# 博士論文の要約

論文題目：Comparative Study of Model Fitting of Interplanetary Flux Rope with Different Treatments of Boundary Pitch Angle
（異なる境界ピッチ角の扱いに対する惑星間空間フラックスロープモデルフィッティングの比較研究）

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Flux ropes (FRs) are magnetic field structures which are expelled from the Sun associated with coronal mass ejections. The magnetic field structure of the FRs is characterized by an axial magnetic field line surrounded by helical magnetic field lines. The formation process of the FRs at the Sun is not well understood.

If the FRs are observed in interplanetary space, these are called interplanetary flux ropes (IFRs). Observational features of the IFRs include strong magnetic field, low plasma $\beta$ (ratio of plasma and magnetic pressures), or smooth rotation of magnetic field vector, which indicates the passage of an FR structure through spacecraft. IFRs often have a strong southward component of magnetic field ($B_z$), and geomagnetic storms are caused by the interaction between $B_z$ of the IFRs and the geomagnetic field. Thus, the prediction of the magnetic structure of IFRs at the Earth is important for space weather forecasting.

The magnetic structures of IFRs at 1 AU have been estimated by various methods, which include the minimum variance analysis, fitting of the force-free magnetic field models (the Lundquist, Gold–Hoyle, and Romashets–Vandas models) to *in-situ* observations of IFRs, fitting of the elliptical cross-section model, and Grad–Shafranov reconstruction method. Some researchers report that different methods give different results for estimated IFR properties.

By the time IFRs arrive at the Earth, the propagation direction of the IFRs can deflect from radial direction or the axis of the IFRs can rotate around its propagation direction during their propagation in interplanetary space. How, when, and why the IFRs deflect or rotate are not well understood.

For the improvement of the accuracy of the prediction of $B_z$, it should be important to understand the formation and propagation processes of IFRs. The formation and

propagation processes are estimated by comparing the magnetic field properties of the IFRs (magnetic flux and axis direction) at the Sun with those at 1 AU from the Sun. Therefore, it is necessary to estimate the correct axis direction and magnetic flux of the IFRs at 1 AU. These IFR properties are often estimated by the fitting of the Lundquist and Romashets–Vandas models to *in-situ* observations of the IFRs. In the fitting of the models, it is conventionally assumed that the angle between the magnetic field at an IFR boundary and axis direction of the IFR (boundary pitch angle $\alpha_{\mathrm{p}}$) is $90^\circ$ (conventional method). However, some observations of IFRs show $\alpha_{\mathrm{p}}$ which is different from $90^\circ$. $\alpha_{\mathrm{p}}$ is closely related to the magnetic field structure of an IFR. Therefore, we speculate that different treatments of the boundary pitch angle affect the resultant axis direction and magnetic flux, which are also related to the IFR structure.

In this thesis, we aimed to develop a method in which the assumption about $\alpha_{\mathrm{p}}$ is relaxed (generalized method) and to clarify whether the generalized method is better at the estimation of correct axis direction and magnetic flux than the conventional method.

In Chapter 2, we developed the generalized method for the Lundquist model fitting and conducted the performance test of the method by applying the method to synthetic time-series data of IFRs which are generated from analytical IFR models with $\alpha_{\mathrm{p}} \neq 90^\circ$. From this analysis, we confirmed that the generalized method performs properly. Then, we applied the conventional and generalized methods to the analysis of observed data for 660 events which are candidates for IFRs, and we obtained 204 and 225 acceptable fitting results for the conventional and generalized methods, respectively. We calculated the statistical distributions of model parameters determined by the fitting. We found that approximately 60% of the events analyzed by the generalized method are within the range of $90^\circ \pm 30^\circ$, which indicates that less sheared arcades above the IFR eruption sites reconnect to form the envelope of the IFRs during their eruption for most of the cases. Then, we investigated the difference between the model parameters fitted by the conventional method and those fitted by the generalized method. We found significant differences in the results of cone angle of axis direction and magnetic flux. Thus, we concluded that it is better to use the generalized method than the conventional method in the fitting of the Lundquist model for the estimation of correct axis direction and magnetic flux. We further confirmed this conclusion by applying the conventional method to an analysis of the same synthetic time-series data as those used in the performance test of the generalized method.

In Chapter 3, we developed the generalized method for the Romashets–Vandas model fitting and conducted the performance test of the method in the same way as in Chapter 2. From this analysis, we confirmed that the generalized method performs properly. Then, we applied the conventional and generalized methods to the analysis of the same events as those analyzed in Chapter 2, and we obtained 142 and 109 acceptable fitting results for the conventional and generalized methods, respectively. We calculated the statistical distributions of the fitted model parameters determined by the fitting. We found that approximately 60% of the events analyzed by the generalized method are within the range of $90^\circ \pm 30^\circ$, which indicates that less sheared arcades above the IFR eruption sites reconnect to form the envelope of the flank of the IFRs during their eruption for most of the cases. We investigated the difference between the model parameters fitted by the conventional method and those fitted by the generalized method. We found a significant difference in the resultant toroidal magnetic flux. Thus, we concluded that it is better to use the generalize method than the conventional method in the fitting of the Romashets–Vandas model for the estimation of toroidal magnetic flux. We further confirmed this conclusion by applying the conventional method to an analysis of the synthetic time-series data of the same synthetic time-series data as those used in the performance test of the generalized method for the Romashets–Vandas model fitting.

In the dissertation summary, we clarified the importance of boundary pitch angle to the estimation of correct IFR properties based on the finding that the generalized method gives axis direction or magnetic flux significantly different from those estimated by the conventional method. We concluded that the generalized method is necessary for the estimation of correct axis direction and magnetic flux. We also discussed what processes may determine $\alpha_\mathrm{p}$ of IFRs at 1 AU and suggested the direction of arcade field lines above the IFR eruption sites and transportation of poloidal magnetic flux along the IFR axis during their propagations in interplanetary space as the two possible processes.