博士論文

Study of Zebra Patterns in Solar Radio Bursts and Physical Processes in the Corona

（太陽電波バースト中のゼブラパターンおよび
太陽コロナにおける物理過程の研究）

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平成 29 年

Abstract

The solar corona, the outermost part of the solar atmosphere, is the very hot, tenuous, inhomogeneous, and time-varying region. The longtime scientific interest in the corona is related to two major issues in solar physics: coronal heating and solar eruptions including flares and coronal mass ejections. In order to understand these phenomena, observations for fine structures leading to physical processes occurring in the corona are indispensable. Particularly, spectral fine structures in solar radio bursts contain rich information on these small-scale features of the corona in their spectral and polarization characteristics. Zebra Pattern (ZP) is one of the most intriguing fine structures among them. It appears as numerous nearly parallel narrow-band stripes superimposed on the continuum spectrum of type IV bursts. Despite a large number of studies and observations devoted to this phenomenon, there are still many unexplained properties. This thesis intends to reveal the nature of ZP and physical processes occurring in the corona underlying the striped spectrum of ZP. For this purpose, we performed comprehensive analyses with the use of highly resolved spectral and polarization data obtained from *the Assembly of Metric-band Aperture TElescope and Real-time Analysis System* (AMATERAS).

ZPs are often observed superposed on the continuum emission of type IV bursts, but not all type IV bursts are accompanied by ZPs. It is highly probable that there are some conditions necessary to generate ZPs, although such conditions have not been known. To address the conditions for the generation of ZPs, we investigated the occurrence characteristics of 21 ZP events observed with AMATERAS for 2011–2015. By comparing the occurrence probabilities of type IV bursts with and without ZPs in association with flares, we found that ZPs are favorable to occur (1) in the decay phase of the flare where the background plasma are sufficiently heated, (2) associated with longer duration flares in which the particle acceleration processes occur successively and gradually at the high altitude in the corona, (3) in larger magnitude flares, implying that the origin of type IV bursts related to ZPs is post-flare loop rather than CME plasmoid, and (4) in the active regions located in low and mid longitudes and there were no ZP associated with limb flares, possibly related to the directivity of ZP emission. We also compared these characteristics within the different types of ZPs which are classified by the variation in frequency separation of the stripes Δf. However, no significant difference was confirmed between them.

Polarization is an important source of information in determining the emission mechanism. Although ZPs are known to have strongly polarized features, its understanding is insufficient because of the lack in the frequency resolution. Therefore we investigated a ZP event on 2011 June 21 and its polarization focusing on the frequency dependence with high resolution data observed by AMATERAS. As a result, we found that the degree of circular polarization (DCP) was rather high approximately 70% in right-handed circularly polarized component (RCP) with almost no frequency dependence, and the left-handed component (LCP) is delayed by approximately 50 ms slightly increasing with frequency. These results can be interpreted in the framework of the fundamental plasma emission generation and subsequent depolarization during the propagation in the corona. Further, a large delay of 50 ms over a wide frequency range suggests that the depolarization process occurred very close to the source of each frequency. However, how the depolarization, partial conversion of O-mode into X-mode, occur is not specified.

To specify the depolarization mechanism implied from an event study mentioned above, we further investigated the polarization characteristics using the 21 ZP events observed with AMATERAS. The obtained polarization characteristics are summarized as follows: (1) DCPs are widely distributed in the range of 0–70%. (2) Delay between two circularly polarized components was found and the maximum delay was approximately 70 ms. (3) Most of the events were polarized in the sense of the O-mode. These results were consistent with the scenario: generation at the fundamental plasma frequency and subsequent depolarization. Furthermore, we found the positive correlation between DCP and delay (rank correlation coefficient was 0.62). To interpret this correlation, we proposed a model for depolarization based on multiple reflections at sharp density boundaries. Comparison between the observations and model calculation indicates that the polarization characteristics of ZPs are determined by the number of depolarizing reflections. These results also suggest that meter-scale density boundaries are present near the source of ZPs in coronal loops.

Various magnetohydrodynamic (MHD) waves have recently been detected in the corona and investigated intensively in the context of the coronal heating and coronal seismology. In the radio wave band, signatures of these waves can be recognized as quasi-periodic modulation in intensity and other quantities. Searching for signatures of such kind of waves, we investigated spectro-temporal variations in Δf and in intensity of a ZP event. Consequently, we found the quasi-periodic modulations in both Δf and radio intensity with the typical periods of 1–2 s and 1–3 s, respectively. The modulation in Δf showed a characteristic negative frequency drift of 3–8 MHz/s. Based on the Double Plasma Resonance (DPR) model, the Δf modulation can be interpreted as small scale (about 8,000 km) disturbances propagating along the coronal loop with speeds of the 3,000–8,000 km/s. Most probably, the Δf modulation was interpreted to be caused by impulsively generated propagating fast sausage mode waves. On the other hand, the intensity modulation can be explained by the quenching of the loss-cone instability, known as negative bursts. A magnetic reconnection phenomena in the low corona might be the source of the both of modulations in Δf and in intensity.

These achievements highlight the significance of radio spectral observations with high time and frequency resolutions in the context of the coronal plasma diagnostics in the flaring region. We propose that coordinated radio observations of a high resolution spectro-polarimeter like AMATERAS and a spectro-heliograph such as Mingantu Ultrawide SpEctral Radioheliograph (MUSER) will be essential not only to determine the generation mechanism of the ZP, but also to probe small-scale phenomena occurring in the corona more quantitatively.