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Generation of sub-ion scale magnetic holes from electron shear flow instabilities in plasma turbulence

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Magnetic holes are coherent structures associated with a strong depression in the magnetic field amplitude. Such structures are ubiquitous in space plasmas and are observed in the solar wind, in planetary bow shocks and magnetosheaths, in the Earth's magnetotail and around comets. Magnetic holes may have very different sizes and properties. The largest ones have a size of hundreds of ion gyroradii while the smallest ones are sub-ion scale structures of the order of a few electron gyroradii. The drop in magnetic field amplitude associated with magnetic holes is often sustained by an increase in plasma density and enhanced ion and electron temperature anisotropies, with temperatures that are typically higher in the plane perpendicular to the local magnetic field. These properties seem to suggest that the generation of magnetic holes may result from the nonlinear evolution of mirror modes whose growth is fed by perpendicular temperature anisotropies and that are characterized by anticorrelated magnetic field and density perturbations. Some observational and numerical studies seem to support the idea of a scenario in which magnetic holes are generated by the mirror instability but in many cases this picture is not consistent with observations, especially in the case of sub-ion scale magnetic holes for which a number of possible generation mechanisms have been considered. Hence, the origin of magnetic holes is still controversial and under debate.

Plasma turbulence is also known as a driver for the generation of coherent structures and may play a key role in the formation of magnetic holes, especially in the solar wind and in the Earth's magnetosheath that are in a turbulent state. Indeed, numerical simulations of plasma turbulence show that sub-ion scale magnetic holes can develop self-consistently out of small scale magnetic fluctuations that locally reduce the magnetic field amplitude and trap hot electrons. However, it is still unclear how such small scale fluctuations can emerge in a turbulent plasma where energy is typically injected at large scales. In this work, we study the formation of sub-ion scale magnetic holes by means of fully kinetic particle-in-cell simulations of plasma turbulence. We show that by injecting energy at scales relatively large with respect to ion scales, the turbulence naturally tends to generate sub-ion scale electron velocity shear layers associated with elongated magnetic field grooves. These elongated magnetic dips then become unstable and break up into sub-ion scale magnetic holes characterized by an intense azimuthal electron current and a strong perpendicular electron temperature anisotropy. We show that the properties of magnetic holes generated by

this mechanism are consistent with satellite observations. Our results may provide a possible explanation of how magnetic holes develop in a realistic turbulent environment.