THE SCOPE MISSION

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Abstract

In order to open the new horizon of research in the plasma universe, SCOPE will perform formation flying multi-scale observations combined with high-time resolution electron detection and will enable data-based study on the key space plasma processes from the cross-scale coupling point of view. Key physics to be studied are magnetic reconnection under various conditions, shocks in space plasma, collisionless plasma mixing at the boundaries, and physics of current sheets embedded in complex magnetic geometries. The SCOPE mission is made up of the 5 spacecraft (s/c) formation put into the equatorial orbit with the apogee at 30Re (Re: earth radius). One of the s/c is a large mother ship which is equipped with a full suite of particle detector including ultra-high sampling cycle electron detector. Among other 4 small s/c one remains near (~10 km) the mother ship and the s/c-pair will focus on wave-particle interaction utilizing inter-s/c communication. Others are used for wave-particle interaction study when the distance from the mother ship is small (~100 km) and are used as the plasma monitors at ion-scales when the distance is larger (100~300 0km). There is lively on-going discussion on the SCOPE-M^3 collaboration, which would certainly make the coverage over the scales of interest better and thus make the mission success to be attained at an even higher level.

Key words: Plasma Universe: Cross-Scale Coupling: Formation Flying Observations

1. The science of the SCOPE mission

1.1. Magnetosphere as a typical piece of the plasma universe

Large fraction of the universe is filled by gas in the plasma state. This implies that the magnetic field would be playing significant role in gas dynamics of the universe and there indeed are growing interests in the magnetic effects in astrophysical situations such as the accretion disks. The plasma universe can be characterized by high-energy, large scale dynamic phenomena, and it is these active features that fascinate us.

Earth's magnetosphere is also a typical piece of the plasma universe. The region is formed by the interaction between the solar wind and the planet's intrinsic magnetic field. The solar wind is a stream of ionized gas from the sun and interacts with the intrinsic magnetic field of the planet. Since the solar wind is super sonic, the bow shock is formed in the front side of the magnetosphere. The boundary that separates the shocked solar wind from the region occupied by Earth's magnetic field (magnetosphere) is a velocity shear layer, a current layer, as well as a density gradient layer, that is, full of potential to behave dynamically. In the night side of the magnetosphere, the field lines are highly stretched anti-sunward to form a current sheet across which the magnetic polarity reverses. The anti-parallel field lines are often subject to the process called "magnetic reconnection" via which energy stored as the magnetic energy is released explosively to the plasma thermal and kinetic energies.

Shocks, boundary layers, and magnetic reconnection are ubiquitous in the plasma universe. On the other hand, the magnetosphere is the only place where detailed observations of these physical processes can be obtained. The solar corona is another piece of the plasma universe. Solar observations do provide us with nice graphical presentation of explosive phenomena in the solar corona, in which magnetic reconnection is playing a crucial role. It is, however, only in the magnetosphere that detailed in-situ data of the phenomena can be obtained. Understanding activities caused by large scale reconnection jets in the night side of the magnetosphere (magnetotail) is one of the most fascinating branches of magnetospheric physics. From the data obtained in-situ in the magnetotail, we are beginning to understand how the ion particles are energized in the reconnection process. Embedded at the origin of the large scale reconnection jets is the engine part in which electron scale dynamics dominates. In the SCOPE mission we will observe simultaneously the electron-scale process inside and MHD-scale dynamics outside of the reconnection engine, which precious information on the "cross-scale coupling" would never be obtainable anywhere else, nor by any other mission.

1.2. Magnetosphere as a precious field for the study of the plasma universe

In trying to construct the true understanding of the plasma universe, detailed observations are not only better but are essential. The reason for this is that the plasma gas filling the plasma universe is in a state that is beyond our common sense. Unlike the ordinary gas that surrounds us, space plasmas are mostly in "collisionless" state, where constituent particles do not collide with each other but interact with each other solely via electromagnetic fields.

The collisionless-ness sets the thermo-dynamical relaxation time scale to be much larger than the dynamical time scale and that there is no usual dissipation process that we take for granted. The non-Maxwellian distribution function is everywhere. Non-thermal particles are not necessarily minor and are not just test particles that only react to given electro-magnetic fields but can play a significant role in determining the time evolution of the system. Energetic particles are everywhere in the plasma universe because they don't lose their energies by colliding with the less-energetic thermal component. Explosive phenomena occur because usual relaxation processes are absent and the dissipation processes that trigger them show anomalous behaviors.

All these fascinating aspects of space plasma dynamics have their roots in this collisionless-ness of the plasmas. If we really are to understand the behavior of space plasmas, we would ultimately have to have the way of description with kinetic effects fully taken into account. Observational data that directly supports effort of this kind is particle data (velocity space distribution function data) obtained in-situ at the site of the phenomena. Electric and magnetic field data are also essential in understanding the dynamics of the particles. In any case it is only in the magnetosphere that these data can be obtained.

1.3. Cross-scale coupling in collisionless space plasmas

Our interest in the magnetospheric dynamics is often biased towards large scale phenomena that have global impacts. When the overall spatial scale of the process is larger than the ion scales (ion inertial length or ion Larmor radius), it has been said that the MHD equations is a good enough approximation to describe the long term behavior of the system. There is no denying the usefulness of the MHD equations as a starting point of discussion. This, on the other hand, does not mean that describing the magnetospheric dynamics by the MHD equations in the present form is the ultimate goal of our research. This should be the same in the plasma universe research context, in which understanding the particle acceleration process is often listed as one of the most important research goals.

We have seen that the fascinating aspects of magnetospheric processes root in the collisionless-ness of the plasma. There is no usual dissipation that will smear out the dynamics at small scales. In a dynamic situation the energy input from a MHD-scale dynamics would cascade down to and give birth to smaller-scale dynamics at sub-MHD (ion and electron) scales. The sub-MHD dynamics often have substantial kick-back to the parent large-scale dynamics. In other words, the true understanding of what we are attracted to comes only when the effects of parasitic sub-MHD scale dynamics are appreciated, that is, only when the collisionless effects (kinetic effects or particle effects) are fully appreciated. MHD system in the present form treats sub-MHD scale dynamics only in an ad-hoc manner by stretching our common sense based on our experience with collisional gases, and that very likely by stretching it out of its validity. Previous studies on kinetic effects mostly dealt with only sub-MHD scales isolated from larger-scale dynamics in an effort to estimate a transport coefficient resulting from the sub-MHD phenomenon alone. This traditional research style has been to summarize the sub-MHD scale effects into a transport coefficient (viscosity, resistivity, ...) and add the term to the MHD equations. One can easily argue that, while this may be good in a collision dominated situation, this form does not necessarily fully appreciate the wonder of the collisonless plasma.

It is the dynamical coupling among the scales, from the bottom of electron-kinetic up to MHD, that the new perspective on the plasma universe should focus upon. In space plasmas, in the absence of usual dissipation, the coupling among the scales is dynamic and we should search for a description style that features the dynamic nature of the cross-scaling coupling in space plasma dynamics. Equipped with new instruments that enable us to inspect magnetospheric dynamics with this new perspective, anywhere in the dynamic magnetosphere turns into an untouched region showing us wonders and providing us with new findings of collisionless plasma physics. With these new data-based inputs we will be able to step forward and to build a truly fundamental understanding of the magnetospheric dynamics. Then we will go on to contribute in establishing the new framework to describe the plasma universe. The magnetosphere is the only field where precious in-situ data that unveil the physics of the plasma universe can be obtained. Without the new mission led by the new perspective, the magnetosphere remains as a virgin land with treasures waiting forever to be dug out.

The SCOPE mission is designed such that observational studies from the new perspective, that is, the cross-scale coupling viewpoint, are enabled. The orbit is so designed that the s/c will visit most of the key regions in the magnetosphere, that is, the bow shock, the magnetospheric boundary, the inner-magnetosphere, and the near-Earth magnetotail. In the following, we pick up the topic of magnetic reconnection and overview some of the past key results that led to this mission concept. The key issues are (1) need for high-time resolution electron measurements and quantitative wave field measurements at electron scales, (2) need for full coverage over the energy range of interests, (3) the powerfulness of the formation flying observations, and (4) need to resolve more than one-scale at a time.

1.4. Magnetic reconnection in the near-Earth tail

Magnetic reconnection is one of the most important processes in the plasma universe. In the process, the field lines separated across a current sheet is re-connected. This causes the change in the field line topology. It also converts the energy stored in the magnetic energy into the plasma kinetic energy, which is the conversion from an invisible form into a visible form, and thus is the origin of various explosive phenomena in the plasma universe. In the magnetosphere, there are three primary regions where the process is operative: the boundary of the magnetosphere (magnetopause), the distant magnetotail, and the near-Earth magnetotail. The field line topology aspect of the reconnection process is important in the former two regions. It is by these processes that the basic structure of the magnetosphere is maintained and by which the solar wind plasma is flowing into the magnetosphere. On the other hand it is its explosive nature of reconnection in the near-Earth tail, which causes a pair of plasma jets to be emanated earthward and tailward from the reconnection region, that makes it one of the highlight phenomena of the magnetospheric dynamics.

One of the most prominent achievements of the Geotail mission (ISAS-NASA, 1992$\sim$) is that it revealed the ion-scale structure surrounding the reconnection region (X-line). X-line is the engine part of the reconnection process where the MHD approximation totally breaks down. Far away from the X-line, the plasma will eventually behave not far from what the MHD theory describes. At ion-scales surrounding the X-line, which is not far enough away from the X-line, the plasma behavior still deviates from the MHD description. This is indeed required to keep the reconnection process running. At the ion-scale essentially the electrons run faster than the ions and the resultant electromagnetic force accelerates the ions, which eventually becomes to constitute the plasma jets. What Geotail observations revealed are (1) identification the current loop surrounding the X-line indicating differential motion between ions and electrons, (2) identification of the current carrier at the kinetic level (velocity distribution function level), and (3) identification of the ion acceleration process at the kinetic level. These achievements owe very much to the properties of the orbit that was set so nicely that the s/c spent more than half of the time within the plasma sheet when the apogee was in the nightside.

In some cases, Geotail s/c went through the middle of the X-line where electron-scale dynamics is dominant. The data shows significant heating of electrons as well as very high activity of plasma waves. That is, there is ample circumstantial evidence of electron-scale dynamics to be operative at the X-line but proceeding further with the data is prohibited by the low-time resolution of the electron particle data.

True understanding of magnetic reconnection process is one of the most significant issues in the plasma universe research. The next generation mission revealing the electron-scale dynamics at the X-line needs to have high-time resolution electron data and fully quantitative plasma wave data. To see how the particles are energized in the process, the particle detectors need to have full coverage over the energy range of interests. To see the physics at the X-line and its larger-scale consequences at the same time we need to have measurements at the locations separated by the ion-scale and by the MHD-scale from the X-line as well. 3-component DC E-field measurements are crucial in inspecting the ion-scale dynamics. To be optimized for the near-Earth tail reconnection study the apogee of the orbit must be at $\sim$30 Re and in the tail-box in the midnight meridian.

1.5. Large-scale full-particle simulations on quick magnetic reconnection triggering

The current sheet in the magnetotail is the site for explosive magnetic reconnection, in which various magnetospheric activities are considered to originate. Magnetic reconnection in a fully developed phase has been recently studied extensively by the Geospace Environment Modeling (GEM) magnetic reconnection challenge project. While the GEM project has revealed an important aspect of two-dimensional (2-D) magnetic reconnection, the questions of spontaneous reconnection triggering and of the non-linear state that emerges out of it have been left open. Especially, we should consider how an ion-scale current sheet would become subject to reconnection triggering, for current sheet thickness observed in the magnetosphere is of this order or even thicker. One of the candidates to initiate reconnection is the tearing instability, however, we have found that there is a critical thickness above which significant effects of the instability are not available and that the critical thickness turns out to be of electron-scale. While this critical thickness severely limits the ability of the two-dimensional tearing mode for triggering quick reconnection, we have also recently shown that the tearing mode survives as a viable process via three-dimensional cross-scale coupling. We have shown that, even if the current sheet thickness is of ion-scale, large scale reconnection is triggered very quickly. The definitive contrast between 2- and 3-D results comes from the difference if the lower-hybrid-drift instability (LHDI) is allowed or not. Only in the 3-D case the freedom in the current direction is included and LHDI is allowed to develop around the outer edges of the current sheet. LHDI at the outer edges induces non-local redistribution of current density within the current sheet that leads to the quick reconnection triggering (QMRT). The triggering is attained as soon as LHDI is saturated and is very quick even for an ion-scale current sheet. It is also emphasized that QMRT is obtained via non-local, cross-scale coupling with LHDI and is not something that can be modeled as a current driven anomalous resistivity.

Recent large scale simulations show that cross-scale coupling almost always appears in large-scale dynamic phenomena and produces the fascinating effects of collisonless space plasmas. Numerical simulations are quite a powerful tool in investigating the basic mechanisms and there will be many sub-MHD-scales-included simulations of local MHD processes in idealized situations that will reveal the wonder and the significance of cross-scale coupling in space plasmas. In the foreseeable future, however, simulations will never be free of limitations. Nice simulation results that will indicate unpredicted effects of cross-scale coupling processes will not solve the problem to the ultimate end but will enhance the need for the SCOPE mission that will enable data-based study on cross-scale coupling processes and that will prove that the wonder truly exists in the real world. The better the simulation results are, the more indispensable the SCOPE mission is towards the true understanding of the plasma universe.

2. The mission strategy

The SCOPE formation flying observations will enable measurements of more-than-one scale at a time and thus investigation into the coupling among the scales. The SCOPE formation consists of 5 s/c. The mother s/c is the large s/c and is capable of 10 msec electron detection. The near-daughter will stay within 10km from the mother to team up with it to focus on the wave-particle issue. 3 far-daughters will study physics at electron scales when the distance from the mother is small (<100 km: Phase 1) and will monitor plasma environment at ion scales when the distance is made larger (>100 km: Phase 2). The key regions to be visited by the s/c are the bow shock, the magnetospheric boundary, the inner-magnetosphere, and the near-Earth magnetotail. These are most of the key regions in the magnetospheric physics and are the regions which host fundamental plasma dynamics that have implications to our understanding of the plasma universe. In the SCOPE mission the key dynamics in these key regions will be inspected from the cross-scale coupling viewpoint.

2.1. Scientific instruments highlight

Fast electron detector. In order to understand the coupling among the scales up from the electron scales, super high time resolution electron measurements in the energy range a few eV$-$40keV is indispensable. So far, electron distribution functions have been measured with the time resolution of the order of a second in the Earth's magnetosphere. There are few other exceptional cases where electron pitch angle anisotropy is observed with time resolution of the order of 10 msec. However, for SCOPE mission, it is mandatory that fully 3-D electron velocity space distribution function be measured with 10msec time resolution. This super high time resolution electron spectrometer has to have large enough geometrical factor for measuring tenuous electrons near reconnection region while keeping its weight and power within acceptable range as a spacecraft borne instrument.

Medium energy particle detector. It is well known that electrons and ions are accelerated to $\sim$ 100 keV range around reconnection region in the Earth's magnetotail. However, their acceleration process is not yet well described due to insufficient time resolution of the medium energy range (10keV/q $\sim$ 200keV/q) electron and ion measurements. Acceleration efficiency would depend on the ion mass pointing to the need to identify the ion species. This is very true in the inner-magnetosphere where 10$\sim$100 keV ions of various species are the dominant pressure carrying constituents. To step ahead with the cross-scale coupling formulation of the physics of this region, identification of ion species and the energy spectrum is the first and the crucial step. For the SCOPE mission, new electron and ion medium energy range spectrometers with time resolution of the order of a spin period (several seconds) are required. Ion medium energy range spectrometer has to have quite a large geometrical factor so that ion mass spectrometry is possible while the total size should be kept as small as possible.

Spin-axis electric field antenna. Three component measurements of wave electric fields are essential in the present mission to realize the quantitative study of wave-particle interactions. While the antennas for the detection of electric fields on the s/c spin plane are the long wire antennas with well-matured deployment system, the measurements of the third E-field component requires the spin-axis antenna, which is very critical. Since the dynamics of the spin-axis antenna are coupled to the s/c dynamics, it should be very stable during/after its deployment. The total weight including its deployment and stabilizer system for the antenna becomes easily large while the weight budget of s/c is always limited. In the current planning, a pair of 10m tip-to-tip spin-axis electric field antenna is under consideration and the test product proves that it is realized with the weight less than 1kg.

Wave-wave correlation analyses. Wave-particle interaction constitutes the channel via which cross-scale coupling from larger-than-ion scales to sub-ion scales is established. The Wave-Form Capture (WFC) receivers are installed on all the SCOPE s/c to make quantitative study on this issue. The observed waveforms contain the information on their phases as well as their amplitudes. With the accuracies on the relative distance and onboard time counters given, the wave-wave correlation analyses allow us to identify the spatial distribution of the wave source region and of wave energy flows by examining Poynting vectors and wavenormal vectors. Furthermore for electrostatic waves, the WFC receivers located in 5 different points would show the 3 dimensional potential structures in the different scales, one being the scale between mother s/c and near-daughter s/c, and the other being the scale between mother s/c and far-daughter s/c. The scale between mother s/c and near-daughter s/c is almost of the order of the electron Debye length. The scale between mother s/c and far-daughter s/c is beyond the electron Debye length. The simultaneous observations of these two different scales provide us with fruitful information on electron dynamics taking place in the space surrounding the fleet of SCOPE s/c.

Three-component DC E-field measurement. Accurate measurements of electric fields are essential for space plasma studies especially when we are concerned with the scales. One typical measurement techniques is the 'Double Probe method', which measures the potential difference between two probes. The two E-field components in the spin plane can be measured by the long wire antennas on the s/c spin plane, which is a well-matured system. The spin-axis antenna for detecting the wave E-field is planned, however, the antenna length is too limited to guarantee the accuracy of the DC E-field measurements, especially in the plasma regions with a large Debye length. Our strategy to detect three-component DC electric field is to utilize the mother and the near-daughter pair. We tilt the the near-daughter spin axis to the sun. Then the mother spin-plane antenna detects in-plane components, say, X and Y components, and the near-daughter spin-plane antenna detects the Y and Z components. Since the separation between the mother and the near-daughter is negligible in the ion-scale measure, this assures first continuous, stable, and well-accurate ion-scale DC electric measurement in the whole key regions in the magnetosphere.

2.2. Key roles of each spacecraft

Mother. This large s/c will make 10 msec time-resolution electron detection, the key measurements that enable investigation into electron scales. With the new instruments covering the 10-100 keV energy range, particle measurements with full coverage over the energy range of interest will be made. Wave-particle correlator that focuses on revealing the electron interaction with high frequency waves is also installed onboard. This s/c will be handling the data obtained by, and relaying the commands from the ground to, the daughter s/c in Phase 1.

Near-daughter. This small s/c will stay close to the mother s/c, that is, inter-s/c distance will stay < 10 km. The attitude of this s/c is such that the spin axis will point to the sun. This makes accurate measurements of the vertical DC E-field component possible. Since the distance from the mother s/c is negligible in ion-scale unit, 3-components of ion-scale DC E-field are obtained by combing the E-field data from the two s/c. 3 components of E and B wave fields are measured, allowing us to make quantitative analyses on the wave-particle interaction issue.

Far-daughter. When the inter-s/c distance is small (<100 km: Phase 1), far-daughters are also devoted to electron-scale measurements by utilizing curlometer technique and by focusing on the wave-particle interaction issue. When the distance is large (>100km: Phase 2), they become the ion-scale plasma monitors that have the time resolution of ~ 3 s.

2.3. Orbit and formation

Orbit. The orbit is equatorial with the apogee at 30 Re geocentric distance. The latitude has to be controlled so that the s/c are in the tail-box at the apogee on the midnight meridian plane. The apogee distance and the tail-box issue are the crucial issues to increase the interval for the s/c to stay in the plasma sheet and to enhance the scientific return of the mission. The key regions to be visited by the s/c are the bow shock, the magnetospheric boundary, the inner-magnetosphere, and the near-Earth magnetotail, whose key dynamics will be inspected from the cross-scale coupling viewpoint. The current planning sets the perigee at the altitude of 7000km, which require least fuel to keep the formation shape (The perturbation sources are the J2 term of the Earth and the gravity of the Moon).

Attitude. The spin rate for all the s/c is 3 sec. The mother and the far-daughters have their spin axes orthogonal to the orbit plane. The near-daughter will have its spin axis pointing to the sun. This realizes uniform sun-lit condition which is crucial for the accurate measurements of the E-field component in the north-south direction.

Formation shape. The mother-far-daughter formation shape should be close to regular tetrahedron in the proximity of the apogee, which is the best shape for obtaining the spatial derivatives. Our study shows that the formation stays in good shape along about half of the orbit encompassing the apogee without any control by thrusters, implying that scientifically significant target regions encountered off the apogee can still be studied by making full use of the merit of formation observations.

Inter-s/c distances. The distance between the mother s/c and the near-daughter is < 10km. In Phase 1 the inter-s/c distance between the mother s/c and the far-daughters are $\sim$100km. Thrusters onboard far-daughters are used to extend it to $\sim$1000km in Phase 2.

Distance measurement and time-synchronization. To meet the scientific objectives of the inter-s/c correlation study on electron dynamics and related wave-particle interactions, high accuracies are required in synchronizing onboard time counters of each s/c and in determining relative distance between each s/c (in Phase 1). The accuracy of the onboard time counters is required for the correlation analyses of propagating waves or flowing electrostatic potentials. The necessary accuracy is estimated to be 5 micro-sec when the mother-daughter separation is 5km based on the expected maximum flow velocity of solitary potential structures $\sim 10^4$ km/s observed in the plasma sheet. On the other hand, the relative error of the inter-s/c distance determination is required to be less than 1% of the mother-daughter separation in order to guarantee the accurate determinations of wavelength or spatial scale of the phenomena. Our study shows that this is doable with a reasonable instrumentation in Phase 1.

2.4. Inter-spacecraft communications

During Phase 1 when the separation distance between the mother and daughter s/c is ∼100 km, all the observation data of the daughters are transferred through the mother s/c. The current planning sets the X band telemetry rate between the mother and the ground at 4 Mbps because of the legal restriction. Since the expected data production rate of the full-resolution mode is ∼60 Mbps, only a part of the full-resolution data can be transferred to the ground. Therefore, a highly efficient data selection technique is necessary. The best way is that all the full-resolution data obtained from each s/c are once gathered into the mother and interesting events are selected by inspecting all the data with the mother s/c CPU. However, the telemetry rate between the mother and the daughters is so narrow, ∼40 kbps average for each daughter at the separation distance of ∼50 km in the present planning, that abandoning the transferred data to the mother s/c, which is indeed costly, by a selection algorithm is not reasonable. Given the fact that the total telemetry band width between the mother and the daughter s/c is narrower than that between the mother and the ground, the dataset once gathered into the mother s/c should be transferred to the ground. With this in mind, we have the following scheme to handle the huge dataset obtained by the high-time resolution observations with limited resources available.

Burst trigger. The data that is worth of the transfer to the mother s/c must be selected beforehand. The data selection must be done by each s/c individually. Hereafter, the selected data is called “burst data”. When a s/c detects an event that satisfies some selection criteria, high time resolution data are recorded. After the event only the time-tags of the burst data interval are transferred to the mother s/c. After the event collecting interval, the mother s/c makes the list of events with the priority ranking attached. Then the data from the events with higher ranking is transferred from the daughters to the mother.

Data storage. The event selection and the data transfer scheme described above requires large volume data storage to be installed on each s/c. Our current planning puts ∼1 GB HDD (or memory) onboard daughter s/c while 100GB HDD onboard the mother s/c. Testing of HDD is already being conducted.

Commanding. During Phase 1 all the commanding to the daughter s/c is issued via the mother ecause the separation of the s/c in terms of view-angle from the ground is too small for individual commanding to be possible.

Phase 2. During Phase 2 when the separation distance between the mother and daughter s/c is ∼1000 km, all the data transfer are done individually from each s/c to the ground. No cooperative data selection procedure is performed because the inter-s/c communication link is unavailable. Every s/c is treated independently in terms of commanding.

3. Notes on SCOPE-M^3 collaboration

It is obvious that the SCOPE mission and the M^3 concept (see the report in this volume) are aiming at essentially the same goal. This is not surprising but only implies that these ideas somewhat point to the next natural step of the space plasma physics mission. On the other hand, the mission concept is demanding and it would be nice if the two missions can be combined together to reach for an even higher mission success. In this sense, we are happy to note that there is lively on-going discussion regarding the possibility of the inter-agency collaboration.

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