論文内容の要旨

論文題目 Observational Study of Non-stationary Shock Structure

（非定常衝撃波に関する観測的研究）

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The dissipation processes at collision-less plasma shocks are one of the most interesting issues in space plasma physics. Due to the collision-less nature of the plasmas, in the course of the dissipation processes non-thermal particle are generated in association with the bulk heating of the main body populations. Previous observations reveal that these supra-thermal electrons are observed to be accelerated up to 20 keV at the quasi-perpendicular region of the Earth’s bow shock. The electron acceleration process itself, however, still remains unclear. Recent numerical simulation results imply that non-stationary behavior of a quasi-perpendicular shock front has a strong impact on the dissipative processes and thus on the electron acceleration mechanism. Observational support for this issue, however, has been rather scarce. One of the obvious reasons is that it is difficult for single spacecraft observations, which is notorious for its inability to distinguish a spatial variation from a temporal one, to unambiguously identify the non-stationarity of a shock front.

The cyclic variation of the shock front structure seen in numerous simulations of quasi-perpendicular shocks is widely known as the shock reformation process. The interaction between the reflected ions and the incoming ions/electrons excites micro-instabilities in the shock transition region, which make contribution to the dissipation required to attain the transition from the upstream to the downstream state, and possibly to the electron acceleration processes. The multi point measurements by Cluster-II enable us to investigate the non-stationary behavior with temporal and spatial variations being discriminated. In this thesis, we show robust evidence of the reformation process obtained from formation flying observations by Cluster and discuss the electron dynamics under the reformation process.

Turning our eyes to ions, it is well known that ions are also accelerated at the Earth’s bow shock and energetic ions are at times observed in its upstream region. While the energy of the solar wind ions is at most a few keV, the energy of the backstreaming ions ranges from several 10 s of keV to several MeV. When the shock angle (Θ_{Bn}, the angle between the upstream magnetic field and the shock normal) is in the oblique range (~50° < Θ_{Bn}<~75°) the upstream ions put on the form of field aligned beam (FAB) whose energies are 10-18 keV, and its generation mechanism is nicely explained by an adiabatic theory for a stationary shock structure. Production mechanism of more energetic upstream ions, however, is an open question. Here we show discovery of a new member of the energetic upstream ions, generated only in the quasi-perpendicular regime, possibly under the influence of the reformation process.

In the parallel regime (Θ_{Bn}<45°), the upstream FAB is well-known to excite ULF waves. The waves are convected back to the shock front and this wave-shock front interaction leads to another type of shock front non-stationarity. While this concept is well known and has been studied extensively for the parallel regime, its application to the oblique regime (45° < Θ_{Bn}<60°) has not been performed. The third topic dealt with in this thesis is the formation flying observations of such a case.

The main body of this thesis is organized as follows.

We start from the discovery of a new member of the upstream energetic ions. In Chapter 3, we show that energetic ions are at times observed in the upstream of the Earth's bow shock and their origin is considered to be in the interaction with the shock front. While the energy of the solar wind ions is a few keV at most, the energy of the backstreaming ions ranges from ~5 keV to several MeV. In the present study we investigate backstreaming energetic ions in the upstream of the Earth's bow shock observed by Geotail during two coronal mass ejection (CME) events. The observed local magnetic field rotated significantly during the events. Using the bow shock model and the observed magnetic field data, we found that the energetic ions appeared only when the upstream magnetic field was connected to the bow shock. The energetic ions showed two distinct distribution function characteristics, namely, the field-aligned beam (FAB) and the loss-cone distribution, respectively. While the former is occasionally detected, the latter having higher energies (30 keV-several hundred keV, compared to <18 keV for FAB) has not been reported before. Using the bow shock model we can also estimate the shock angle at the point on the shock surface that the upstream field line is connected to, and find that the distribution function shape transits from FAB to the loss-cone distribution as the shock angle becomes larger (transition at Θ_{Bn}=70-80°). We discuss the possible mechanisms responsible for the production of the newly found member of the energetic upstream ion family. Many simulation studies show that the nonstationary structures (reformation and ripples) appear at high Mach number quasi-perpendicular shock regime. It is a possible that the energetic ions with energy up to 800 keV are accelerated at the quasi-perpendicular shock region under the non-stationary structure. These non-stationary structures may be important in understanding the particle acceleration mechanisms at the bow shock. These nonstationary structures have not been clearly identified by the experimental data.

The discovery described in Chapter 3 motivated us even more to understand observationally the non-stationarity of shocks. In Chapter 4, we search for nonstationary shock structures at the quasi-perpendicular bow shock by using the Cluster data. In order to search for the non-stationary shock structures, we performed event survey of critical shock events observed at quasi-perpendicular bow shock with parameters Alfven Mach number (Ma) >3 and Θ_{Bn}>60° in 2002. The number of selected events is 41. Correlation analysis between spacecraft pairs is used to examine shock structure. The shock structures observed by each spacecraft pair can be classified into 3 types of shock structures based on the observational time delay and the cross-correlation coefficient; (A) Stationary event and ripples, (B) Reformation event, and (C) Uncertain event. Examples are shown of a number of bow shock phenomena observed by Cluster, including stationary shock, periodic structure, reformation event, and candidate events for possibly new phenomena at quasi-perpendicular shocks that have not been discussed to date in the theoretical framework.

The survey through the dataset made us detect one event that seems to be a robust evidence of the reformation process of a quasi-perpendicular shock. In Chapter 5, this event is reported in detail. Previous computer simulation studies have suggested the importance of the non-stationary behavior of the collisionless shock structure in the context of energy dissipation. This issue, however, has been difficult to deal with by single spacecraft observations. A cyclic temporal variation of a shock front is widely known as the self-reformation process. On April 20, 2002, Cluster four probes, with the maximum inter-spacecraft distance of ~150 km, crossed a quasi-perpendicular shock front within ~1.3 s. The magnetic and electric field data taken by the four spacecraft with the time differences showed different characteristics, which we attribute to the shock front non-stationarity of gyro frequency time scale, namely the shock reformation. The two types of profiles are seen by the four spacecraft: (1) A steepened magnetic field profile and a large spiky electric field at the shock ramp, which we consider to be taken during the ”steepened” phase of reformation. (2) A profile of magnetic field broadened toward shock upstream and fluctuating electric field in the foot region, which we consider to be taken during the ”broadened” phase. In order to better interpret the data, we carried out simulations dedicated to comparison with the observations. The comparison of electromagnetic field structure is found to support the above interpretation. Moreover, a prediction from the simulations that a class of electrostatic wave mode would be observed at the shock front in the "broadened" phase is tested positively in the data.

Many simulation studies have indicated that the shock reformation appears at high-Mach number and quasi-perpendicular shocks, while the shock structure at less oblique shock has not been discussed so much using experimental and simulation data. In Chapter 6, to take into account the effect of shock angle on the shock structure, the Cluster data with separation distance ~1300 km in 2005 are used to study the statistics of type of the quasi-perpendicular shocks. The number of selected high- Mach number and quasi-perpendicular shock events (Ma>3 and $\Theta_{Bn}>45^\circ$) is 76 in 2005. The experimental data show that the oblique shock fronts put on nonstationary behaviors due to interaction with the upstream waves that are generated by the backstreaming ions in the upstream and are convected toward the shock front. While the process of the non-stationary structure shares many characteristics with previous self-reforming quasi-parallel shock simulations, there are differences, which are the target of the study described in Chapter 7.

In Chapter 7, we found a non-stationary and reforming shock structure at the oblique shock. The oblique shock, observed by Cluster at a separation distance of ~1300 km, had Alfven Mach number (Ma) of ~6.4 and the shock angle of ~55°. All the four Cluster spacecraft saw essentially the main shock ramp structure and ultra-low frequency (ULF) waves (0.03 Hz in the spacecraft frame) in the upstream of the shock front presumably excited by field-aligned beam (FAB) ions. The non-stationarity behavior was captured as a precursor magnetic pulsation, detached by ~450 km from the main shock ramp, was seen to grow in time (over the 2 minutes interval during the observations by the Cluster formation). The amplitude of the largest pulsation was so high that it was starting to play the role of the main shock ramp. Furthermore, the local magnetic field was so modulated by upstream ULF waves that the new shock front behaved as a perpendicular shock. Indeed flat-topped electrons and spiky electric field were seen at the new shock front, which is consistent with the properties of the quasi-perpendicular shock transition. In addition to these electron dynamics, slowing-down and moderate heating of the solar wind ions were also seen. The observations suggest that a cyclic shock front reformation is induced in a class of oblique shocks by the upstream ULF wave convected downstream-wise by the solar wind flow. In striking contrast to the well-known quasi-parallel shock cases, which are also upstream wave driven, the reformation at the oblique shock is found to occur in a coherent manner, with the shock front itself having quasi-perpendicular properties. Two more oblique shock events (1st: Ma=6.1, β_i=1.2, and $\Theta_{Bn}=61^\circ$; 3rd: Ma=6.2, β_i=0.26, and $\Theta_{Bn}=49^\circ$), that were obtained within 1.5 hour from the one described above and had similar shock parameters but different temporal behavior are also described in detail to indicate the sensitivity of the oblique shock behavior to the parameters such as the shock angle and the upstream beta.

Chapter 8 summarizes the novel points of these issues and the suggestions for the future works.