Magnetic reconnection in space plasma

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Abstract: Magnetic reconnection is a fundamental energy conversion process in plasmas that drives transport and leads to explosive large-scale magnetic energy releases such as substorms, solar flares and gamma-ray bursts. While these consequences such as acceleration and heating of the plasma are distributed over larger scales, magnetic reconnection operates as changes in the topology of the magnetic field take place inside a small region where electrons as well as ions are demagnetized. Geospace is an ideal plasma laboratory for studying how such magnetic reconnection operates in nature since plasmas and fields in action can be directly measured at high cadence. In particular, the in-situ measurement capability of the four Cluster and Magnetospheric Multiscale (MMS) spacecraft enabled to resolve kinetic physics of ions and electrons, respectively, and have significantly advanced the study of magnetic reconnection and relevant plasma processes in space. In this presentation, we summarize the current understanding of magnetic reconnection in space based on these multi-point observations in geospace. We also highlight several unsolved questions and introduce a newly proposed multi-point multiscale observatory in the Earth's magnetosphere, Plasma Observatory (PMO), for studying cross-scale coupling of fundamental plasma processes in geospace including magnetic reconnection

Introduction: Magnetic reconnection takes place when frozen-in condition of plasma breaks down in a small region. In this region the magnetic field diffuses so the magnetic field get cut and then reconnect therefore change its topology. The overall consequence of magnetic reconnection is the mixture of the plasma from different region and acceleration and heating of plasma. Magnetic reconnection is an important energy conversion process in the collisionless plasma, driving global plasma transport or leading to explosive magnetic energy release on global scales in systems. Among the different plasma environments, geospace is a natural plasma laboratory to study how magnetic reconnection operates in nature, since plasmas and fields in action can be directly measured. The first evidences of the magnetic reconnection from the in-situ measurements are the detection of the spatial pattern of the magnetic field orientation and associated fast reconnection jets. These observations suggested the frozed-in flux tubes that experienced the topology changes due to magnetic reconnection deduced from single spacecraft measurmenets. Multi-point measurements can deduce temporal and spatial variations independently and are essential for studying local processes inside the reconnection region, Cluster and THEMIS enabled us to resolve magnetic reconnection covering down to ion-scale structures from the multipoint measurements. With the high-resolution in-situ measurement capabilities onboard the four MMS spacecraft [1], studies of magnetic reconnection and relevant plasma processes have been significantly advanced by including the electron-scale physics, In this presentation we first highlights the observations of magnetic reconnection in the magnetosphere in the MMS era and discuss the outstanding problems of magnetic reconnection and introduce a future research direction, introducing a newly proposed Plasma Observatory Mission (PMO).

In-situ observations of magnetic reconnection MMS era: With the advances in in-situ measurement capabilities, studying non-ideal MHD and kinetic physics of magnetic reconnection and relevant plasma processes became possible for the first time from spacecraft observations. A number of new analysis schemes have been developed for characterizing the temporal/spatial changes of the complex plasma processes. Stimulated by these new observations advanced theory and simulations were developed and quantitative comparison with the simulation have been made. These advances are summarized in [2] and reference therein. These new observations include detailed structure and electron dynamics of the electron diffusion region by taking into account the different types of current sheet, i.e with or without asymmetry and different levels of magnetic and flow shears across the current sheets. With the multi-point measurements quantitative analysis of the different terms in the generalized Ohm's law, determination of reconnection rate, energy conversion process were realized. Observations of kinetic behaviors of the electrons and ions in the vicinity of the diffusion region have suggested complex 3D processes around the diffusion region. These include large-amplitude waves interacting with the agyrotropic electron distributions in the electron diffusion region (EDR), wavy and turbulent current sheets inside EDR.

The spacecraft fleet in geospace in MMS era enabled us also to discover different types of transient current sheets with active reconnection. These include dynamic multiple secondary reconnections, reconnections at the forshock transition layers, turbulent, partially electron-only reconnection in the magnetosheath, vortex-induced 3D reconnection in the flank magnetopause, transient reconnection at the reconnection jet front layer. Further study of macroscale consequence includes the large-scale chain of the solar-wind magnetospheric interaction and particle acceleration. Selected examples of these new observations will be highlighted in the talk.

Outstanding problems: While significant advancement has been made with new observations and new simulations, there are still a number of unsolved questions in magnetic reconnection both in the kinetic physics as well as macro-scale consequences as discussed in [3] and reference therein. Four topics related to significant outstanding question are identified: (1) Complex dynamics and structures in the diffusion region, (2) Cross-scale dynamics and regional coupling, (3) Onset of reconnection, (4) Energetics, acceleration, and heating. These topics are not mutually independent but closely related. For example, (3) the onset problem is naturally a multi-scale problem since the free energy of reconnection is determined by large-scale current sheet processes and its consequences (such as acceleration of particles) affect the large-area in space, while the dissipation of a tearing mode occurs at scales of the ion or electron gyroradius. That is, it is requires to understand (1) complex dynamics in the diffusion region as well as (2) cross-scale coupling processes and involves sudden energy release (4) accelerating/heating particles. The limitation in the current observation capabilities covering all the necessary scales makes it very difficult to compare with theoretical/numerical descriptions.

These unsolved questions are not only related to geospace magnetic reconnection but relevant to other plasma environments but with some differences in the observational constraints. For the onset problem of the near-Earth magnetotail reconnection, for example, one needs to understand both the buildup of the thin current sheet and explosive energy release. Yet all the local observations are snapshots of some stage of reconnection evolution at given spatial scale, either fluid, ion, or electrons, scales covered by the in situ-measurements. Multi-scale observations, which monitors both the ion- and electron-scale evolution of the current sheet simultaneously, are essential for confirmation of the different onset mechanism of fast reconnection in the magnetotail current sheet. Similar to the magnetotail reconnection, how the magnetic energy is build up in the corona and how its sudden release are triggered need to be explained to understand the flare onset. The large-scale accumulation of energy preceding the reconnection onset and its transport down to kinetic length scales are important also for solar flares in coronal loops, and hence it is a multi-scale problem. In contrast to the magnetotail case, however, the kinetic scales are inaccessible from observations. On the other hand, the complex 3D evolution of the flare have been extensively studied based on multi-wavelength observations.

Future research direction: To advance our understanding of magnetic reconnection one of the important direction of new research in future would be more interdisciplinary studies involving those from space, solar, astro and laboratory. Through the common framework of theory and simulations, processes occurring in solar and astrophysical systems mainly captured with large-scale remote-sensing images can be bridged to those in space and laboratory environments where plasma are "directly" measured. The understanding and knowledge gained from in-situ kinetic-scale measurements in geospace can be applied to other planetary environments and serve as a foundation to understand larger scale systems such as solar flares and astrophysical phenomena, for example, relativistic jets in quasars. Direct comparison of the energy spectra between the solar flare and magnetotail reconnection has proven to be already a successful scheme for studying particle acceleration in magnetic reconnection.

In geospace monitoring simultaneously fluid-scale and kinetic-scale is desired for magnetic reconnection studies with observations as discussed before. Plasma Observatory (PMO) [4,5] is a ESA M-class mission candidate and is a seven spacecraft mission which is tailored to study plasma energization and energy transport within the Earth's Magnetospheric System. With the seven spacecraft simultaneously covering at least two scales simultaneously, the mission is expected to improve also our understanding the multi-scale problems of magnetic reconnection alongside with other science goals such as shock, turbulence, and different topics in the magnetospheric boundaries. Understanding plasma energization and energy transport is an open challenge of space plasma physics, with important implications for space weather science as well as for the understanding of distant astrophysical plasma.

Summary: Recent advancements in in-situ plasma measurements, which have enabled the study of collisionless magnetic reconnection physics, including kinetic physics, led to new discoveries as well as many of the open questions discussed in the previous sections. More comprehensive discussions of these topics are given in [6], which is a collection of reviews on progress in research of magnetic reconnection and relevant processes in space plasma, based on recent in-situ multipoint observations and theoretical simulations in and beyond geospacer.

References

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