論文の内容の要旨

論文題目：Simulation Study of Astrophysical Shocks Mediated by Cosmic Rays

（宇宙線の影響を受けた天体衝撃波についてのシミュレーション研究）

氏名：斎藤　達彦

Galactic cosmic rays (GCRs) are believed to be accelerated at the shockwaves of supernova remnants (SNRs) in our galaxy. The diffusive shock acceleration (DSA), which is known as first-order Fermi acceleration, is a standard theory to explain the particle acceleration at the shocks, and have a good agreement with the observed power-law energy. In addition to this it is known that the spectral index for the power-law spectrum can be determined only by the shock compression ratio. Although the standard DSA theory assumed that not only the cosmic ray (CR) density but also the energy density is negligible compared with the thermal gas (test-particle assumption), several recent observations suggest that the energy densities of CRs around the shocks are not necessarily negligible, and can be more or less comparable to those of the background plasma. In such a situation, the dynamical feedback effect of the CRs should be taken into account. Since the CR pressure has a spatial gradient in front of the shocks, the flow

structures of the background plasma are modified drastically, and it is known that the total shock compression ratio may increase. As the result, CRs can be accelerated more efficiently than the test-particle limit of DSA. This acceleration mechanism is known as nonlinear DSA (NLDSA), and the modified shocks in NLDSA are called as cosmic ray modified shocks (CRMSs). The CR production rate in NLDSA is thought to be optimistically enhanced, simply because the larger population of CRs can make shocks more compressive and the spectrum more harder. However, such a positive feedback effect might not be permitted in the nature of physics. Our main purpose of this study is to address the question how efficiently the NLDSA can produce CRs. In this thesis, two important issues on cosmic ray physics are investigated: one is the stability/stationarity of the non-linear shock in a fluid approximation. The other is to understand the kinetic plasma process in the non-linear shock beyond the fluid approximation. It is well-known fact that the CRMSs have the multiple (up to three) steady-state solutions for a given upstream parameter. These three solutions are different in the CR production efficiency, and one of the solutions with the maximum efficiency is believed to be realized in the supernova shocks. As the first step to understand the nature of CRMSs, we investigated the stability of these solutions in the two-fluid approach, where both of the thermal gas and non-thermal CRs are approximated by fluids. By the numerical simulations for two-fluid time evolutional equations, we find that two solutions/branches with the maximum and minimum CR efficiencies and stable, while the intermediate branch is unstable in time, and this stable features are independent of any shock parameters. We also study the time evolution of the CR production and find that only the inefficient branch with the minimum CR production is realized among three multiple solutions. Our findings suggest that the CR production efficiency of CRMSs is less efficient than believed before. We can conclude that the production of CRs plays a role of negative feedback in NLDSA. Next, we extend the above two-fluid model by taking into account of the momentum-dependent CR kinetic effects. This model is called CR-kinetic model, and enables us to discuss about the spectrum of the CRs that can be compared with the observations. In addition, we investigated the effect of Alfvénic waves excitation on NLDSA, which is believed to play an important role in NLDSA. In the shock precursor region where the CRs are streaming upstream, the streaming CRs have a free energy that can excite the Alfvénic waves through a current-driven plasma instability. The energy density for these excited waves may become comparable to or not be negligible to that of the thermal background plasma. Hence, we should take into account the feedback from the amplified waves as the essential behavior of CRMSs. We include the elementary processes of the wave generation and dissipation model in the CR-kinetic system, and study the steady-state solutions with our own semi-analytical methods. Our numerical parameter surveys about the steady-state solutions clearly reveal that the wave pressure effect reduces the CR production by suppressing the shock compression ratio. Moreover, the heating of the background plasma in the precursor region by the dissipation of waves leads to the further depression of the CR production efficiency. Such tendencies are robust regardless of the Mach numbers, the injection parameters and the wave parameters, such as Alfvén velocities and subshock compression ratios for the waves. These results conclude that the CR production is less efficient than the "standard" (without consideration of waves) NLDSA predicts. Finally, our findings suggest that the negative feedback process involved in NLDSA may be carefully taken into account in the theoretical/observational studies for collisionless shocks such as supernova shocks and Interplanetary shocks and so on.