An Introduction to Magnetosphere-Ionosphere-Thermosphere Coupling Small Satellite Constellation

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Abstract A future Chinese mission is introduced to study the coupling between magnetosphere, ionosphere and thermosphere, i.e. the Magnetosphere-Ionosphere-Thermosphere Coupling Small Satellite Constellation (MIT). The scientific objective of the mission is to focus on the outflow ions from the ionosphere to the magnetosphere. The constellation is planning to be composed of four small satellites; each small satellite has its own orbit and crosses the polar region at nearly the same time but at different altitude. The payloads onboard include particle detectors, electromagnetic payloads, auroral imagers and neutral atom imagers. With these payloads, the mission will be able to investigate acceleration mechanism of the upflow ions at different altitudes. Currently the orbits have been determined and prototypes of some have also been completed. Competition for next phase selection is scheduled in late 2015.

Key words Coupling, Magnetosphere, Ionosphere, Thermosphere, Small satellite

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Introduction

Above the Earth’s atmosphere, extending from about 50~100km above the sea level to about 1000km, are the ionosphere and thermosphere, respectively. Some of the neutral particles of the high atmosphere are ionized by radiation from the Sun, resulting in free electrons and electrically charged atoms and molecules. The ionosphere contains a significant number of free electrons and positive ions, as well as some negative ions at lower altitudes. The medium has equal numbers of positive and negative charges within a given volume, and is globally electrical neutral. Generally, the ionosphere changes significantly with variation of the solar angle. The percentage of the ionization increases with altitude, and reaches 100% at around 1000km which is the bottom of the Earth’s magnetosphere.

The Earth’s magnetosphere extends from 1000km to an altitude varying from a few $R_e$ (Earth radius) to hundreds of $R_e$, depending on local latitude and time. It is occupied by full ionized plasma of very low density. Although the magnetic field is not very strong in this region (10~1000nT), the plasma transportation and oscillation is largely controlled by the magnetic field, so that this region is called magnetosphere.

Although the Earth’s magnetosphere and ionosphere are located at different altitude, they are coupled through the exchange of energy and materials. The coupling of ionosphere and thermosphere denotes the coupling between ionized and neutral particles at this altitude. The Earth’s magnetosphere-ionosphere-thermosphere system is the region where most of the man-made spacecrafts are working. Sometimes the plasma environment in this region may be hazardous to the safety of the instrument and human-being onboard\(^{[1]}\). The region also channels the exchange of energy and materials between the Earth system and interplanetary space\(^{[2~3]}\). To understand the coupling of magnetosphere-ionosphere-thermosphere system is not only valuable for a practical purpose, but also important for scientific discovery.

Lots of effort has been cast to study Magnetosphere and Ionosphere. Dynamic Explorer (DE) was launched in early 1980s to investigate the coupling of magnetosphere and Ionosphere. Later NASA launched FAST and POLAR to investigate the magnetosphere\(^{[4~8]}\). CHAMP and other missions were launched to study ionosphere and thermosphere. Recently, NASA launched Van Allen Probe to investigate radiation belt where hazardous energetic particles concentrate. There are also rocket programs launched to investigate the ionosphere. However, none of these missions targeted the coupling of Magnetosphere-Ionosphere-Thermosphere system.

In this paper, a future Chinese mission, Magnetosphere-Ionosphere-Thermosphere Coupling Small Satellite Constellation (MIT) is introduced, targeting at the coupling of magnetosphere-ionosphere-thermosphere system. The constellation will be composed of two magnetosphere small satellites and ionosphere/thermosphere small satellites, mainly focusing on the material exchange between magnetosphere, ionosphere and thermosphere.

1 Scientific Objectives of the MIT Mission

The Magnetosphere-Ionosphere-Thermosphere Coupling Small Satellite Constellation mission is designed to investigate the physical processes involved in the coupling of the MIT system. Its major scientific objectives are to investigate the origin of the outflow ions and their acceleration mechanisms, to understand the impact of the outflow ions on magnetic storm development, to characterize the ionosphere and thermosphere storm caused by magnetic storm and to explore the key mechanisms for the magnetosphere, ionosphere and thermosphere coupling.

These four scientific objectives are elaborated as follows.
1.1 Origin of the Upflow Ions and Their Acceleration Mechanisms

The \( \text{O}^+ \) ions are tracers of the upflow ions. It has been well known that particles in the magnetosphere originate from either ionosphere or solar wind. The oxygen ions in solar wind are mainly \( \text{O}^6+ \) and \( \text{O}^7+ \), and most of the magnetospheric \( \text{O}^+ \) ions have ionospheric origin and their distribution in magnetosphere traces the transportation of the upflow ions from ionosphere. The question remaining unanswered is how the \( \text{O}^+ \) ions transport from ionosphere to magnetosphere at higher altitude.

The oxygen ions move up against the gravity, and they must gain enough energy to reach upper Magnetosphere. The physical processes for them to gain energy actually vary at different altitude as shown in Fig. 1.[7]

At very low altitude, sunlight or the precipitation electrons heat electron at lower altitude first[8]; so electrons have higher temperature than other particles in ionosphere. At higher altitude, the wave ions interaction and electric field parallel to the magnetic field make effects. The wave ion interaction is quite a complicated process, but can be analog to surf in the water. When the particles move together with the wave front, they can obtain energy from the wave. The electrons are much lighter than ions so that it is easier for them to fly up along the magnetic field and end up with a parallel electric field pointing up. The electric fields accelerate ions moving up along the magnetic field. At even higher altitude, the eccentric force becomes a major acceleration process. The particles circle the magnetic field line like beads on a rode. If the magnetic field is disturbed, like the rode was shaken, then the particles are accelerated as beads on a shaking rode[9].

1.2 Understand the Impact of Outflow Ions on Magnetic Storm Development

During storm time, the sudden increase of oxygen ratio in the ring current is a puzzle, so is the impact of increased oxygen ions on ring current. The intense ion upwelling from the ionosphere into the magnetosphere is so strong that ionospheric \( \text{O}^+ \) can dominate the high altitude ion pressures. This alters magnetospheric dynamics by modifying magnetic reconnection both on the dayside and on the nightside. Fig. 2 shows multi-fluid simulations of the magnetosphere with protons only (left panel) and both protons and oxygen (right panel). When adding a tailward plasma flow at the magnetic tail, the magnetosphere nearby with protons only is stable and the flow has little impact on the near Earth space, called the inner magnetosphere and the ring current region. On the contrary, the magnetosphere with proton and oxygen ions are disturbed by the plasma flow and the magnetic field configuration is significantly modified, especially the field in the near Earth space. The additional oxygen ions control the processes near the magnetic tail and make the magnetosphere more unstable[10].

1.3 Characterize the Ionosphere and Thermosphere Storm Caused by Magnetosphere Storm

During a geomagnetic storm, the near Earth space including the ionosphere and thermosphere can be disturbed. The thermospheric density increases significantly and quickly at high altitude; the peak elec-
tron density in the F region of the ionosphere is also modified, and it either increases or decreases, depending on the local time, season and latitude.

The understanding of ionosphere and thermosphere response to geomagnetic storm is important not only for scientific interest but also of great practical value. The low orbit satellites decay more rapidly as a result of the denser thermosphere. The disturbed ionosphere may affect satellite communication, GPS positioning and even power transportation facilities on the ground. How geomagnetic storm causes ionospheric storm and thermospheric storm has been investigated for decades. However, there are still many unknowns.

During storm time, a large amount of energy was injected into magnetosphere from the solar wind, and then from the magnetosphere into the ionosphere and thermosphere. There are three discrete ways for magnetosphere to deposit energy and momentum: precipitation aurora electron and protons, Joule heating and ion drag. The precipitation particle heating, which is only from 10 GW to 20 GW during quiet time, increases to over 100 GW during storm time. However, previous studies showed that particle heating contribute only a small portion of energy source. The precipitation electron and proton ionize part of the atmosphere and increase the atmosphere conductivity. The electric field from the magnetosphere causes ion drift in the ionosphere. As the ions move through the thermosphere, they exchange energy with the neutrals in the forms of Joule heating and neutral wind acceleration or deceleration (kinetic energy). Joule heating, which contributes hundreds of GW to the ionosphere/thermosphere, is due to the
magnetosphere convection electric field and increased conductivity. Ion drag can either transport energy into or from the neutral particles depending on directions and magnitudes of the ion drift and the neutral wind. The neutral gases are forced to follow the ions through collisions. It should be noted here that the ionosphere is very collisional at lower altitude, contrary to the collisionless magnetosphere.

Joule heating causes upwelling and moves heavier molecules like O$_2$ and N$_2$ to higher altitudes, therefore changes the thermospheric composition. Because these heavier molecules increase the ion recombination rate, ion density decreases in the region of strong heating. Joule heating also can change the pressure gradient and redirect the neutral winds, which spread the depleted ionosphere to a larger area in the lower latitudes. That is the general understanding of the negative phase of the ionosphere. However, there are a lot of questions remaining unanswered about how geomagnetic storm causes ionospheric and thermospheric storm. Uncertainties in estimating the Joule heating and lack of neutral wind data are the major hurdles for a better understanding of the ionosphere and thermosphere interaction. Whether there are other causes for the negative phase besides the neutral composition change remains unknown. The ionosphere and thermosphere system is quite different from the magnetosphere due to the existence of neutral particles and collision. The system is more complicated, and shows very puzzling character during storm time. The proposed MIT mission can address these issues with an instrument such as UV imager, which can record O$_2$ and N$_2$ composition. Such an imager can provide an instant global view of the ionospheric density and help track ionospheric response to geomagnetic storms. This kind of imaging data is invaluable to both scientific research and space weather applications.

1.4 Explore Key Mechanisms for the Magnetosphere, Ionosphere and Thermosphere Coupling

The auroral current circuit is assumed to include (i) a magnetospheric generator at high altitude, which provides energy to the system, mainly as Poynting flux, (ii) the auroral acceleration region around 1 $R_e$ altitude, where the Poynting energy is converted into particle energy, mainly of precipitating electrons, and (iii) the ionospheric load, where the energy is dissipated. MIT will provide a unique opportunity to investigate this current circuit systematically, by triple conjunction event studies. Double conjunctions, between one or both low altitude satellites and one of the high altitude satellites, will provide as well ample information for systematic studies. MIT will also enable a close examination of the neutral winds’ influence on auroral electrodynamics. While this influence is in general disregarded, since the equivalent electric field of the neutral winds is typically small compared to the auroral electric field, the effect of the neutral winds can become significant when the electric field is small. One specific example is the so called Ha- rang region, near midnight, which plays a key role in the substorm cycle[13]. The plasma convection reversal boundary here is located deep inside the auroral oval and the electric field can remain small over fairly large areas around this boundary.

The major scientific objectives focus on the heating, acceleration and transport processes of ions in the polar regions and on their impact on the ring current and radiation belts. Because of the dynamic nature of these processes that also vary with altitude (Fig. 1), it is imperative to cover with MIT altitudes from a few hundreds of kilometers to several Earth radii. This will be accomplished with 4 spacecrafts in polar orbits as described below. This constellation of 4 spacecrafts will also provide an excellent platform for the exploration of auroral electrodynamics, in particular for the investigation of the auroral acceleration region at altitudes of about 1 $R_e$ and for the investigation of the influence of neutral winds on auroral electrodynamics. This constellation of 4 spacecrafts will also provide an excellent platform for the exploration of auroral electrodynamics, in particular for comprehensive investigations of the auroral...
current circuit. Systematic studies on the influence of the neutral, thermospheric winds on auroral electrodynamics will be made possible as well.

2 Orbits of the MIT Spacecraft

The mission plans a constellation composed of four satellites orbiting the Earth at three different altitudes as shown in Fig.3 and Table 1. The spacecrafts on the higher orbit are called MA and MB. They are in a polar orbit of \((2 \times 8) R_e\), with the orbital phase adjusted so as to have MA and MB at the same time at apogee and perigee, respectively. The low-altitude spacecrafts are called ITA and ITB with a polar orbit of 500 km \(\times 1500\) km and a period of \(1/9\) of the MA/MB spacecrafts. If MA, MB and ITA, ITB start from the North Pole, after half a period of MA, both MA and MB are located at the South Pole. The ITA and ITB spacecraft complete 4.5 orbits at the same time, providing now measurements over the South Pole. This configuration with 4 spacecrafts at 3 different altitudes in the polar region provides ideal coverage for the investigation of transport and acceleration processes of ions and electrons during quiet times and magnetic storms.

3 MIT Instrumentation

The instrumentation proposed for MIT has state-of-the-art capability to measure the electric and magnetic fields, the cold plasma and neutral wind, 3D ion and electron distribution functions, low-energy neutral particles and UV from the aurora, utilizing identical instruments onboard the two high altitude (MA/MB) and low altitude (ITA/ITB) spacecrafts, respectively. The high-altitude spacecrafts MA/MB are spin-stabilized with a spin period of 6 s. The low-altitude spacecrafts are 3-axis stabilized. A summary of all MIT instruments is provided for MA/MB in Table 2 and for ITA/ITB in Table 3. In the following chapters only the particle instrumentation will be discussed in some detail, because this was the main emphasis of the MIT Forum.

3.1 Instrumentation Onboard the High-altitude Spacecrafts MA and MB

The two high-altitude spacecrafts will provide simultaneous measurements in the polar regions of the Earth at altitudes between 1 \(R_e\) and 7 \(R_e\). The scientific

<table>
<thead>
<tr>
<th>satellite</th>
<th>Ionosphere/Thermosphere</th>
<th>Ionosphere/Thermosphere</th>
<th>Magnetosphere</th>
<th>Magnetosphere</th>
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</thead>
<tbody>
<tr>
<td>inclination/(^\circ)</td>
<td>90</td>
<td>90</td>
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<tr>
<td>perigee altitude</td>
<td>500 km</td>
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<td>1 (R_e)</td>
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<td>apogee altitude</td>
<td>1500 km</td>
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Fig. 3 Orbits of the four spacecrafts of the MIT Constellation mission
fic objectives of the MIT mission require the determination of the 3D distribution functions of electrons and ions with high time resolution (1 spin) over a large energy range, covering energies from the ionospheric source at low energies (about eV) up to the energy of accelerated particles in the ring current (about 500 keV). In order to unambiguously determine the source of the particles, it is also mandatory

<table>
<thead>
<tr>
<th>payload</th>
<th>measurements</th>
<th>parameter range</th>
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<tbody>
<tr>
<td>thermal plasma analyzer</td>
<td>thermal ions, electron composition and distribution</td>
<td>ion energy: 0.6<del>500 eV; electron energy: 0.03</del>50 keV</td>
</tr>
<tr>
<td>suprathermal ion analyzer</td>
<td>suprathermal ion composition and distribution</td>
<td>ion energy: 0.3~50 keV</td>
</tr>
<tr>
<td>energetic particle detector</td>
<td>energetic ion/electron intensity</td>
<td>ion energy: 0.05<del>4 MeV; electron energy: 50</del>400 keV</td>
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<tr>
<td>fluxgate magnetometer</td>
<td>DC/AC magnetic field vector (3 components)</td>
<td>magnetic field: ±65 000 nT</td>
</tr>
<tr>
<td>electric field instrument</td>
<td>DC/AC electric field vector (3 components)</td>
<td>electric field: ±1 V·m⁻¹, DC~100 kHz</td>
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<tr>
<td>low-frequency electromagnetic wave detector</td>
<td>magnetic field vector (3 components)</td>
<td>magnetic fluctuation frequency: 0.01~20 kHz</td>
</tr>
<tr>
<td>wide-band wave analyzer</td>
<td>field data analyzer, turn field into spectrum</td>
<td>frequency: 0.025~77 kHz</td>
</tr>
<tr>
<td>neutral atom imaging system</td>
<td>ring current energetic particle image</td>
<td>energy: 40~300 keV</td>
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to measure the mass per charge composition of the ions over a wide energy range, to distinguish between ions of magnetospheric origin (e.g. He$^+$, O$^+$) and solar wind origin (e.g. He$^{2+}$, O$^{6+}$, O$^{7+}$). The large energy range covering more than 5 orders of magnitude requires two electron sensors and three ion sensors as summarized below.

3.1.1 Low-energy Electron Measurements

High time resolution with 3D coverage can be achieved on a spinning spacecraft with a spherical analyzer in top-hat configuration as schematically shown in Fig. 4. This sensor design was first proposed about 20 years ago and since then successfully used for electron and ion measurements on many missions (e.g. FAST, Cluster). The energy per charge of the particles is determined by sweeping a voltage on the inner hemisphere (positive for electrons, negative for ions), see Fig. 4b), and only particles in a narrow energy window that depends on the voltage setting, and on the spacing and the radius of the spherical analyzer hemispheres, can pass the analyzer and are then counted at the exit by suitable detectors, e.g. channeltrons or Microchannel Plates (MCP). The top-hat configuration (Fig. 4a) provides an instantaneous 360° coverage. Mounting the sensor perpendicular to the spin axis provides 3D coverage in half a spin period. The Low Energy Electron Analyzer uses the top-hat configuration with detector of microchannel plates and covers the energy range from 30 eV to 50 keV, with an angular resolution of 22.5° × 11.25°.

3.1.2 Thermal and Suprathermal Ion Composition Measurements

The scientific objectives of the MIT mission require the determination of 3D distribution functions of ions over the large energy range of about 1 eV to 50 keV, with sufficient mass per charge resolution to identify H$^+$, He$^+$, and O$^+$. The state-of-the-art configuration to accomplish this task is the combination of a hemispherical top-hat analyzer with time-of-flight measurement and post-acceleration. The large energy range requires two separate sensors, the Thermal Ion Mass Spectrometer (TIMS) and the Suprathermal Ion Analyzer (SIA), covering different energy ranges as shown in Table 2. This operating principle was successfully used onboard the FAST, Equator-S and the four Cluster spacecrafts and is shown schematically in Fig. 5. The energy per charge of the ions is measured by sweeping a negative voltage on the inner hemisphere of the analyzer. At the analyzer exit the ions are accelerated by a high voltage (about 15 kV for MIT) and enter the time-of-flight section through a thin carbon foil (about 3.5 mg cm$^{-2}$). Ions penetrating the carbon foil generate secondary electrons that provide a start signal at a MCP at the exit of the time-of-flight section. The stop signal is provided by the ions that also hit the MCP. The energy per mass ($E/M$) of the ions can be derived from the length of the flight path and from the flight time ($t = t_{\text{stop}} - t_{\text{start}}$), typically in the range of 2 ∼ 20 ns cm$^{-1}$ in this energy range. The mass per charge ($M/Q$) of the ions can then be computed from $M/Q = (E/Q)/(E/M)$ (see also Fig. 5). The TIMS sensor has been tested in May 2014.
(1) Energetic Ion Composition Analyzer (EICA)

The energetic ion composition analyzer will cover the energy range of about 50 keV to 500 keV and provide mass per charge resolution to identify the dominant ions in the ring current (H\(^+\), He\(^+\), O\(^+\)). The EICA discriminates the ion composition by measuring the ion flight time in the instrument, which is similar with the work principle of TIMS. The start signal is provided through the secondary electrons produced by the ions penetrating through the carbon foil. The stop signal is provided through the secondary electrons produced by the ions hitting on the solid state detector. The ion energy is measured by the solid state detector. The design of EICA is similar with the Suprathermal Ion Telescope (SIT) on STEREO (Fig. 6). The development of EICA is supposed to be an international collaboration between NSSC (National Space Science Center, Chinese Academy of Sciences) and IEAP (Institute of Experimental and Applied Physics) of Christian Albert University in Germany.

(2) Energetic Particle Detector (EPD)

The energetic particle detector (EPD) will cover the energy range of about 50 keV to 4 MeV for ions (predominantly protons) and 50 keV to 400 keV for electrons, respectively. The sensor design is based on a Solid State Detector (SSD) telescope where electrons are swept out of the ion telescope by a magnet and protons below about 400 keV are stopped in the electron telescope by a thin foil (Fig. 7). The design is similar to the SEPT sensor onboard the STEREO spacecraft that has been successfully operated for more than 7 years. The prototype of EPD for MIT will be ready for test in May 2014.

3.2 Instrumentation Onboard the Low-altitude Spacecrafts ITA and ITB

The main purpose of the low-altitude spacecrafts ITA/ITB is the investigation of the physical condition and dynamic processes in the source region of the ions that are subsequently observed throughout the magnetosphere. These observations require the measurement of electric and magnetic fields and wave spectra, as well as the in-situ determination of density, temperature and velocity of the cold plasma and neutral wind at low altitudes. Furthermore, the payloads include an energetic particle detector to measure precipitating electrons and ions at low altitudes as well as a far UV spectrograph for the remote measurement of aurora generated by precipitating particles.
Instrumentation for the determination of parameters of the cold plasma in near-Earth orbit has been developed since the early times of spaceflight in the 1960s and is now in a very advanced state. Electron density and temperature will be measured with Langmuir probes and the ion parameters density, temperature and composition will be determined with Retarding Potential Analyzers (RPA) and Ion Drift Meters (IDM). The electron and ion density and temperature are calculated from the voltage-current curves achieved by sweeping voltages applied on the Langmuir probes and RPA, respectively. The ion drift velocity is calculated from the ratio of the current signals measured by the four adjacent collectors. The Langmuir probes developed by NSSC for the sounding rockets have been launched successfully in 2011 and 2013. The development of the prototype of Langmuir probe, RPA and IDM for the China Seismo-Electromagnetic Satellite has already been finished.

(2) Neutral Atmosphere Analyzer (NATA)

The Neutral Atmosphere Analyzer consists of 4 sensors for the measurement of density (1 sensor), composition (1 sensor) and velocity of the neutral wind in the direction of the velocity vector of the spacecraft (1 sensor), and velocity perpendicular to it (1 sensor). The sensor design of measurement of velocity in the spacecraft direction is based on a recent development for the US small satellite C/NOFS (Communication/Navigation Outage Forecast System) launched in 2008. The density and composition sensors are heritage from Tiangong-1, which is the Chinese manned space station. Velocity parallel to the satellite flying is measured from the energy of the neutral wind particles, and velocity perpendicular to the satellite flying is measured from the neutral particles density variation with the position of the sweeping baffle before a density sensor. The design of velocity sensors is similar with WATS on DE-2 satellite. The prototype of Neutral Wind Analyzers for MIT will has been tested in May 2014.

3.3 Spacecraft Charging Effects

The conductive surface of a spacecraft in sunlight will charge up due to the combined effects of the plasma environment and the emitted photoelectrons. The spacecraft charge will depend on the spacecraft configuration and on the density and temperature of the plasma environment. Spacecrafts at altitudes of MIT MA/MB are typically positively charged with spacecraft potential values varying in the range of a few volts up to tens of volts. This variable potential would severely limit the capability to measure the velocity distribution of particles at low energies, and it is because of the repelling potential for positive charged particles (ions), energies below the spacecraft potential would be cut-off. With positive spacecraft potential, negative charged particles (electrons) would be accelerated, thus severely distorting electron energy.
spectra at low energies.

The effect of spacecraft charging can be mitigated by an active spacecraft potential control being used, for example, the emission of a positively charged ion beam. Dependent on the plasma environment and the beam current, the spacecraft potential can be controlled. This technique, utilizing an indium beam of about 5 keV, has been successfully used on several missions (Equator-S, Cluster, Double Star TC-1) and is presently implemented for the four spacecrafts of NASA MMS (Magnetospheric Multiscale) mission launched in March 2015[14]. Active potential control will be important for MIT MA/MB and it is planned to implement this technique on MIT MA/MB in an international cooperation with the team that is presently working on the implementation for MMS.

4 Summary

Acceleration and transportation of the outflow ions from ionosphere are key questions in space physics. To answer these questions will not only help the human being to understand the magnetic storm, but also process leading to the exchange of materials between the Earth’s geospace and the interplanetary space. The MIT mission will provide an unprecedented opportunity for scientists to study the upflow ions and their acceleration at different altitudes simultaneously. With the onboard payloads to detect ions and plasma waves, many puzzles related to the outflow ions will be solved.

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