Direct Measurement of Excitation and Growth of Large Amplitude Cyclotron Waves in Front of Shock by Reflected Ion Beams

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Wave-particle interaction plays a critical role in producing the newborn waves/turbulence in the foreshock region in front of supercritical shock, which is prevalent in the heliosphere. It has been a long-lasting goal to catch and witness the excitation and growth of waves/turbulence by identifying the ongoing process of wave-particle interaction. This goal cannot be fulfilled until the arrival of the MMS's era, during which we can simultaneously measure the electromagnetic fields and particle phase space densities with the unprecedented data quality. By surveying the data of burst mode, we are lucky to find some good examples illustrating the clear signals of wave activities in front of the shock. The active waves are diagnosed to be right-handed cyclotron waves, being highly circularly polarized and rotating right-handed about the background magnetic field vector. The waves are large amplitude with dB being greatly dominant over B0, or in other words, almost the whole magnetic field vector is involved in the circular rotation. Furthermore, we investigate the growth evolution of the large-amplitude cyclotron waves by calculating the spectrum of dJ.dE and its ratio to the electromagnetic energy spectrum. As far as we know, it is the first time to provide the spectrum of growth rate from in-situ measurements. Interestingly, we find that the contribution to the growth rate spectrum mainly comes from $dJ_{e,perp} \cdot dE_{perp}$ rather than $dJ_{e,para} \cdot dE_{para}$ or $d\mathbf{J}_i \cdot d\mathbf{E}$. Although the eigen mode to couple the oscillating electromagnetic field is the electron bulk oscillation, the ultimate free energy to make the eigen mode unstable comes from the ion beams, which are reflected from the shock. The dynamics of 3D phase space densities for both ion and electron species are also studied in detail together with the fluctuating electromagnetic field, demonstrating the ongoing energy conversion during the wave-particle process.