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Magnetic cavities in space plasmas: from MHD to kinetic scale

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Magnetic cavities, also termed magnetic holes, dips or depression structures, have an observable magnetic field decrease in a short time span and have been widely observed in the solar wind plasmas, comet magnetospheres, terrestrial/planetary magnetosheaths, magnetospheric cusps and magnetotail plasmas since 1970s. In early observations, the structures were found in MHD scale, from tens to thousands of ρi (proton gyroradius) with corresponding temporal scales from seconds to tens of minutes. The plasma mirror mode instability and slow mode solitons were considered as possible sources of such kinds of magnetic cavities. A significant feature for most of the cavities is that they can confine hot plasmas as magnetic bottles, although previous studies were mostly limited by the measurement resolution of on board instruments. The higher resolution observations needed to understand the microphysics at the ion gyroscale or even the electron dynamics scale has only become available in recent years. With this key advance, kinetic scale magnetic cavities were detected in the earth's magnetotail and magnetosheath, with size less than ρi and sometimes close to several ρe (electron gyroradius) and often associated with a significant electron vortex around the structure. Surprisingly, it has been found that such a small structure contains an abundance of phenomena, including different kinds of ion and electron distributions, electron or ion vortices, various types of waves, and even particle acceleration and declarations. In this talk, we will show our recent observations of magnetic cavities from MHD scale to kinetic scale in the solar wind, magnetosheath, cusp and magnetotail. MHD scale magnetic cavity structures were observed in the solar wind and the occurrence rate is found to be comparable to that in other planets, which imply that these structures carry information on the dynamics in the solar corona. In the magnetosheath, downstream of the bow shock, the mirror mode instability can generate magnetic dip and peak trains. We developed a technique to distinguish flux ropes and mirror structure peaks which both have magnetic bipolar signatures. Using data from the new NASA satellite constellation MMS, we have found that electrons exhibit a new 'donut' shaped distribution function related to particle deceleration processes. Using boundary normal and velocity determination techniques, we found that MHD scale magnetic cavity structures can expand or shrink, and they can enter the cusp regions along with the entry plasmas. In the turbulent magnetosheath and quiet magnetotail, we have observed kinetic scale magnetic cavity structures with scales comparable or less than one ρi. An EMHD model of the slow-mode soliton has been developed to explain the formation of the structures during quiet times, and our calculation of the propagating velocity together with the amplitude and size fit well with the theory of EMHD solitons. Other theories will also be introduced and compared. We have found that such a small structure contains a rich set of exciting physical processes, including electrostatic and electromagnetic waves, diamagnetic current, unique electron distributions and current systems. Using a unique technique – particle sounding technique, we found that in the sheath the electron scale magnetic cavity has a circular cross section and it is a magnetic bottle in 3-D. We have also found that these structures shrink due to increases in the surrounding magnetic field, and this shrinkage of the small scale magnetic cavity can induce an electric field that accelerates the electrons to a significantly higher energy. Qualitatively distinct from other acceleration mechanisms, this process indicates a new type of non-adiabetic acceleration, and has been confirmed by the observed electron distribution function and test particle simulations. This discovery in space physics also has implications for understanding energy conversion in astrophysical plasmas, the origin of cosmic high-energy particles and plasma turbulence. The fundamental process described in this talk may also potentially provide a means of efficient particle acceleration required in a range of applications, such as charged particle beams and plasma jet generators.