Normal-mode Magnetoseismology as a Virtual Plasma Mass Density Instrument and Its Use in Investigation of Oxygen Torus during Magnetic Storms

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Previous studies have demonstrated that the field line resonance (FLR) frequencies detected on closed magnetospheric field lines can be used to estimate the plasma mass density in the inner magnetosphere. This method, also known as "normal-mode magnetoseismology," can act as a virtual instrument that turns spacecraft measurements of magnetic and/or electric field into plasma mass density, which is a fundamental physical quantity that is difficult to measure directly but important to investigations involving the MHD timescales, reconnection rates, or instability/wave growth rates.

In this study, we use normal-mode magnetoseismology to help investigate the characteristics of the oxygen torus, which is the narrow region of enhanced O⁺ density in the vicinity of the plasmapause that may form during the storm recovery phase. The formation of the oxygen torus is still an outstanding question, and the geomagnetic mass spectrometer effect and the direct ring current heating of the ionosphere have been proposed as two possible causes. We identify the location and timing of oxygen torus occurrence by examining the FLR-inferred plasma mass densities in Magnetospheric Multiscale (MMS) and Van Allen Probes (RBSP) observations and compare them with the charge densities derived from the upper hybrid resonance frequency detected by the respective plasma wave experiments on the spacecraft. We find that, while MMS and RBSP could both observe clear enhancements of heavy ions during a magnetic storm, the degree and the width of O⁺ enhancement can vary with location. The timing of oxygen torus occurrence may differ from storm to storm. In RBSP measurements, we also compare the bulk densities with the partial densities of low-energy ions detected by the HOPE instrument. While the average ion mass can be greater for 30 eV – 1 keV ions than that for the bulk plasma in the oxygen torus, it is evident that the majority of the ions in the oxygen torus are below 30 eV, confirming the need to examine the bulk mass and charge densities through electromagnetic sounding methods.