Study of slow-mode shock formation in the symmetric magnetic reconnection based on hybrid simulations

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Fast magnetic reconnection is achieved in the Petschek' s reconnection theory [1964] via a pair of slow-mode shocks on each side of the diffusion region. The occurrence of these slow-mode shocks has been established in MHD regime by the various MHD and Hall-MHD simulation studies [e.g., e.g., Hoshino and Nishida, 1983; Biernat et al., 1989; Lin and Lee, 1993; Hau and Wang, 2016]. However, in the kinetic regime, their existence is still debated. Some of the hybrid and PIC simulations studies of magnetic reconnection region show slow-shock like structures, where either all the Rankine-Hugoniot (RH) or the Mach number conditions are not satisfied [e.g., Krauss-Varban and Omidi, 1995; Lottermoser et al. 1998; Higashimori and Hoshino, 2012], while some show the presence of Petschek like slow-mode shocks [e.g., Lin and Swift, 1996; Liu et al. 2012; Innocenti et al., 2015]. With satellite observations, the presence of slow-mode shocks have been confirmed for both asymmetric dayside magnetopause reconnection [Walia et al., 2018 and Sonnerup at al., 2016] and symmetric magnetotail reconnection [e.g. Feldman et al., 1987; Saito et al., 1995; Eriksson et al., 2004]. Walia et al. [2018] and Saito et al. [1995] reported that the detection probability of slow-mode shocks at around 20% and 10% in the dayside magnetopause and the magnetotail, respectively. One of the reasons for low detection probability of slow-mode shocks can be that the non-slow mode shock crossings used in the observational studies are very close to the X-point, and hence the slow-mode structure has not developed fully. The error in the determination of the shock normal direction and the shock frame of reference can be another reason for lack of observations of slow-mode shocks. In situ measurements via the use of the satellite data, can help us to look into the detailed structure of a magnetic reconnection crossing, but if one wants to look at the whole structure of magnetic reconnection region, simulation studies are needed. Especially, if one wants to look into the transition from the kinetic scales to MHD scales to find out how the structure of reconnection region changes and slow-mode shocks or other discontinuities form and develop.

In the present study we use 2D hybrid simulations for symmetric magnetic reconnection with isotropic temperature to investigate the formation of slow-mode shocks. The presence of slow-shocks in the magnetic reconnection region is established by checking the satisfaction of the RH conditions and specific conditions of Mach numbers, normal angles etc. [e.g., Seon et al., 1995, 1996]. We check the set of 12 slow-mode shock conditions and use the 30% satisfaction criteria [e.g., Walia et al., 2018; Eriksson et al., 2004] at all distances from the X-point to study the formation of slow-mode shocks from the ion inertial length scales to MHD scale. We found that the Petschek like slow-mode shocks can be identified as close as ~10 λ_i (λ_i = ion inertial length) to the X-point. Below, 10 λi slow-mode shocks are not fully developed, and rather slow shock-like structure is present. Also, it is found that the slow-mode shock identification is sensitive to the slow-shock normal determination. We will also report the differences in the satisfaction of various conditions (e.g., RH conditions, Mach numbers) and the characteristics of the ion distribution functions between the regions with slow-mode shocks and slow shock-like structures.

Keywords: Magnetic reconnection, Slow-mode shocks

