The relation between high-frequency whistler waves and energetic electrons in the quasi-perpendicular bow shock

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The dissipation at the collisionless shock must be provided by nonlinear wave-particle interactions. Therefore, the generation of waves and associated heating have been the central topic of collisionless shock research. A fraction of ions that are reflected back at the shock (the reflected ions) and the strong current associated with the steep magnetic field gradient provide the primary sources of free energy that drive various kinds of instabilities. Indeed, waves at all the spatial and temporal scales (i.e., from the electron scale to MHD scale) have been observed at the Earth's bow shock. However, the relative roles played by the waves for the heating and acceleration of particles are still largely unknown.

Meanwhile, Oka et al. (2006) discovered that the so-called whistler critical Mach number regulates the non-thermal electron acceleration efficiency as quantified by the spectral index. The whistler wave is essentially a high-frequency counterpart of low-frequency Alfven waves that may have higher phase and group velocities. This thus defines the critical Mach number beyond which whistler waves of any frequency/wavenumber are no longer able to propagate upstream against the flow. The definition, therefore, considers the wave property alone and has nothing to do with particle energization. Nonetheless, Oka et al. (2006) clearly demonstrated that harder spectra were observed primarily at the super-critical regime, whereas large scatters in spectral indices, perhaps intrinsic to the solar wind, were seen at the sub-critical shocks. The observations can, in principle, be explained by considering a self-generation mechanism of high-frequency whistlers by accelerated electrons (Amano & Hoshino, 2010). The self-generated waves may then trigger the stochastic shock drift acceleration (SSDA) that leads to the formation of a power-law spectrum (Katou & Amano 2019).

In this study, we use Magnetospheric Multiscale (MMS) measurements of the bow shock to investigate the relation between the properties of high-frequency whistler waves and energetic electron production. We compare the wave properties between bow shock crossing events with efficient and inefficient energetic electron production. We found that the whistler waves observed in the efficient events were more intense and had bi-directional propagation characteristics with respect to the background magnetic field. In contrast, at least one of these properties was not satisfied with waves seen in the inefficient events. The efficient events were highly super-critical with respect to the whistler critical Mach number, whereas the inefficient events were either marginal or sub-critical. This observation implies the presence of a wave generation mechanism that becomes active only in the super-critical regime. Theoretical interpretation of the measured wave properties will be discussed.

Keywords: shock wave, plasma wave, particle acceleration

