2-2 High-Energy Particle Acceleration in the Heliosphere

OKA Mitsuo and TERASAWA Toshio

For the development of space weather forecast, it is important to achieve the prediction of the flux of high energy particles which are associated with solar flares and CMEs. Recent studies have revealed that the cause of the high energy particles is deeply related to the interplanetary shocks originated from these eruptive phenomena. The investigations of particle acceleration mechanisms in the interplanetary space have also contributed to the elucidation of the origin of the high energy cosmic ray particles. In this report, some topics from the interplanetary observations are presented.

Keywords
Anomalous cosmic rays, SEP, Diffusive shock acceleration, Pickup ions, Interplanetary space

1 Introduction

In the sparse plasma of space, Coulomb two-body collisions occur only infrequently; instead, indirect collective interactions via electromagnetic forces dominate. Recent studies have revealed that in space, plasma deviation from the thermal equilibrium state is ubiquitous, and that non-thermal particles, which have far greater energy than thermal energy particles, are created in association with intense dynamic phenomena and play a fundamental role in system development. In particular, cosmic ray particles with a wide range of energies (from several tens of MeV to 10^{20} eV) are dominant. Although these particles were discovered early last century, their origins remained a mystery for decades. This is because while these particles were predominantly thought to originate from supernovae (based on their energetics), it was not possible to explain how they featured energy spectra of $E^{-2.7}$ in an energy range spanning no less than six digits, from GeV (10^9 eV) to PeV (10^{15} eV). However, theoreticians such as Blandford and Ostriker (1978)[1], refining and applying Fermi's classical stochastic acceleration theory to the shock environment, explained the energy power spectrum in a simple manner, leading to the development of today's standard model, which states that cosmic ray particles are accelerated in the shocks associated with supernova explosions. Firstly, observations have revealed evidence of electron shock acceleration up to approximately PeV in the of supernova remnant SN1006. Recently then, observation of another supernova remnant (RX J1713.7-3946) yielded evidence of proton acceleration up to about 10 TeV (10^{13} eV). (All of these represent the significant results of X- and γ-ray observation projects organized by Japanese researchers[2][3][4].)

It is not too much to say that acceptance of this theory, which situates the origins of cosmic ray particles within supernova shocks, represented the greatest achievement in plasma physics in the last quarter of the twentieth century. However, these acceleration stages are remote, and current observation techniques do not allow for direct analysis of their space-time structures. Therefore, to specify the physical mechanism of this acceleration, we can construct a model only through extrapolated application of the theoretical tools we now possess.

As an experimental science, physics requires verification of its theories: in this respect, from the late 1970s until the early 1980s, while the diffusive shock acceleration theory was under development, near-simultaneous observations of heliospheric shocks played a critical role[5] [6].

A variety of shocks exist in the heliosphere, and serve as stages for non-thermal particle acceleration. These shocks consist of the following: (1) bow shocks created at the front of the magnetosphere of the earth and other planets; (2) corotating interplanetary shocks (CIRs) created as the solar wind's fast-moving region catches up with its slowly moving region; (3) a solar wind termination shock created at around 100 AU from the sun, where the solar wind shifts from supersonic to subsonic speeds; and (4) interplanetary shocks associated with eruptive energy-releasing phenomena on the surface of the sun. In this report, we first discuss Anomalous Cosmic Rays (ACRs), which are thought to be created by the termination shock, and we present one of the most successful examples of the application of the standard diffusive shock acceleration theory. In Chapter 3, we describe the acceleration of Solar Energetic Particles (SEPs), a process that is of particular importance in space weather forecasting.

2 Anomalous Cosmic Rays (ACRs)

2.1 The basic model and the standard acceleration theory

Particles referred to as ACRs (including He, N, and O) were discovered in the 1970s as the excess component of the theoretical value that could not be explained applying the standard model of galactic cosmic ray modulation to the low-energy band (several tens of MeV/nucleon)[7] [8] [9] (Fig.2). These particles are believed to originate within the interstellar gas. When the neutral particles enter the heliosphere, they are ionized by (for example) ultraviolet radiation from the sun. These particles are then picked up (captured) by the solar wind, carried to the termination shock, and subjected to diffusive shock acceleration. This represents the generally accepted scenario[10] [11]. The termination shock was assumed to be the acceleration site because of the correlation between ACR intensity and distance from the sun. Moreover, pickup ions (PUIs) of interstellar origin usually feature a charge state of one. Therefore, the above-referenced scenario was established after a charge state of one was observed for ACR oxygen (several to 20 MeV/nucleon). If ACR particles were to remain in the heliosphere for more than several years, it would be expected that their charge states would increase from one to two. Observations have shown that, among oxygen components, O^{2+} and O^{3+} components predominate above 30 MeV/nucleon; direct data relating to acceleration efficiency has thus been obtained (Fig.3). According to the data, there is a necessary acceleration efficiency of about 10 MeV/nucleon per year[12]. This acceleration efficiency can be explained by the theory stating that the acceleration occurs in the quasi-perpendicular region of the termination shock[13].

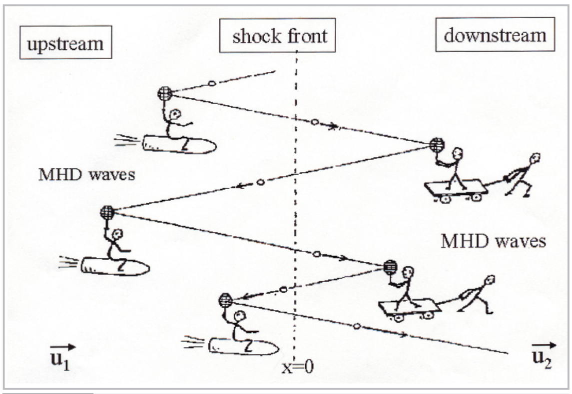

Fig.1 *The principle of stochastic acceleration is integrated in the divergence and convergence terms of the plasma velocity field in the cosmic rays transport equation (advective diffusion equation). Courtesy to M. Scholer*

In the case of shocks, the velocity difference between the upstream region and the downstream region gives increased velocity to the particles, which are scattered by the turbulent magnetic field. Note that the standard theory assumes the isotropy of the accelerated particles and ignores the effects of reaction.

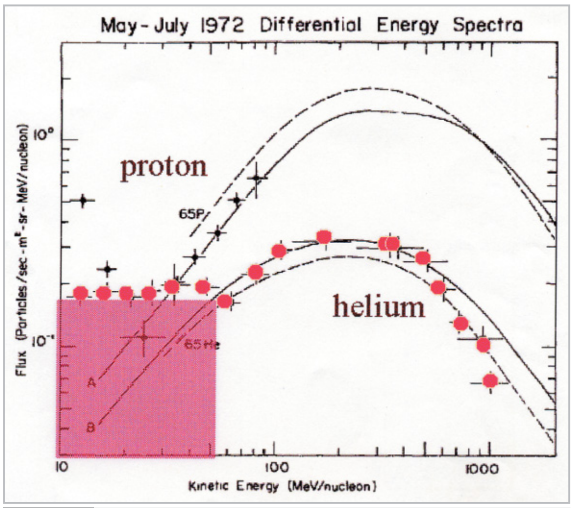

Fig.2 *(Left) The energy spectrum of ACRs obtained by the IMP-5 satellite* [7]

While it was observing galactic cosmic rays, IMP-5 detected an increase in flux (shaded area) in the low energy band (10–30 MeV/nucleon) that could not be explained under the solar wind modulation model (indicated by solid lines and dashed lines). The small and large circles represent hydrogen and helium, respectively. Note that He/H>1below 30 MeV/nucleon.

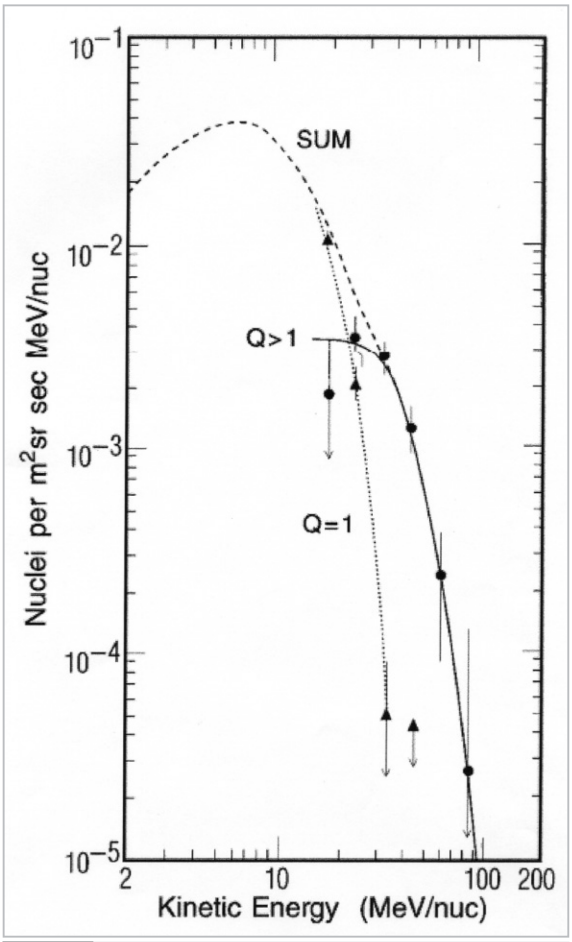

Fig.3 *(Right) Observational evidence regarding ACR charge states obtained by the SAMPEX satellite* [12]

The SAMPEX satellite is a polar satellite and can determine ACR charge states of the incident particles by the combined use of the observed energy value per nucleon and the observed value of the cut-off position (which is a function of the rigidity of the earth's magnetic field at that point). This evidence has revealed that the charge states for ACR oxygen over 30MeV/nucleon is greater than or equal to 2.

2.2 The injection step

PUIs were discovered in 1985[14], and following the discovery of ACRs, PUIs have been proposed as the sources of ACRs. For the stochastic acceleration mechanism to be effective, the accelerated particles must move freely between the upstream and the downstream of the shock. Since the shock in space plasma features a transition zone whose thickness is approximately the same as the thermal velocity, the accelerated particles must first be moving at non-thermal velocities. Because the PUIs featured a wide pitch-angle distribution and twice the velocity of the solar wind at its maximum, their "injection" efficiency into the acceleration was thought to be higher than that of the solar wind. (In the past, the velocity distribution function for PUIs has been discussed assuming a spherical-shell-like distribution, as the observations were limited to one or two dimensions. However, recent three-dimensional observations have revealed a more plausible PUI distribution (Fig.4, from [15]).) However, because perpendicular shock featuring the acceleration efficiency described in the last section requires particularly high injection efficiency, in practice PUIs need first to be accelerated to more than 1 MeV. What is the mechanism for this preliminary acceleration? Due to the difficulty of this "injection problem," this question was tabled for some time; recently, however, progress has been made, as discussed below.

The first observational verification of diffusive shock acceleration of PUIs was found in the corotating interplanetary shock (Fig. 5, from[16]). According to these observations, an H^+ flux of 5 keV rapidly increased after the passage of the shock, indicating that in the solar wind PUIs of about 1 keV received initial acceleration at the shock front. On the other hand, H^+ flux at 200 keV indicated a moderate increase before the passage of the shock, supporting the diffusive shock acceleration theory. This observation lends support to the two-step acceleration model, in which shock acceleration is considered in terms of two separate steps: an injection step (at low energies) and a step governed by the standard acceleration theory (at high energies). Recent reports have also indicated initial acceleration of PUIs in the stationary shocks at the earth front[17], and PUIs are believed to be strongly accelerated by numerous shocks in the heliosphere.

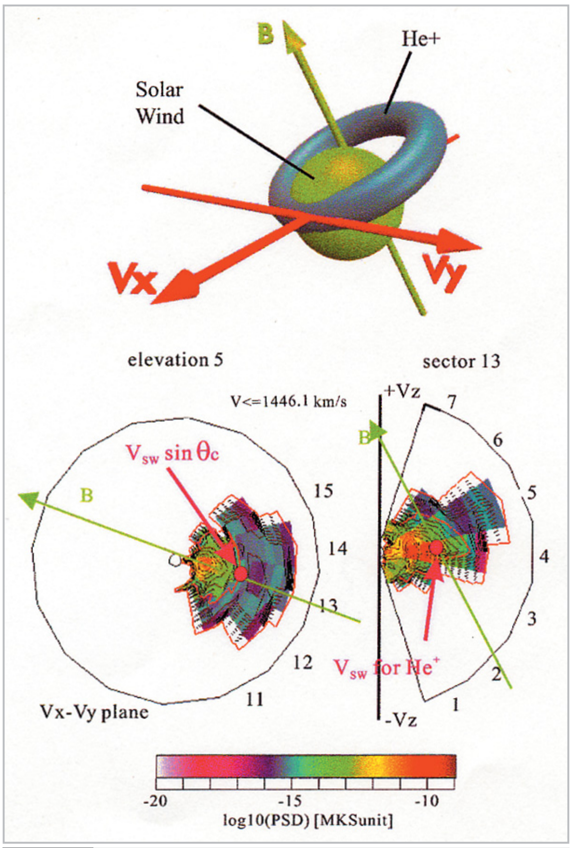

Fig.4 *PUIs showing a torus-like velocity distribution, as observed by the GEOTAIL satellite* [15]

The upper panel represents a schematic drawing of this distribution. Although partly overlapping with heavy-element ions in the solar wind, PUIs have a wide pitch angle distribution and a velocity approximately twice as large as that of the solar wind at its maximum. The lower panels show sectional views on the planes perpendicular (left) and parallel (right) to the central axis of the torus. PUIs are believed to be accelerated by the termination shock and to serve as the origin of ACRs. Observations of the termination shock have yet to be conducted, but Voyager is expected to arrive within the range of observation soon. Further, acceleration of PUIs has been reported at the corotating interplanetary shock and at the earth's bow shock, and PUIs are thought to be strongly accelerated by the interplanetary shocks associated with solar flares as well.

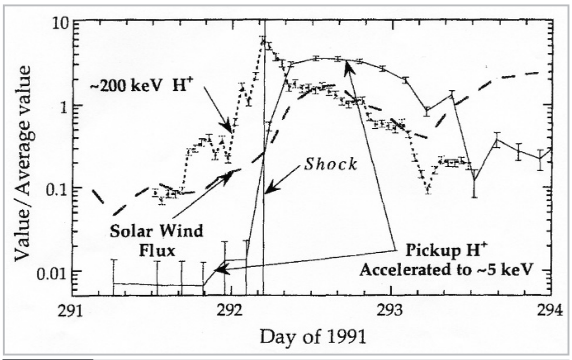

Fig.5 *The acceleration of PUIs by the corotating interplanetary shock observed by Ulysses on October 18, 1991* [16]

The spacecraft passed through the shock a little after 4:00 on that day. At low energy (5 keV) PUI flux increased after the passage of the shock, while at high energy (200 keV) there was an exponential increase in PUIs beginning before the passage of the shock, as predicted under the standard theory.

2.3 The nonlinear step

Since strong shocks create non-thermal particles extremely efficiently, energy displayed by non-thermal particles may become comparable to or greater than the energy of the thermal particles and of the magnetic field. In this case, the structures of the shocks are not determined solely by the thermal particles and the magnetic field, as in the usual MHD Rankine-Hugoniot scenario, and the contribution of accelerated non-thermal particles must also be taken into account. The same applies to the solar wind termination shock, where the proportion of non-thermal PUIs increases relative to the solar wind plasma. These possibilities have been raised in theory from an early stage; the shocks that show the reaction, or nonlinear effect, have been referred to as Cosmic-Ray-Modified Shocks (CRMS)[18]. However, examples of observational verification are few, and it was not until recently that an interplanetary space shock associated with relatively large solar flares and Coronal Mass Ejections (CMEs) was identified as CRMS[19].

3 Acceleration of Solar Energetic Particles

The event observed by a ground-based neutron detector on July 25, 1946 (occurring at the same time as a large Hα flare) led to Forbush's thesis asserting, for the first time, that the acceleration of high-energy particles was associated with energy-releasing phenomena on the surface of the sun[20]. Since then, following observations throughout the International Geophysical Year (IGY), our understanding of the physics of Solar Energetic Particles (SEPs) has advanced significantly.

There are two types of SEP events: long-duration events (LDEs), which last for more than several hours, and impulsive events, which last for less than an hour. Of these two types of events, LDEs are associated with CMEs; we will discuss these sorts of events first. Many LDE observations have revealed that the time profiles of SEPs may be classified as a function of the relative differences in longitude between the cause of the acceleration, the Interplanetary Shocks (IPSs) preceding CMEs, and the observer. Fig.6 illustrates this classification as it stands today (from Fig. 2 in[21]). Shock intensity and acceleration efficiency are usually at their maximums at the longitude closest to the "nose" of the CME. Although IPSs will sometimes occur without significant event, as shown in Fig.6,

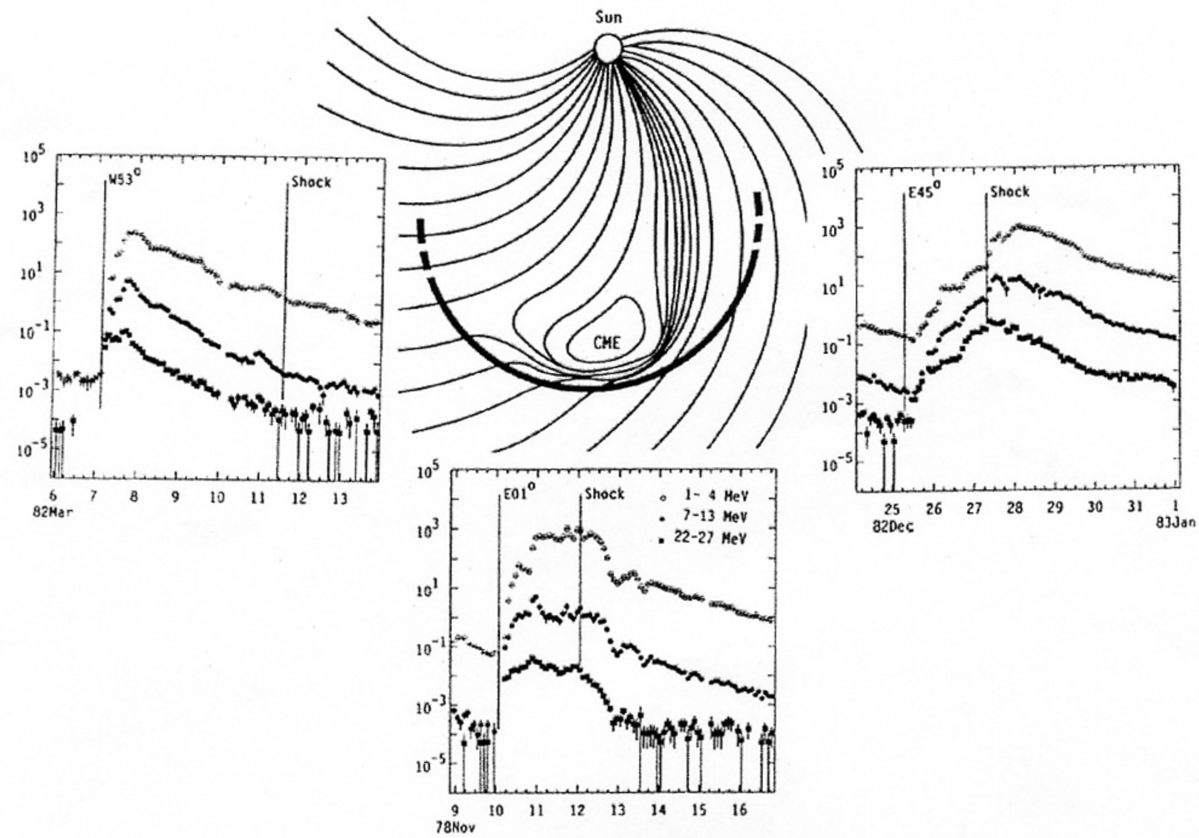

Fig.6 *Depending on the physical relationships between the CME, the IPS (curve depicted by a bold line) that precedes it, and the observer, the time profiles of particle flux (the vertical axes in the three insets) are qualitatively different*

When the CME is to the west of the observer (left inset), a rapid increase in flux is observed, since the observer and the acceleration region are connected by magnetic field lines. When the CME is at the same solar longitude as the observer (central inset), they are connected by magnetic field lines until the passage of the IPS, and this connection is broken after the passage of the IPS. On the other hand, when the CME is to the east of the observer (right inset), they are not directly connected by magnetic field lines before the passage of the IPS, and the peaks of the flux are delayed since it is after the passage of IPS that the connection with the "nose" region of the CME is established.

strong IPSs will occasionally display a maximum in flux over several hours as they occur. This is shown schematically in Fig.7 (from Fig.1 of[21]), from which it may be concluded that as a result of the excitation of local turbulence close to the IPSs, the collection and acceleration of particles continue, leading to an increase in flux. This increase in particle flux over several hours around the occurrence of IPSs has historically led to the description of this flux as consisting of Energetic Storm Particles, or ESPs. More than a decade ago, it was assumed that ESPs were the only results of acceleration due to IPSs, and that particle flux arising just after CME emission was thought to be due to some other acceleration mechanism, such as stochastic acceleration in the solar flare region. However, it is now commonly thought that all increases in flux have their origins in the diffusive shock acceleration associated with CMEs.

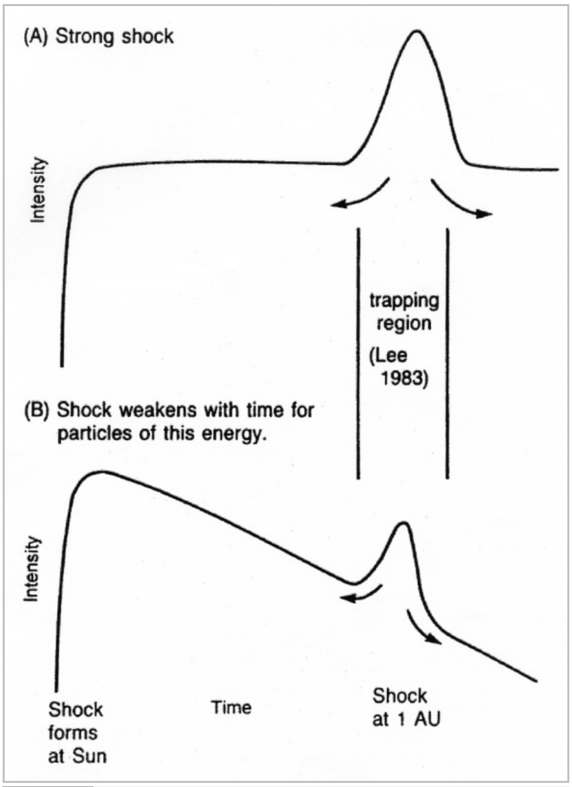

Fig.7 *Time variation of particle flux observed at 1 AU: (A) the case of strong IPSs or particles with relatively low energy; (B) the case of relatively weak IPSs or particles with relatively high energy*

The peak in flux when the shock arrives in the vicinity of 1 AU has been referred to as ESP. In the case of very weak IPSs, they are efficiently accelerated only when they are close to the sun, and when they arrive at 1 AU the acceleration mechanism is often already inactive (as the turbulence necessary for shock acceleration has subsided). On such occasions, ESPs are not observed.

Next we will discuss the differences between LDEs and impulsive events. Before the early 1980s, the dominant theory posited that the differences between these two types of events arose out of differences in particle propagation in interplanetary space. According to this theory, particle propagation becomes pervasive when particle scattering in interplanetary space (the accepted theory classifies this as cyclotron resonance scattering due to Alfvén waves) is strong, thus explaining the observed time profile of LDEs. On the other hand, the theory asserts that when scattering is weak, the particles move in beam-like paths along magnetic field lines, creating an impulsive event. (The pitch angle distribution of the particles in impulsive events is actually beam-like.) Objections to this theory began with the observation that the particle compositions of these two types of events differ: LDEs had roughly the same composition as ordinary coronas, whereas in impulsive events $^3He/^4He$ was extraordinarily high. Moreover, these two events had been simultaneously observed[22]; such synchrony would not have been possible if these types of events were distinguished by scattering intensity. Thus, a completely new theory became necessary. The currently accepted theory argues that the acceleration mechanism of impulsive events differs from that of LDEs, and acceleration in the impulsive events is considered to occur in the relatively low-altitude region of the corona such as the reconnection site. (The increase in ^3He may be attributed to ion cyclotron resonance heating in impulsive events.) This theory is also supported by the observation that the temperature in the acceleration region of impulsive events differs from that of LDEs. The charge state of Fe in LDEs is about 14; this coincides with the charge state of Fe in ordinary coronas, whereas the average charge state of Fe in impulsive events is 19, indicating that the temperature in the acceleration region reaches over five million degrees[23].

A topic worth noting here relating to SEPs deals with an increase in the He^{+} flux of tens of KeV in events associated with CMEs (see example[24]). Normally, He^{+} is present in a proportion of only a few percent relative to He^{2+}, while it has been observed that, in SEP events associated with CMEs, the fraction He^{+}/He^{2+} sometimes exceeds 1. As the origin of this He^{+}, we can point to the low-temperature component in the solar atmosphere released in association with solar flares and to the PUIs of interstellar origin (as discussed in the last chapter). The latter particles are better candidates as a source of He^{+} since they are easily accelerated due to their characteristic velocity distribution, and are drawing attention not only as a source of ACRs but also as a source of SEPs.

4 Conclusions

After summarizing the standard acceleration theory using the example of ACR acceleration phenomena in interplanetary space, we have attempted a brief review of the topics related to the particle acceleration phenomenon associated with solar flares. Here we should note that empirical research on the entire process of particle acceleration (i.e., from the injection step to the nonlinear step), exemplified by the current research on ACRs, began fairly recently. Although the solar cycle has now passed its peak, we will nevertheless continue to witness significant activity over the next several years. During this period, we expect that a number of satellites will amass a large amount of high-quality data. In Japan in particular, projects such as the L5 and Bepi-Colombo missions are currently underway, aimed at the extensive observation of interplanetary space, and successful heliospheric scale multipoint observations are expected in the current and in the next solar cycles. The information obtained through these observations will contribute to the development of quantitative arguments relating to particle acceleration phenomena in the interplanetary space between the sun and the earth, and—it is hoped—it will bring about increased accuracy in space weather forecasting.

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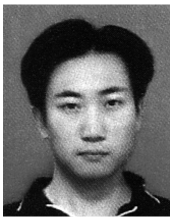

OKA Mitsuo

Graduate Student, Graduate School of Science, University of Tokyo

Space Plasma Physics

***TERASAWA Toshio**, Dr. Sci.*

Professor, Graduate School of Science, University of Tokyo

Space Plasma Physics