
<td>1</td>
<td>7(\times)10(^{9})</td>
</tr>
<tr>
<td>K 0</td>
<td>4 800</td>
<td>0.8</td>
<td>0.4</td>
<td>14(\times)10(^{9})</td>
</tr>
</tbody>
</table>

* The case for the sun is taken as the unity.

Fig. 2.2.10. The Crab nebula.

shown theoretically that the lower limit of the mass for stars to explode as supernovae is 1.4 solar masses. It is therefore thought that the sun is unable to explode as a supernova, but will become a white dwarf at the end of its life.

It is now thought that most cosmic rays have been accelerated in association with the supernova explosions which have occurred at the ends of the lives of massive
stars. The outermost envelopes of such stars are scattered away into outer space during these explosions. Shock waves are generated with the explosions and, later on, propagate outwards through the interstellar matter around the exploded stars. The expanding envelopes are heated to temperatures of several billion degrees or more by these explosions, and nuclei heavier than those of the iron group are rapidly synthesized successively within such envelopes. It is thus thought that these synthetic nuclei and ambient charged particles are accelerated due to their interaction with the expanding shock waves and become the nucleonic components identified as cosmic rays.

However, there exists evidence to show that the origin of cosmic rays cannot be wholly explained by the very high-energy particles accelerated during stellar explosions. It seems, therefore, impossible to conclude that cosmic rays are of galactic origin. It is certain that the matter within the expanding envelopes ejected from the supernova explosions is identified as the original material of cosmic rays, but it should be remarked that the acceleration of particles does not seem to occur only during the supernova explosion. Since this problem is now being investigated extensively using the observed chemical composition of cosmic rays, important new information on the acceleration of cosmic rays should be revealed.

In association with solar flares, the sun occasionally produces high-energy particles like cosmic rays. These particles had been denoted as solar cosmic rays until recently, but they are now called solar-flare particles because most of them are confined in the relatively low energy range of MeV/n. Since a large number of the stars in the Galaxy are sun-like stars, it seems that the cosmic ray particles of MeV energy ambient in interstellar space are released from these stars. It has been made clear, however, that though being gathered together, these particles as a whole are still insufficient to explain the observed space density of cosmic rays in interstellar space. It is therefore very difficult to assume that the origin of cosmic rays is attributable to the high-energy particles produced from stellar and solar flares.

2.2.4 Relation to cosmology

Cosmology, the science of understanding the structure and evolution of the universe, is rapidly being advanced at present. It is known that this universe has been expanding for about $1.2 \times 10^{10}$ years since the big bang. During the evolution of the universe, the galaxies were born first, and then evolved the stars including our sun. Therefore, the nature of cosmic rays themselves must have varied with the evolution of the universe.

It may be thought that the chemical composition of cosmic rays contains some information on the synthetic processes of the elements during cosmic evolution, and that various interesting phenomena in astrophysical research have been produced as a result of the interactions of cosmic rays with the background 3 K radiations, as evidence of the big bang cosmology. Since most cosmic rays seem to have been produced by supernova explosions, it does not seem that cosmic rays themselves contain much information on the evolution of the universe. However, such phenomena as the interaction of cosmic rays with the cosmic background radiation
may have modified the chemical composition and the energy spectrum of cosmic rays during their lifetime. It seems, therefore, that the results obtained from cosmic ray research may sometimes afford important insight on cosmological studies.

An enormous number of neutrinos, which contain important information on the early stages in the evolution of the big bang universe, exist as a background component in this vast universe. The possible interactions of cosmic rays with these neutrinos should be considered in the process of cosmic evolution, though their frequency may be extremely low.

As is well known, the energy density of cosmic rays is of the same order of those of the magnetic field and the turbulent gas motion in interstellar space. This fact indicates that the role of cosmic rays cannot be neglected in the process of cosmic evolution. This is expected to be true almost everywhere in this universe. For this reason, it is necessary to take into account the role of cosmic rays as a remarkable non-thermal component in this universe when we search for the evolution of the universe.

2.3 Cosmic Rays and Their Associated Phenomena

As shown in Fig. 2.2.1, both the characteristic times and lengths are widely dispersed among the various fields in cosmic ray research. Each of such fields has been investigated, experimentally and theoretically, by means of the methods proper to them from various points of view. Since cosmic rays play an important role in various aspects of this universe as mentioned in the last section, the fundamental problems concerning cosmic rays, such as research on their chemical composition and energy spectrum, are never pursued without consideration of their relation to various astrophysical phenomena.

Cosmic ray research may be said to have two distinct fields; the behaviors of cosmic rays in each domain specified by different characteristic time and length as shown in Fig. 2.2.1, and the relation between these behaviors and various astrophysical phenomena.

2.3.1 Fundamental problems

The most important problem in cosmic ray research seems to be the search for the origin of cosmic rays. In order to study this problem, it is first necessary to collect together all the experimental results in order to understand the nature of cosmic rays. These results contain the chemical compositions of cosmic rays at their birth and in the space near the earth, the flux and the energy spectrum of cosmic rays, the isotopic distribution and the electron-to-positron ratio in cosmic rays. The chemical composition, the energy spectrum and the isotopic abundances of cosmic rays obtained by observations to date shown in Figs. 2.3.1, 2.3.2 and 2.3.3, respectively.

In order to estimate the chemical composition of cosmic rays at their sources based on the observed data near earth, it is necessary to know both the age of cosmic rays and the propagation mechanism of cosmic rays in the space between their birth place and the earth. From observations of the abundance of $^{10}$Be nuclei in cosmic rays,
it is now known that the mean life of cosmic rays is about $3.0 \times 10^7$ years in galactic space.\(^{17}\) This means that cosmic rays spend this time, on average, to propagate through interstellar space from their birth place to the vicinity of the earth. During this time, the original chemical composition of cosmic rays given at their birth place is significantly modified before they reach the vicinity of the earth, through their interactions with the matter and photons in interstellar space. The chemical composition of cosmic rays as shown in Fig. 2.3.1 is that which has been theoretically deduced by taking into account these interactions which are assumed to have taken place during the passage of cosmic rays from their source positions to the earth's neighborhood.\(^{18}\) It is clearly seen in this figure that the chemical composition of cosmic rays at their source positions is significantly different from that which is currently observed near the earth. Table 2.3.1 summarizes the recent observational results on the chemical composition of cosmic rays at their sources as derived by several authors.\(^{19}\)

The sources which have produced most of the cosmic rays as currently observed may be identified as some of the supernovae which have exploded intermittently during the last $10^7$ years in galactic space. In other words, cosmic rays seem to have been generated from the matter ejected from the explosions of some supernovae.
Therefore, we are unable to directly look at the mechanism for the generation of cosmic rays in the space near or inside the exploding supernovae. But, viewed from the theoretical consideration of the acceleration mechanism of high-energy particles during supernova explosions or by rotating pulsars, it is certain that cosmic rays are accelerated in association with such explosions or in the space around rapidly rotating pulsars like the Crab nebula as shown in Fig. 2.2.10. Even if so, it is still impossible to observe directly both the chemical composition and the energy spectrum of cosmic rays at their source positions. This is the reason why we need to learn the propagation mechanism of cosmic rays quantitatively on the basis of detailed observations of various astrophysical phenomena and their theoretical studies.

When large solar flares occur on the sun, they sometimes produce high-energy particles in the GeV range. It is known that such solar flares usually occur about twenty times, on the average, in one solar cycle (about eleven years). Furthermore, solar flares associated with particles of MeV energy generally occur about a hundred times in one solar cycle. Through studies of these solar-flare particles, we may, therefore, find some hint on the mechanism as to how high-energy particles are so
efficiently accelerated in the regions where some violent phenomena occur from an astrophysical point of view. For this reason, the investigations of the acceleration of high-energy particles in solar flares and their propagation in the solar corona and interplanetary space seem to give some clue important to the research on the origin of cosmic rays in cosmic space.

As regards the chemical compositions of galactic cosmic rays and solar-flare particles, the ratios of these two to the solar atmospheric compositions for each element, which are defined as the enhancement factors, are shown in Fig. 2.3.4 as a function of the atomic number of the elements. In this figure, these three compositions are normalized to the abundance of $^{16}\text{O}$ nuclei. The results shown in this figure indicate that the chemical compositions of cosmic rays and solar-flare particles become relatively more enhanced compared to that of the solar atmosphere with increase of the atomic number of the elements. The fact that the chemical composition of cosmic rays at their sources is similar to that of solar-flare particles suggests that the
Table 2.3.1. The chemical composition of cosmic rays at their sources.

<table>
<thead>
<tr>
<th>Element</th>
<th>García-Munoz, Simpson(^1) (G-S)</th>
<th>Shapiro et al.(^2)</th>
<th>Lezniak, Webber(^3)</th>
<th>Galaxy Meyer(^4)</th>
<th>(G-S)/Galaxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>3.070 ± 0.200</td>
<td>2.600</td>
<td>2.980 ± 0.60</td>
<td>(2.08 ± 0.46) × 10^4</td>
<td>0.148 ± 0.034</td>
</tr>
<tr>
<td>C</td>
<td>100 ± 1</td>
<td>100</td>
<td>100 ± 2</td>
<td>100 ± 23</td>
<td>1.00 ± 0.23</td>
</tr>
<tr>
<td>N</td>
<td>6 ± 1</td>
<td>8 ± 2</td>
<td>8 ± 2</td>
<td>17.7 ± 7.7</td>
<td>0.34 ± 0.16</td>
</tr>
<tr>
<td>O</td>
<td>128 ± 3</td>
<td>111 ± 2</td>
<td>112</td>
<td>177 ± 38</td>
<td>0.72 ± 0.16</td>
</tr>
<tr>
<td>F</td>
<td>0.7 ± 0.5</td>
<td>0.7 ± 0.5</td>
<td>0.4</td>
<td>7.15 × 10^-3</td>
<td></td>
</tr>
<tr>
<td>Ne</td>
<td>16.0 ± 2</td>
<td>15 ± 2</td>
<td>16.0 ± 0.9</td>
<td>20.8</td>
<td>0.77</td>
</tr>
<tr>
<td>Na</td>
<td>2.7 ± 1</td>
<td>0.9 ± 0.4</td>
<td>0.7 ± 0.6</td>
<td>0.43 ± 0.7</td>
<td>6.3 ± 2.6</td>
</tr>
<tr>
<td>Mg</td>
<td>29.5 ± 2</td>
<td>24 ± 2</td>
<td>23.6 ± 1.1</td>
<td>8.08 ± 0.23</td>
<td>3.65 ± 0.27</td>
</tr>
<tr>
<td>Al</td>
<td>4.4 ± 1</td>
<td>2.3 ± 1</td>
<td>3.0 ± 0.9</td>
<td>0.65 ± 0.03</td>
<td>6.8 ± 1.57</td>
</tr>
<tr>
<td>Si</td>
<td>28.0 ± 2</td>
<td>21 ± 3</td>
<td>23.1 ± 1.3</td>
<td>7.69 ± 0.23</td>
<td>3.64 ± 0.28</td>
</tr>
<tr>
<td>P</td>
<td>0.6 ± 0.4</td>
<td>0.2 + 0.4</td>
<td>0.074 ± 0.0015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>3.8 ± 0.6</td>
<td>3 ± 0.6</td>
<td>3.7 ± 0.3</td>
<td>3.46 ± 1</td>
<td>1.10 ± 0.36</td>
</tr>
<tr>
<td>Cl</td>
<td>0.3 ± 0.2</td>
<td>0.1 + 0.5</td>
<td></td>
<td>0.036</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.8 ± 0.3</td>
<td>0.8 ± 0.5</td>
<td>&lt;0.8</td>
<td>0.69</td>
<td>1.16</td>
</tr>
<tr>
<td>K</td>
<td>0.7 ± 0.3</td>
<td>0.1 + 0.5</td>
<td></td>
<td>0.028 ± 0.009</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>3.7 ± 0.5</td>
<td>2.4 ± 0.8</td>
<td>1.6 ± 0.3</td>
<td>0.48 ± 0.06</td>
<td>7.71 ± 1.42</td>
</tr>
<tr>
<td>Ti</td>
<td>0</td>
<td>0 ± 0.5</td>
<td></td>
<td>0.10 + 0.1</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>0</td>
<td>0 ± 0.5</td>
<td>&lt;1.6</td>
<td>0.37 ± 0.046</td>
<td>4.59 ± 1.0</td>
</tr>
<tr>
<td>Mn</td>
<td>0</td>
<td>0.1 ± 0.5</td>
<td></td>
<td>0.48 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>30.5 ± 2</td>
<td>22 ± 3</td>
<td>26.5 ± 1.8</td>
<td>6.77 ± 0.46</td>
<td>4.51 ± 0.43</td>
</tr>
<tr>
<td>Ni</td>
<td>1.7 ± 0.3</td>
<td>0.8 ± 0.2</td>
<td>1.1 ± 0.2</td>
<td>0.37 ± 0.046</td>
<td>4.59 ± 1.0</td>
</tr>
</tbody>
</table>

physical state of the area where cosmic rays are accelerated, and also their acceleration mechanism, are both not much different from the environment where solar-flare particles are generated in solar flares.

In recent years, the isotopic abundances in cosmic rays have been observed with respect to elements such as Si, Ne and Mg. Furthermore, the isotopes of iron nuclei have sometimes been observed separately. Since these data are able to give us an important clue to search for the physical state of the birth place and the acceleration mechanism of cosmic rays, rapid progress is now expected in these research fields.

2.3.2 Association with astrophysical phenomena

All of the observed data on cosmic rays are considered as fundamental material in the search for the origin of cosmic rays, i.e., the search for the acceleration and the propagation mechanisms of cosmic rays and the physical state of cosmic ray sources. But, it is impossible to progress in the study of the origin of cosmic rays by using these data only. In order to do so, information has to be available on the locations where
cosmic rays are generated and the space in which cosmic rays propagate after accelerated. This is the reason why it is necessary to investigate the nature of various astrophysical phenomena, both experimentally and theoretically.

In the meantime, the era when the search for the origin of cosmic rays had begun steadily may be identified as several years since the beginning of the 1950s. During these years, the outline of the birth and evolution of the stars and the relation of stellar populations with the shapes of stellar clusters had been made clear. Furthermore, rapid progress had been made in radioastronomical research on the physics of interstellar space. The progress in these subjects as cited above opened up new research fields on the causal relation of the chemical composition of cosmic rays with those of the stars, and on the non-thermal galactic radio emissions as related to the sources of cosmic rays.

During those years, a hypothesis had been put forward on the possible connection of synchrotron emissions from relativistic electrons with such non-thermal radio emissions as observed in supernova remnants like the Crab nebula shown in Fig. 2.2.10. Thus, supernova remnants had been identified as cosmic ray sources. Later on, the fact that those non-thermal radio emissions, including optical emissions, were significantly polarized, was found from radio-astronomical observations on the Crab nebula. Heavy nuclei are more abundant in the chemical composition of cosmic rays than in stars of population II. Since such observed overabundances in heavy nuclei coincided with those seen in the chemical composition of stars of population I like the sun, it had been inferred that cosmic rays were mostly of supernova origin, because the chemical composition of the matter ejected from supernovae could be estimated as very similar to that of the stars of population I. As mentioned above, progress in astrophysics sometimes played an important role in cosmic ray research.

Observational and theoretical investigations of astrophysical phenomena always play an important part in the understanding of cosmic ray phenomena. Since the birth of radioastronomy, observations of astrophysical phenomena have been extended into other energy regions such as X-rays, ultra-violet rays, infrared rays and gamma-rays. As a result, our own view on the universe at present has become completely different from that which had been prevailing during the early 1950s.

At present, various astrophysical phenomena interesting to us have been found in different energy ranges since the discovery of the X-ray stars. Among them, such interesting objects as pulsars, neutron stars, black holes, the birth place of the young stars and many kinds of organic molecules have been discovered in the Galaxy. The relation of these objects and others with the structure of the Galaxy has recently been well understood. As an example related to the result shown in Fig. 2.2.3, the one-dimensional distributions of pulsars, supernova remnants, H I and H II regions, and the relative abundances of CO and H₂O molecules in the Galaxy are shown in Fig. 2.3.5 with respect to the radial distance from the galactic center. It is clear from this figure that many high-energy astrophysical phenomena have been taking place within the circular region distant by about 5 kpc (≈15000 light years) from the galactic center. Furthermore, the massive stars of O and B types are also distributed relatively
Fig. 2.3.5. The radial distributions of γ-ray emissions, HI and HII regions, CO and H₂O molecular clouds as a function of the distance from the galactic center. ²
more densely in this circular region. The flux of the continuum gamma-ray emissions is higher in this circular area than in the other areas, inside and outside, as shown in Fig. 2.3.6.\(^{26}\)

In order to search for the physical processes associated with the acceleration of cosmic rays at their source, gamma-ray observations have been proposed, relating to the gamma-ray line emissions from radioactive \(^{26}\)Al (half life=7.2×10^5 years) and other nuclei produced from the r-process during supernova explosions. Table 2.3.2 summarizes the gamma-ray line emissions which seem to be useful in searching for the physical processes mentioned above.\(^{27}\) The important role for gamma-ray line emissions associated with solar flares to play in the study of particle acceleration in solar flares will be considered in Chapter 8. It is, therefore, only mentioned here that the direct observations of gamma-ray emissions from solar flares may give us some useful hint to infer the physical processes associated with the acceleration mechanism of cosmic rays in their source regions.

The shock waves associated with supernova explosions propagate into outer space. The remnant matter ejected from the explosions also expands into this space following these waves.\(^{28}\) After many years, a region filled by hot plasma (10^5 to 10^6 K), illuminated by soft X-rays, seems to be eventually formed around each supernova. For instance, the Veil nebula in the constellation Cygnus as shown in Fig. 2.3.7 is identified as a structure formed as a result of the expansion of a supernova remnant which might have exploded about 14000 years before. High-temperature plasmas which are irradiated by soft X-ray emissions still occupy the region surrounded by these veil structures of the nebula. At present, many such hot bubbles filled with high-temperature plasmas have been detected in interstellar space, and some of them are connected with each other. Since the galactic magnetic field is rejected by the expanding hot plasmas from inside these bubbles, there exists the possibility that the mean intensity of the magnetic field is very weak inside the bubbles.

Our solar system is in motion inside one of these hot bubbles at the present moment.\(^{29}\) Although the size of this bubble is not known clearly as yet because of many uncertainties, its diameter has been estimated as 100 pc (see Fig. 2.3.8). Using this diameter, the age of the supernova since the explosion can be deduced to be of the order of a million years. Therefore, the cosmic rays which are now being observed on the earth and in its vicinity must have arrived in the inner region of the solar system by crossing this bubble. It thus seems that the cosmic ray density which is being observed now is necessarily different from that which seems to be found outside the bubble.

As have already been described, observations of various gamma-ray line emissions (see Table 2.3.2) are important in the direct search for the physical processes associated with the acceleration of cosmic rays and the physical state of cosmic ray sources.\(^{27}\) In fact, there is one more method to investigate these physical processes. This is to detect high-energy neutrinos released from supernova explosions into outer space. At the present moment, the project named DUMAND (Deep Underwater Muon and Neutrino Detection) is in rapid progress,\(^{30}\) which plans to build a large Cerenkov detector system under the sea near the Hawaii islands and then to detect neutrinos from the sky and muons produced from these neutrinos below the sea level.
Table 2.3.2. Gamma ray line emissions important in the search for the cosmic ray sources.

<table>
<thead>
<tr>
<th>Decay Pattern</th>
<th>Mean Life (yr.)</th>
<th>Number of Nuclei for a Supernova</th>
<th>Photon Energy</th>
<th>Photon Number per Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{56}\text{Ni} \rightarrow ^{54}\text{Co} \rightarrow ^{54}\text{Fe}$</td>
<td>0.31</td>
<td>$3 \times 10^{54}$</td>
<td>0.87</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.238</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.598</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.771</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.038</td>
<td>0.13</td>
</tr>
<tr>
<td>$^{57}\text{Co} \rightarrow ^{57}\text{Fe}$</td>
<td>1.1</td>
<td>$7 \times 10^{52}$</td>
<td>0.122</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.014</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.136</td>
<td>0.12</td>
</tr>
<tr>
<td>$^{22}\text{Na} \rightarrow ^{22}\text{Ne}$</td>
<td>3.8</td>
<td>$3 \times 10^{52}$</td>
<td>1.275</td>
<td>1</td>
</tr>
<tr>
<td>$^{44}\text{Ti} \rightarrow ^{44}\text{Sc} \rightarrow ^{44}\text{Ca}$</td>
<td>68</td>
<td>$6 \times 10^{51}$</td>
<td>1.156</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.078</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.068</td>
<td>1</td>
</tr>
<tr>
<td>$^{60}\text{Fe} \rightarrow ^{60}\text{Co} \rightarrow ^{60}\text{Ni}$</td>
<td>$4.3 \times 10^{5}$</td>
<td>$5 \times 10^{50}$</td>
<td>1.332</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.173</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.059</td>
<td>1</td>
</tr>
<tr>
<td>$^{26}\text{Al} \rightarrow ^{26}\text{Mg}$</td>
<td>$1.1 \times 10^{6}$</td>
<td>$4 \times 10^{50}$</td>
<td>1.809</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.130</td>
<td>0.04</td>
</tr>
</tbody>
</table>

If we are able to detect these neutrinos successfully, we would become ready to search for the physical process for cosmic rays to be accelerated in the expanding envelopes of supernovae by referring to the observed data on gamma-ray line emissions.

As has been mentioned so far, it is clear that the search for the origin of the universe is being investigated by taking into account electromagnetic emissions in a wide frequency range, from low frequency radio waves, via optical light quanta, to high-energy gamma-rays. Even cosmic rays sometimes play an important part in research in some fields of high-energy astrophysics. At the same time, the results obtained from astrophysical research often become useful in the search for the origin of cosmic rays.

2.4 The History of Cosmic Rays

It takes about $3.0 \times 10^{7}$ years for cosmic rays to reach the earth since their birth somewhere in the Galaxy. This age is considered to be the mean life of cosmic rays in the Galaxy. In other words, after being accelerated somewhere, cosmic rays are confined in galactic space for a long time before reaching the earth. It is thus thought that most cosmic rays are leaked away out of the galactic space during this time.

The age of the universe is longer by three orders of magnitude than that of cosmic rays. Also, the mean life of massive stars like O and B types is of the same order as the age of cosmic rays, or less, as shown in Table 2.2.1. It seems, therefore, natural to assume that the cosmic ray density has never remained constant, but perhaps has varied secularly in galactic space during the lifetime of cosmic rays. It is expected that, while moving across galactic space, the solar system must have passed many times through the galactic arms or hot plasma bubbles (supernova remnants).
Furthermore, a variation of cosmic ray intensity on a time scale much shorter than the age of cosmic rays is, of course, expected, since solar activity is not invariable, but varies with different time scales. In consequence, the existence of a secular variation in cosmic ray intensity is expected in the inner solar system.

2.4.1 Secular variation of cosmic rays

As mentioned earlier, the age of cosmic rays is estimated to be about $3 \times 10^7$ years based on the analysis of the relative abundance of radioactive $^{10}$Be nuclei in cosmic rays.\textsuperscript{17} The secular variation in the intensity or flux of cosmic rays on time scales shorter than this can be examined by using such radioactive isotopes as the nuclei $^{26}$Al (half life = $7.2 \times 10^5$ years) and $^{36}$Cl (half life = $3 \times 10^5$ years). However, cosmic ray variations on such time scales have not yet been observed. Although the irradiative ages of meteorites and cosmic dust by the bombardment of cosmic rays have been estimated from the analysis of the relative abundances of $^{53}$Mn and $^{59}$Ni nuclei in
them, they do not indicate any evidence suggesting significant long-term variation of cosmic rays in the vicinity of the earth. On the basis of these results, it is now thought that the production rate of cosmic rays in galactic space has varied little during the age of cosmic rays.

The fact that the cosmic ray intensity near the earth has always been almost the same as that currently observable strongly suggests that cosmic rays have never reached the space near the earth since they were produced from supernovae, which, as the Crab nebula, occurred several thousand years in the past. The pulsar discovered in the constellation Vela, distant from the solar system by about 500 pc, is located within the remnant of a supernova formed from a star explosion 12000 years ago, and is similarly a strong gamma-ray emitter as the Crab nebula. The front of the gas cloud,
called the Gum nebula, ejected from this supernova, has already arrived at about 100 pc from the solar system as shown in Fig. 2.4.1. However, there has been no evidence to suggest that cosmic rays produced from this supernova have arrived at the earth. If the diffusion velocity of cosmic rays calculated by Wentzel\textsuperscript{33} were acceptable, cosmic rays would have never reached the solar system from this supernova.

Cosmic rays are continuously modulated by the solar wind in the solar system, because the physical quantities such as wind speed and magnetic intensity are highly variable with the phase of the solar activity cycle. Since solar activity changes irregularly with many different time scales, the cosmic ray intensity does likewise on corresponding time scales. At present, such variations in the cosmic ray intensity are estimated by analysing the quantity of radioactive carbons, \( ^{14}\text{C} \), accumulated in tree rings after formation in the atmosphere due to cosmic ray interactions with atmospheric nuclei. Since the production rate of \( ^{14}\text{C} \) nuclei in the atmosphere varies with the phase of the solar activity cycle, the variability of the cosmic ray intensity can be examined on time scales equal to or less than the half life of the decay of \( ^{14}\text{C} \) atoms (5730 years).\textsuperscript{34} The result shown in Fig. 2.4.2 indicates the secular variation of the production rate of \( ^{14}\text{C} \) atoms from tree rings, the absolute ages of which are known.\textsuperscript{25} In this figure, observed results from sunspot numbers and auroral records are indicated, too, for the recent past. It becomes clear from these results that the production rate of \( ^{14}\text{C} \) atoms was significantly higher during the years when solar activity was extremely low. Astonishing is that such periods of extremely calm solar activity have occurred at least three times since the medieval age. The climate during these three periods was extremely cold and they are now named the Wolf, the Spörer

Fig. 2.4.1. The Structure of the Gum Nebula (a sketch).\textsuperscript{32}
and the Maunder Minima in historical order. It is remarkable that, among these three minima, the Maunder Minimum corresponded to the coldest period of the Little Ice Age, during which the earth’s climate was bitterly cold.  

A large number of solar-flare particles were produced during the eras when solar activity was unusually high. It is now conjectured that the background mean density of these particles might have been high enough in the solar system during these eras, such that the ozone layer would have been partly destroyed by the bombardment of these particles into the earth’s upper atmosphere. Since extensive research on the secular variation of the production rate of these particles is currently under way, it is expected that the details of the long-term change of this rate over geological time can be made clear.

2.4.2 Interactions with cosmic matter

While propagating through galactic space, cosmic rays interact with matter and photons to produce various new nuclei which are mostly absent in the original chemical composition of cosmic rays at their sources. For instance, light nuclei like Li, Be and B are produced from the fragmentation of heavier nuclei due to their interactions with interstellar matter, though these light nuclei are hardly detected at all in optical stellar spectra. Nuclei of medium mass, such as C, N and O are also produced partly from these fragmentations and added to the source composition of cosmic rays.  

Knowledge of these fragmentations and their yields is thus very important in the study of the propagation mechanism of cosmic rays and their chemical composition at their origin. As mentioned earlier, the mean life of cosmic rays can be estimated from the relative abundances of $^{10}\text{Be}$ nuclei in observed cosmic rays. Using the data on secondary components in the light and medium nuclei as described in the last paragraph, some causal relation can be obtained between the above mean life and the matter traversed by cosmic rays in interstellar space. Thus it becomes possible to infer the propagation path of cosmic rays in this space. As a result of these studies, it is believed that cosmic rays may not be confined in the galactic disk as shown in Fig. 2.2.5. Based on the possible behavior of cosmic rays in the galactic disk and halo, the magnetic structure of the Galaxy is being investigated extensively.

2.5 Cosmic Rays in the Solar System

Topics on cosmic ray research in the region of the solar system are concerned with solar-flare particles associated with solar flares and the modulation of galactic cosmic rays. After having propagated through interstellar space, cosmic rays partly diffuse into the solar system as they encounter the outer boundary of the heliosphere. Cosmic rays gradually begin to be modulated by the solar wind as they propagate deeply into the space of the solar system. The problems such as the pattern of motion of cosmic rays in interplanetary space and the modulation of cosmic rays with interplanetary disturbances associated with solar flares are, therefore, important subjects for cosmic ray research in the solar system.

Solar-flare particles are generated in solar flares. After being accelerated in solar flare regions, they are released into interplanetary space and finally diffuse out of the heliosphere. Therefore, the propagation of solar-flare particles in interplanetary space can be investigated by referring to the behavior and the modulation of galactic cosmic rays in this space. In other words, the results from research on this propagation are also useful as a means of study on the modulation of cosmic rays in the solar system. Although the spatial and time scales related to research on cosmic rays in the solar system are relatively small as shown in Fig. 2.2.1, this field of research is considered important.

2.5.1 Solar-flare particles

The sun is the only star which can be investigated by directly observing the phenomena taking place on its surface and in its atmosphere. Though being very common as a star, the research results from direct observations of surface phenomena give us many powerful hints necessary to understand the observed phenomena in high-energy astrophysics. For this reason, it becomes very important to obtain detailed experimental data on the physical properties of solar-flare particles relating to their chemical composition and energy spectrum. Then, it is necessary to examine the characteristics and the developmental pattern of solar flares responsible for the production of solar-flare particles on the basis of the observed data on them, and eventually to make clear the relation of the mechanism of solar flares with the
acceleration of high-energy particles in them. Up to now, however, some ambiguities still remain in the observations and theories on solar flares, and it is also necessary to refine the experimental technique of observing high-energy gamma-ray emissions associated with solar flares. Thus it is difficult to fully understand the acceleration mechanism of solar-flare particles based on present observational results.

Many observations of solar phenomena were accumulated by the Skylab Experiments from 1973 to 1974. Thus it is now possible to investigate many important problems on the development of solar flares and associated phenomena in greater detail. Since satellites observing high-energy radiations from the sun have recently been launched, research on the mechanism of solar flares and on the acceleration of high-energy particles in solar flares has been rapidly advanced using the observed results from these satellites.

After being accelerated in the solar flare regions, solar-flare particles first propagate through the corona and then gradually diffuse out into interplanetary space where the solar wind plays a dominant role. Later on, a part of these particles arrives in the vicinity of the earth, and can be detected by satellites or ground-based observatories. The possible behavior of solar-flare particles in the solar corona is shown schematically in Fig. 2.5.1. Randomly scattered by the irregularities of plasmas and magnetic fields in the solar wind, solar-flare particles propagate mainly under the guidance of the large-scale magnetic field in interplanetary space (Fig. 2.2.6), after their release from the sun. Figure 2.5.2 shows the observed results of the intensity variations of solar-flare particles with time at three different locations in interplanetary space. In this figure are also shown theoretical intensity-time profiles for these locations, calculated using a simple theory of particle diffusion in three-dimensional space. As inferred from this figure, in general, the majority of solar-flare particles propagate outwards to the boundary of the heliosphere by means of diffusion. After reaching this boundary, they finally leak away into interstellar space to constitute the low energy component of galactic cosmic rays.

Fig. 2.5.1. The behavior of solar-flare particles in the vicinity of the sun (a model).
The sun belongs to stellar population I and has a relative overabundances of heavy nuclei in its chemical composition. Since the chemical composition of solar flare regions is known to be almost the same as those of other regions in the solar atmosphere, it seems that the chemical composition of solar-flare particles reflects that of the sun itself. If the former could be precisely determined experimentally, both the acceleration mechanism of particles in solar flares and the physical state in the solar flare regions would, therefore, be understood eventually. In fact, it is known that the observed chemical composition of solar-flare particles tends to vary depending on the particle energy per nucleon, but the results on the compositions for the sun and these particles of energy higher than several ten MeV per nucleon are shown in Fig. 2.5.3 as a function of the atomic numbers of the elements. In this figure, the chemical compositions are normalized with the relative abundance of hydrogen atoms as $10^6$. It follows that the chemical composition of the sun is very similar to that of solar-flare particles.

In the energy range less than about 20 MeV per nucleon, on the contrary, the heavier nuclei become relatively overabundant in solar-flare particles as shown in Fig. 2.3.4, compared to the chemical composition of the sun. Even now, however, no
Fig. 2.5.3. The comparisons among three chemical abundances on solar-flare particles of energy higher than about 100 MeV/nucleon, the photosphere and the corona (normalized by H=10^5).\textsuperscript{14}

interpretation has been given about how such dependence of the chemical composition of solar-flare particles on particle energy as mentioned above has been causally introduced.

2.5.2 Modulation mechanisms of cosmic rays

As described in Subsection 2.2.2, the heliosphere is formed by the solar wind flowing outwards up to about several 10 AU or more as viewed in the ecliptic plane. This situation does not seem much different even when viewed from the direction far
off of this plane. Since the solar wind transports the magnetic lines of force in the coronal region extended from the photosphere into the interplanetary space, cosmic rays are necessarily affected by the solar wind as soon as they enter into the heliosphere. Since the physical state of the heliosphere changes with solar activity throughout the solar activity cycle, the effect of the solar wind on cosmic rays varies with solar activity too, though being dependent on the cosmic ray energy. As a result, the integral intensity and the energy spectrum of cosmic rays at the earth’s orbit and its vicinity are necessarily modulated by solar activity.\textsuperscript{42}

Solar activity varies with the growth and decay of sunspot groups on the solar photosphere. In consequence, as regards the modulation effects on cosmic rays, there are known to be several different types of variations of cosmic ray intensity in accordance with the changing patterns of solar activity; for instance there are the 27-day periodic change related to the solar rotation, the 11- or 22-year variation associated with the solar activity or magnetic cycle, and the long-term irregular variation on a time scale of about 100 years associated with that of the solar activity. These variations in cosmic ray intensity are all considered as modulational effects on cosmic rays which are associated with solar activity as a whole. In other words, they are not phenomena temporarily accompanied by solar flares. It may thus be said that the variations in solar activity as a whole over many years directly affects the intensity and the energy spectrum of cosmic rays. The solar-cycle variation of this intensity is shown in Fig. 2.5.4 as an example.\textsuperscript{43}

On a shorter time scale, the cosmic ray intensity occasionally decreases rapidly in a few hours and then gradually recovers in a week or so back to the intensity before the onset of the event. Such variations in the intensity are usually associated with strong geomagnetic disturbances denoted by magnetic storms. It is now known that most cases of such disturbances are produced as a result of the encounter of the earth’s magnetosphere with the shock waves and the coronal plasma clouds ejected from solar flares. Solar flares thus not only produce high-energy particles, but sometimes become the cause of such disturbances associated with the decrease of cosmic ray flux as just mentioned. Such a decrease of the cosmic ray intensity is now called the

![Graph](image)

Fig. 2.5.4. The variation of the cosmic ray intensity as dependent on the phase of the solar activity cycle (the continuous records of the neutron component yielded in the atmosphere).\textsuperscript{43}
Forbush decrease, after the scientist who first studied this phenomenon (see Fig. 2.5.5).\textsuperscript{441}

Even now, it is still impossible to explore experimentally the outer boundary of the heliosphere and its vicinity. The observed results obtained by deep-space explorers on the spatial distribution of cosmic rays are able to give some clue to investigate the expanse of this boundary. Taking into account the observed results obtained from the spacecraft Pioneers 10 and 11 on the cosmic ray flux in the region up to about 20 AU from the sun, the radius of the heliosphere has been theoretically estimated as about 50 AU in the ecliptic plane (see Fig. 2.5.6).\textsuperscript{41} In order to explore the heliospheric boundary using groundbased data on cosmic ray observations, research on the modulation effect on the cosmic ray flux for the energy range between $10^{11}$ and $10^{13}$ eV has already been begun, since the gyro-radii of these cosmic ray

![Cosmic Ray Intensity Graph](image)

Fig. 2.5.5. The Forbush decreases as seen on the cosmic ray intensity.\textsuperscript{441}
Fig. 2.5.6. The radial distribution of the cosmic ray flux in the interplanetary space as a function of the distance from the sun and the size of the heliosphere as deduced from this distribution.  

particles moving in the magnetic field prevailing in the solar wind seems to be of the same order of the spatial extent of the heliosphere.

2.5.3 Planetary magnetospheres and cosmic rays

The earth’s magnetosphere (Fig. 2.5.7) may be considered spatially the smallest among the scales characteristic of cosmic ray research, since the magnetospheres of Jupiter and Saturn are both several tens of times larger than that of the earth. Historically, the space surrounding the earth had long been considered a vacuum, but the discovery of the modulation effect on cosmic rays by the geomagnetic field, i.e., the geomagnetic effect on cosmic rays, in the late 1920s had shown that cosmic rays mainly consisted of charged particles. Furthermore, the discovery of the so-called east-west effect on cosmic rays had shown that most cosmic rays were positively charged.

From the historical point of view, the nature of cosmic rays had been pursued through investigations on the modulation effect on cosmic rays by the geomagnetic field during those early years. At the present moment, however, it is thought that these investigations have only historical significance, except for those on the so-called van Allen belts where high-energy particles are trapped in the magnetospheric region. Although the theory of the geomagnetic effect on cosmic rays as extensively investigated in the 1930s had played an important part in the later studies on the explanations of the van Allen belts and the anisotropy of solar cosmic rays in the
initial phase of their arrival at the earth, no development has recently been made in this field except for the exact calculations on the orbital motion of cosmic rays in the magnetosphere as shown in Fig. 2.5.7.

Since the spacecraft Pioneer 10 discovered various nuclei and electrons being accelerated to high energy in the Jovian magnetosphere, the relation of planetary magnetospheres with cosmic rays has again become one of the important subjects in cosmic ray research. Many new observed results on energetic particles in the Jovian and Saturnian magnetospheres, hitherto unexpected, have been obtained by the spacecraft Pioneers 10 and 11 and Voyagers 1 and 2 from their observations over several years in the recent past. The discovery of the fact that various nuclei and electrons are accelerated to MeV energies in these massive magnetospheres seems to give us some hint on the research for the origin of cosmic rays. Since the rotation periods of the planets Jupiter and Saturn are both relatively rapid (about 10 hours), it is thought that the mechanism generating a strong electric field induced from the rotation of the magnetosphere may give observational evidence on the acceleration mechanism of high-energy particles in pulsars rotating rapidly, though their characteristic scale length is much shorter. The observed fact that the accelerated nuclei and electrons are released into interplanetary space from those magnetospheres strongly suggests that both Jupiter and Saturn together with the sun play an important role in the spatial and temporal distributions of high energy particles in the heliosphere.
The investigations on the generation mechanism of high-energy particles in planetary magnetospheres are now being made based on the direct observations of these particles in the three magnetospheres of Jupiter, Saturn and the earth. Plasma processes in these magnetospheres are not particularly energetic, as viewed from the particles in them, relative to those in solar flares, but theoretical and experimental research on these processes are thought to be able to contribute to the research on the origin of cosmic rays.

2.6 Behavior of Cosmic Rays in the Atmosphere

As shown in Fig. 2.3.2, high-energy particles of energy higher than \(10^{20}\) eV are contained in cosmic rays, though their number is extremely small. Since the energy spectrum of cosmic rays is approximated by a power law with negative index, the number of high-energy cosmic ray particles incident on the earth becomes so small that they are only rarely detected here. In consequence, some special technique becomes necessary to detect particles of such extremely high energy. The energy and species of these cosmic rays has to be inferred from observations of the development of secondary components produced during their collisions with atmospheric nuclei.

The research on cosmic rays advanced in parallel with those on atomic nuclei and elementary particles until the late 1940s. High energy particles which were energetic enough to study the interactions between atomic nuclei and elementary particles were found only in cosmic ray particles during those years. As a result of the rapid progress in the development of the accelerator technique in recent years, such studies as these interactions are now mostly done using accelerators. However, it should not be forgotten that \(\pi\) and \(\mu\) mesons and positrons were first discovered in cosmic rays.

The research in these fields by means of cosmic rays gradually shifted to higher energy with the progress of the accelerator technique; since then, cosmic ray interactions in the energy range higher than \(10^{12}\) eV have become the main subject of cosmic ray research. Because of the extremely low flux of cosmic rays in this high energy range, the secondary components yielded from their interactions in the atmosphere can be observed for several months or a year by setting many detectors of these components in a wide area. These phenomena, known as extensive air showers, which consist of particles secondarily produced in the atmosphere due to cosmic ray interactions with atmospheric nuclei after they enter the atmosphere, are being extensively investigated to understand the very high-energy nuclear interactions and the development of extensive air showers. Furthermore, the investigations of these showers are considered as an important means of research on the anisotropy and the chemical composition of ultra high-energy cosmic rays.

2.6.1 High-energy phenomena and the air showers\(^{46}\)

A part of the cosmic ray population arrives at the earth and its vicinity after traversing through galactic space. This space is generally considered a vacuum since there exists only one hydrogen atom per 1 cm\(^3\), except for the regions where stars or interstellar gas clouds exist. It seems, therefore, that the probability for cosmic rays to
interact with ambient hydrogen atoms and photons is usually extremely low. But, some fraction of cosmic rays is destroyed as a result of their collisions with these atoms and photons since their mean life is as long as $3.0 \times 10^7$ years.

After entering the atmosphere, cosmic rays of ultra high-energy begin to interact with the atmospheric nuclei at the top of the atmosphere. In consequence, though dependent on the energy of incident cosmic rays, various secondary components such as protons, neutrons, pions, muons and neutrinos are yielded from these interactions.

These secondary components can, therefore, be made use of to investigate nuclear interactions and the nature of nuclei and elementary particles. As is well known historically, such investigations on the secondary components produced by cosmic rays had been considered as the most important themes in the period before accelerators became much improved and able to produce such high energy particles as observed in cosmic rays. Since, at present, the research on the nature of high-energy interactions can be more efficiently made by using accelerators, experimental research using cosmic rays have been already replaced by those with accelerators.

For this reason, the research on high-energy interactions using cosmic rays has been shifting to those which deal with the elementary processes produced by ultra high-energy particles of $10^{15}$ eV or more. But the cosmic ray flux is extremely low in this energy region, so it is necessary to operate many cosmic ray detectors distributed over a large area to detect the secondary components produced from such high-energy cosmic rays over long periods. If superpowerful accelerators capable of producing such ultra high-energy particles were invented sometime in the future, this area of research would also be made using such accelerators, because the efficiency and accuracy would be much higher than in the cosmic ray technique.

It should be noted, however, that the spatial distribution of the arrival directions of ultra high-energy cosmic rays, i.e., their anisotropy, and their chemical composition can be found from the analyses of the structure of the air showers produced by cosmic rays in the atmosphere. Hence it is expected that the investigations of these cosmic rays will give some information important to some aspects in high-energy astrophysics. It is now suggested, for instance, that the power index of the energy spectrum of cosmic rays seems to become smaller in the energy range higher than $10^{19}$ eV, and that the anisotropy observed in these high-energy cosmic rays may be explained by the excess flux from the cluster of galaxies in the direction of the constellation Cygnus. It seems that the cosmic ray research in this direction will become more important through the experimental research on extensive air showers. The results from this research would give some clue on the acceleration mechanism of cosmic rays, too.

2.6.2 Cosmic ray sources and astrophysical neutrinos

It seems that cosmic rays of energy higher than $10^{20}$ eV may have originated in extragalactic space, since they are not confined in galactic space. While propagating in the space beyond the Galaxy, however, they must have been modulated by the weak magnetic field existing there. Indeed, cosmic rays originating in the Galaxy carry no information on their source directions because of their modulation by the galactic
magnetic field. For this reason, information on the birth place of cosmic rays can never be obtained from observations of the physical properties of cosmic rays themselves (see Subsection 2.2.2).

As have been described in Subsection 2.3.2, information on the birth place and the acceleration processes of cosmic rays are obtained from observations of various gamma-ray line emissions.\(^\text{27}\) In addition, other information on the initial stage of cosmic ray production is available from the observation of the numerous high-energy neutrinos produced in association with supernova explosions as identified as the possible sources of cosmic rays.\(^\text{47}\) No direct observations have yet been made of these gamma rays and neutrinos, but the research to detect them is in progress on a world-wide basis. It is certain that the observational results on them will not only be useful to the investigations on the origin of cosmic rays, in particular, on the physical state of their birth place and their acceleration mechanism, but also to those on the physical processes associated with supernova explosions and their debris.

More than ten years have already passed since the beginning of direct observations of neutrinos which seem to have been produced in the central part of the sun, and some important results are now available on the efficiency of fusion processes taking place in the solar core, and other related problems.\(^\text{48}\) If the neutrinos produced during supernova explosions were detected at the earth like those from the sun, a new field would be opened on the quantitative research on the so-called astrophysical neutrinos which seem to be ambient in the Galaxy.\(^\text{30}\) From this research, “neutrino astronomy” would be established as a branch of high-energy astrophysics.

Although one of the fields of cosmic ray research necessarily shifts to experimental research on the components of ultra high-energy cosmic rays, research on astrophysical neutrinos will progress in parallel with that on high-energy muons and neutrinos or proton decays in the coming years. Since these researches seem to need an enormous amount of money and large facilities, it is probably necessary to proceed on an international cooperative basis.

2.7 Relations among Research Fields

So far we have reviewed the behavior of cosmic rays in different domains as characterized by spatial and time scales from the farthest space from the earth to the thin atmospheric layer surrounding the earth. As shown in Fig. 2.2.1, the characteristic time scale of the behavior of cosmic rays necessarily becomes shorter with a decrease of the characteristic scale in space. As regards the time scale of cosmic ray phenomena, some of them are related to the age of the universe, but others only exist for as short as \(10^{-16}\) sec, such as the elementary processes of high-energy interactions in the atmosphere.

The different domains in cosmic ray research as shown in Fig. 2.2.1 are, furthermore, causally related to various phenomena associated with astrophysics, geophysics and particle physics. For this reason, wide knowledge on these branches of science is necessarily required by every investigator in cosmic ray research. Thus, it is
clear that all we cosmic ray physicists are required to be interested in every field of science related to cosmic ray physics. Furthermore, it should be remarked that every field in cosmic ray physics has to be pursued with its own particular methods. Even if so, it is necessary to consider the situation that all research fields are closely related to each other, since these fields have to be investigated by taking into account astrophysical phenomena as observed in this vast cosmic space. If we were to confine ourselves only to one field of cosmic ray research without understanding these wider characteristics in cosmic ray physics, progress would become slowed down eventually.

Cosmic rays are the non-thermal component necessarily generated from the evolutionary processes of the universe. Thus, it seems that cosmic ray particles would give us direct information of astrophysical phenomena taking place in the evolution of the universe. The importance of cosmic ray research from the astrophysical point of view can be clearly seen in this respect.

REFERENCES


43) Wada, M.: Personal communication (see Chapt. 9).


