Development of Magnetosphere-Ionosphere Coupling Model Generalized for Exoplanetary Auroral Radio Emission

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The magnetic field of a planet is integral to its habitability, shielding life from harmful stellar and cosmic radiations. Detection of the magnetic field in exoplanets is essential for evaluating their habitability. While previous observations attempted to constrain the magnetic field strength through various methods, e.g. transit observations, optical signatures of star-planet interactions (Cuntz et al. 2000) and analysis of near-ultraviolet light curve asymmetries (Vidotto et al. 2010, 2011), direct measurements using a model-independent methodhas not been achieved yet. However, in recent years, radio observation of planetary aurora is believed to be a key for the direct detection of planetary magnetic fields as radio observations can directly constrain the amplitude of the magnetic field without relying on complex model assumptions. The circular polarization of these emissions enables them to be easily differentiated from other radio sources (Wu & Lee, 1979), and their emission frequency is theoretically proportional to the magnetic flux density in the radio source region above the planetary surface, as suggested by Farrell et al. (1999). Despite this, there have been only a few detections of auroral radio emission from an exoplanet (Turner et al., 2021), none of which have been validated by follow-up observations.

Furthermore, current modeling studies on the physical nature of radio emission are not generalized and tend to focus on specific types of exoplanets, which makes auroral radio prediction for diverse exoplanets difficult. Studies conducted by Nichols (2011) applied the magnetosphere-ionosphere (M-I) coupling model common to the Jovian bodies in the Solar System to Jupiter-like exoplanets. The model predicts Jupiter-like plasma conditions in exoplanetary system and is suitable to predict emissions only from Jupiter-like planets. Additionally, a study by Saur et al. (2013) suggested star-planet coupling mechanism which results in the formation of Alfvén wings that communicate energy for auroral formation in exoplanets. This model can only be applied to planets that are closely located to its host star which emphasizes its limited application.

Here, we developed a new generalized analytical model of the M-I coupling that predicts the exoplanetary auroral radio power, based on the pioneering exoplanetary M-I coupling model by Nichols (2011). Our model expanded from previous model by attempting to depart from a conventional corotating plasma model as the driving force of auroras in Jovian bodies to accommodate auroral formation in terrestrial planets as well. Validation of our model with Jupiter’ s auroral radio emissions suggests that our model successfully describes the auroral current density and radio emission power with uncertainty within a factor of 10. The upward field-aligned current density is of the order of 0.01 μA m^{-2} , at invariant co-latitude ~16° , one order of magnitude smaller than the modeling results of the M-I coupling process by Cowley et al. (2002). This difference is attributed to the application of a dipole magnetic field model in our approach: we map the dynamo electric field in the magnetosphere to the polar ionosphere by using the dipole model, while the previous study used a non-dipole model. We are going to further validate and modify our model based on a comparison with the auroral radio emission observations for other solar system bodies, ultracool (Kao et al., 2023) and brown dwarfs (Berger et al., 2001; Kao et al., 2016, 2018) before application to exoplanets. Here, we present the current status of our modeling and validation.

Keywords: exoplanet, auroral radio emission, magnetosphere-ionosphere coupling, radio telescope

