Recreating outer space plasma systems in the lab

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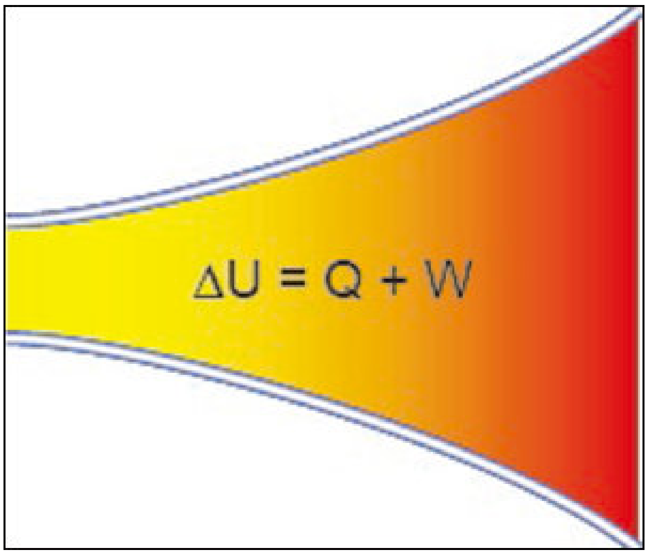

Physical picture of the electron gas expanding in the magnetic wall, where Q = 0 for the adiabatic expansion, resulting in a change of the internal energy of the electron gas is equal to the work done on their surroundings. The magnetic field can behave as a flexible wall with no heat transfer, i.e., the perfectly adiabatic wall. Credit: Kazunori Takahashi

Thermodynamics provides insight into the internal energy of a system and the energy interaction with its surroundings. This relies on the local thermal equilibrium of a system. The application of classical thermodynamics to systems in disequilibrium is challenging. These include granular gas and materials, hard sphere packing in 3-D, and plasma systems.

The expansion of a gas with no electric charge has typically been studied using traditional thermodynamics. Experiments with simple gases can easily be carried out in laboratories, whereas those involving gaseous plasmas of astrophysical and solar interest pose a number of difficulties. Observations near the sun and in Earth orbit have been interpreted as a demonstration that solar wind does not expand adiabatically from the sun, as would be expected for this near-collisionless environment. Rather, it expands isothermally, implying that heating of the plasma occurs as it propagates through interplanetary space.

Many laboratory-based experiments under adiabatic conditions have also shown a nearly isothermal expansion in magnetic nozzles and the relation with astrophysical plasmas. However, in these expanding adiabatic systems, it appears that electric fields may have a significant effect on the dynamics of the electrons, and a very strong electric field trapping the electrons usually forms at the plasma-wall boundary in laboratory plasmas. So what would happen if there were no electric fields trapping the electrons?

Researchers from Tohoku University and the Australian National University have studied the energy state of of plasma when it interacts with magnetic and electric fields [Fig1]. The study has implications for the understanding of magnetic nozzle plasma thrusters used to propel spacecraft, since energy conversion is the essential process to determine the thruster performance.

In a laboratory at Tohoku University, researchers Kazunori Takahashi, Christine Charles, Rod W Boswell and Akira Ando have performed a specially designed experiment in which they removed the electric field-trapping electrons in the system, resulting in the electrons solely interacting with the expanding magnetic field. The experimental results show the decreasing electron temperature along the expansion, following a near-perfect adiabatic expansion of an electron gas upon removal of the electric fields from the system.

Keeping in mind the first law of thermodynamics, there is presently no heat transfer, but work must be done on the walls surrounding the system to lower its internal energy. The expanding magnetic field is not a physical boundary, so no heat is transferred. When the electric fields within the plasma are removed, none of the electrons are trapped in the plasma system, leaving the electrons free to interact with the confining magnetic wall—the plasma pressure force does work on the magnetic boundary. This pressure force can also be understood as a Lorentz force generated to propel a spacecraft in a magnetic nozzle plasma thruster.

Hence, the decrease in the electron temperature along the expansion results from lowering the internal energy of this adiabatic system with the electron gas doing work on the expanding magnetic field. This implies that classical thermodynamic principles can be extended to the expansion of a collisionless electron gas, being far from equilibrium, in a magnetic nozzle.

By removing the plasma-wall boundary in their laboratory plasma and thereby removing the corresponding electric field and electron trapping, the researchers reproduced the boundary-free conditions in space. The results give new insight into plasma thermodynamics and technology applicable to space physics and plasma propulsion development. Further detailed experiments are planned. The paper was published in *Physical Review Letters*.

More information: Kazunori Takahashi et al, Adiabatic Expansion of Electron Gas in a Magnetic Nozzle, *Physical Review Letters* (2018). DOI: 10.1103/PhysRevLett.120.045001