

# 論文内容要旨

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## 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 heliographic longitude of  $\pm 0\text{--}30^\circ$  and  $\pm 40\text{--}70^\circ$ , 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  $\Delta f$ . 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  $\Delta f$  and in intensity of a ZP event. Consequently, we found the quasi-periodic modulations in both  $\Delta f$  and radio intensity with the typical periods of 1–2 s and 1–3 s, respectively. The modulation in  $\Delta f$  showed a characteristic negative frequency drift of 3–8 MHz/s. Based on the Double Plasma Resonance (DPR) model, the  $\Delta f$  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  $\Delta f$  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  $\Delta f$  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.

## 論文審査の結果の要旨

太陽電波IV型バーストは、フレア発生後に広い周波数帯域と数10分スケールの継続時間で出現する電波現象であり、多様な動スペクトル構造を伴うことが知られている。その中で、周波数方向に準周期的な縞状の強度変動を持つバーストが時折出現し、ゼブラパターン(ZP)と呼ばれている。ZPは1950年代に存在が同定されて以来、多くの観測研究がなされてきたが、出現特性や発生・伝搬の物理過程には今尚未解明の課題が多数残されている。金田和鷹提出の博士論文は、東北大学の世界屈指の高時間・高周波数分解能を持つ太陽電波望遠鏡 AMATERAS で取得された ZP の解析に基づき、それらの課題究明を目指したものである。

2章ではIV型バーストの統計解析に基づき、未解明の ZP 発生条件が考察された。計54例のIV型バーストを調査し、ZPを含む場合とそれ以外の差異を詳細に調査した結果、ZPは概して長寿命フレアの崩壊期に出現することが多いこと、また、規模の大きいフレア時に出現頻度が増すことを明らかにし、ZPはフレアによるプラズマ加熱が進行し、電波発生に関わる加速粒子が継続的に供給される条件下で発生し易いことを示した。3,4章ではZPの事例・統計解析に基づき、未解明のZPの偏波特性の成因を考察した。先ず一例のZPの偏波解析から、その円偏波性は電波発生後に発生域に近接した領域で変調を受けた伝搬起因として解釈されることを示した。更に21例のZPの統計解析から、円偏波性と左右円偏波間の遅延時間には正相関があること、それはZPが発生域付近の急峻なプラズマ密度変化域で反射しながら伝搬したと考えると矛盾無く説明されることを明らかにした。5章では事例解析から、未解明のZP発生に関わる物理過程を考察した。明瞭な縞構造を示すZPの動スペクトル解析から強度と周波数幅の両方に秒オーダーの準周期的な変化が含まれることを見出し、これらはフレア時の磁場再結合に伴って生成される、高エネルギー電子パルス群とFast sausage modeの磁気流体波が磁力線に沿って電波発生領域に到達しZPを発生させたと解釈すると無理がなく説明されることを示した。以上の成果は何れもZPの高時間・高周波数分解解析で初めて明らかにされたもので、X線～赤外線太陽撮像観測では分解出来ない時間・空間スケールで発生する物理過程の存在を示しており、太陽コロナプラズマ研究に新しい示唆を与える重要な成果である。

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