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Space weather explorer – The KuaFu mission

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Abstract

The KuaFu mission is designed to explore the physical processes that are responsible for space weather, complementing planned in situ and ground-based programs, and also to make an essential contribution to the space weather application. KuaFu encompasses three spacecraft. KuaFu-A will be located at the L1 libration point and have instruments to observe solar extreme ultraviolet (EUV) and far ultraviolet (FUV) emissions and white-light coronal mass ejections (CMEs), and to measure radio waves, the local plasma and magnetic field, and high-energy particles. KuaFu-B1 and KuaFu-B2 will be in elliptical polar orbits chosen to facilitate continuous (24 h per day 7 days per week) observation of the northern polar aurora oval and the inner magnetosphere. The KuaFu mission is designed to observe globally the complete chain of disturbances from the solar atmosphere to geospace, including solar flares, CMEs, interplanetary clouds, shock waves, and their geo-effects, with a particular focus on dramatic space weather events such as magnetospheric substorms and magnetic storms. The mission start is targeted for the next solar maximum with launch hoped for in 2012. The initial mission lifetime will be 3 years. The overall mission design, instrument complement, and incorporation of recent technologies will advance our understanding of the physical processes underlying space weather, solve several key outstanding questions including solar CME initiation, Earth magnetic storm and substorm mechanisms, and advance our understanding of multi-scale interactions in and system-level behavior of our Sun–Earth space plasma system.

Keywords: KuaFu mission; Space weather science; Heliospheric physics; Geospace physics; Solar-terrestrial relations

1. Introduction

Space weather refers to the conditions on the Sun, in the solar wind, and in the geospace, that can influence the performance and reliability of space-borne and ground-based systems. Modern "hi-tech" society is increasingly vulnerable to disturbances from outside our Earth system, and in particular to those initiated by explosive events on the Sun. The economic consequences are enormous (see, e.g., Siscoe, 2000; Baker, 2002). Understanding and predicting space weather is important for space exploration (including manned space flight) and the economic exploitation of space.

Space weather phenomena are controlled by universal physical processes that are not fully understood. These universal physical processes include transient evolution of magnetic structures such as flares, coronal mass ejections (CMEs), substorms and storms and the sudden magnetic energy release such as reconnection, acceleration, and heating, which also control the plasma universe. The space weather events taking place in the Sun–Earth system provide a chance to study these universal processes and contribute to the development of the basic science.

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To understand the underlying physical processes demands on heliophysical and geospace observations. Clearly, in order to understand the pathways by which energy and mass make their way from the Sun to the Earth environment, we have to monitor the source. Thus, quantitative and continuous synoptic observations of the primary sources of the events on the Sun are essential. It is equally clear that we need contemporaneous long-term quantitative synoptic observations of the various sinks in geospace which are affected by the output from the Sun. It is also important for a mission to provide in situ quantitative observations of parameters of physical processes such as magnetic reconnection, macroscale instabilities, convection, and wave-particle interactions that affect how energy and mass make their way through geospace. The previous and ongoing explorations, which have involved SOHO, ACE and Wind near the L1, Cluster, Double Star, Polar, Geotail, and IMAGE flying in Earth orbit have made fruitful observations from the solar atmosphere to the geospace.

These observations show a time sequence of the space weather events. Based on some statistical phenomenological linkage, several theoretical models have been developed for understanding the energy and mass transport during the major events, such as flares and CMEs, sub-storms and storms. However, it is difficult to prove or disprove these models due to the limitations of previous observations. Although SOHO spacecraft has made plenty observations on the solar flares and CMEs from chromosphere to the distant corona, in most cases it is impossible to trace an event from its source to the developed phase. Cluster, Polar and Geotail have provided first ever signals of magnetic reconnections in geospace. However, the questions about how these reconnection events relate with the energy transfer from the solar wind to the magnetosphere and the energy release in the magnetosphere are still waiting to be clarified.

It is clear that, for discovering the underlying physical processes which control the space weather explosive events, we need observations of consecutive chain of events from the Sun to the geospace with emphasis on the global images to track their development with time and space continuously. The present satellites in service can not provide this kind of observations and are now well past their nominal lifetimes. The planed missions for the near future, such as the solar missions STEREO, SOLAR-B, SDO, Solar Orbiter and the geospace missions SWARM, THEMIS, MMS and RBSPs, and ITSPs are not for this purpose. A new Sun–Earth mission is badly needed.

The proposed "KuaFu Space Weather Explorer" (Space storms, Aurora and Space Weather Explorer) is perfectly suited to meet the present needs of space weather science. The name "KuaFu" is drawn from an ancient Chinese myth, in which Mr. KuaFu was said to insist on running to catch up with the Sun's movement on the sky. The KuaFu mission is an "L1 + Polar" triple satellite project composed of three spacecraft: KuaFu-A, KuaFu-B1 and B2. The mission is designed to observe globally the complete chain of disturbances from the solar atmosphere to geospace, including solar flares, CMEs, interplanetary clouds, shock waves, and their geo-effects, such as magnetospheric sub-storms and magnetic storms, and auroral activities in general. The KuaFu mission will observe the mass and energy inputs and outputs of the Sun–geospace–Earth system in a systematic way.

KuaFu-A will be located at L1 and have instruments to observe solar EUV, FUV and X-ray emissions and white light CMEs, and to measure radio waves, the local plasma and magnetic field, and high-energy particles. KuaFu-B1 and KuaFu-B2 will have a polar orbit appropriate to observe for 24 h a day the north polar auroral oval, the local magnetic field and high energy particles (see Fig. 1). The instruments will also make use of new technologies to allow new fundamental science. The scientific definition team intends for the start date to be near the next solar maximum (ideally in 2012), and that it should have a lifetime of three or more years. KuaFu data will be used for the scientific study of physical processes at the heart of

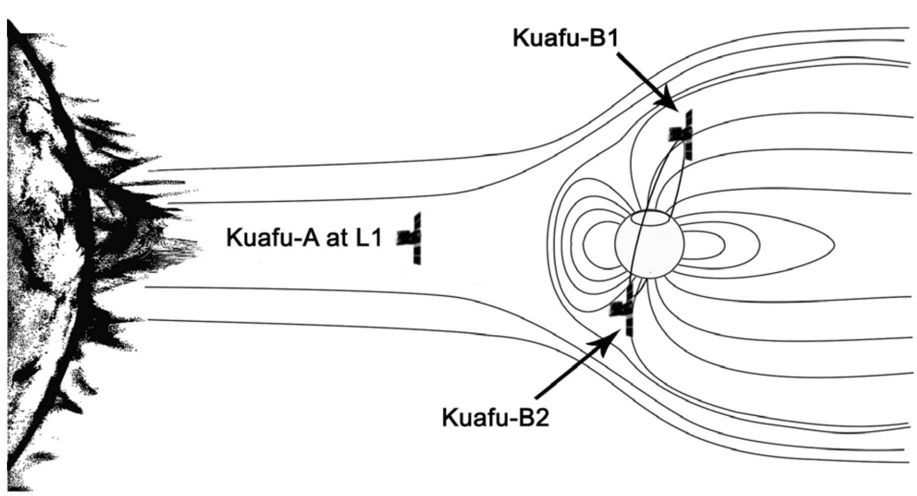

Fig. 1. Heuristic illustration of the proposed three spacecraft of the KuaFu mission (for more details see text).

space weather, and for space weather monitoring and forecasting purposes. KuaFu will be a mission utilizing robust instruments with proven heritage and reliable data transmission. It will provide an excellent complement to the forthcoming scientific solar and geospace missions mentioned above.

The KuaFu "pre-study" has been supported as a key project of the National Natural Science Foundation of China (NSFC) since 2005. KuaFu project is included in the ILWS program. The pre-study is carried out as collaboration by an international group of scientists. A comprehensive review on the overall mission system including scientific goals, scientific instruments, technical feasibility and financial budget which is required and supported by China National Space Administration (CNSA) is now being carried out.

In Section 2, we will describe the scientific goals of the mission including the frontier space weather science in the inner heliosphere (Section 2.1), the frontier space weather science in geospace (Section 2.2) and the frontier space weather science in the Sun–Earth relations (Section 2.3), thus highlighting the contributions KuaFu may make to heliospheric physics, geospace physics, and the connection between the two. In each of those subsections, we first summarize the previous observations and their limitations in terms of studying space weather processes. We then describe the unsolved science issues. We complete each subsection with the necessary novel measurements, and the related instruments on KuaFu and the new design of the KuaFu-B orbits. In Sections 3 and 4, we will describe in more details the instruments proposed for KuaFu.

2. Mission goals – space weather science and new science objectives

The KuaFu mission goals are composed of three principal science objectives. The first two objectives related to the Sun and geospace will be described in Sections 2.1 and 2.2, respectively. The third objective targeting the coupled Sun–Earth system will be described in Section 2.3. In each of the subsections, we point out the novel observations that must be made to facilitate meeting the objectives we have set for the mission, as well as the scientific and technical firsts that we expect from the new observations.

2.1. Frontier space weather science in the inner heliosphere: precursors, initiation, evolution, and propagation of CMEs

Since space weather phenomena are powered by the Sun, solar observations play a key role for analyzing and forecasting space weather (Webb et al., 2001; Schwenn, 2006). KuaFu-A serves two basic purposes: the support of fundamental research in order to understand the solar processes and basic space-plasma physics that drive solar storms, and the continuous surveillance of the Sun and heliosphere (see Fig. 1).

2.1.1. The basic science issues of space storm in the inner-heliosphere

Solar energetic transients such as flares, CMEs and their associated phenomena, have always attracted the attention of the solar physics community. Flares were first observed in 1859 (Carrington, 1860). Since then, it was established that solar activities are linked with the episodic phenomena we call geomagnetic storms. This was first elucidated by the pioneering work of Chapman and Ferraro (1930), who postulated that transient eruptions of material from the Sun interacted with the terrestrial magnetic field leading ultimately to magnetic storms. CMEs as a new type of dramatic solar activity were directly verified in the early 1970s. In 1973, the white-light coronagraph on board Skylab found several cases of fast expansion of large bright loops with sizes of several solar radii. The project expansion speed was usually around 500 km/s, but could in some cases exceed 1000 km/s. Huge amounts of mass were ejected and energy released from the solar atmosphere into space. These most dramatic processes were thus called coronal mass ejections (CMEs). A central question in this field is about how the huge mass is ejected against both solar gravity and the confinement to closed magnetic loops, and how it is finally accelerated.

Various theoretical and numerical models have been presented to explain the formation of CMEs (see a review by Zhang and Low, 2005). Among these models there are two paradigms: the breakout and catastrophe models. In the breakout models magnetic shearing is considered responsible for adding energy to the pre-eruption structure. Magnetic reconnection is assumed to play a key role and to allow the stored energy to be released (Antiochos et al., 1999; Su and Su, 2000). These models may explain some CMEs. In the catastrophe models the magnetic energy is built up in a pre-eruption flux rope (Forbes et al., 1994; Hu et al., 2003; Lin and van Ballegooijen, 2002). When the force balance is lost the flux rope expands outwards and magnetic reconnection just enables further outward expansion and escape. Chen and Shibata (2000) presented an emerging flux triggering model. The reconnection of the emerging flux with the pre-existing field destroys the force balance of the pre-eruption structure and hence leads to eruption. Zhang et al. (2006) introduced a pre-eruption quadrupole magnetic field into a catastrophe model and obtained both horizontal and vertical current sheets, which could possibly explain the mechanism resulting in both flares and CMEs in one explosive event.

Both fast and slow CMEs have been described by a unique model developed by Zhang and Low (2004) and Low and Zhang (2002). According to their model, the fast CMEs are originating from the pre-eruptive normal polarity prominences and the slow CMEs from the inverse polarity prominences. The normal and inverse polarity prominences are discriminated by whether the horizontal magnetic field at the bottom of the magnetic rope supporting the prominence has the same or opposite directions with respect to the underlying photospheric magnetic fields

(Leroy, 1989). However, some other models (Chen and Krall, 2003; Lin, 2004) do not require this specific relationship.

Although the latest generation of space-based instruments has allowed us to make major advances in our understanding of the processes involved near the Sun, in interplanetary space, and in the near-Earth environment (see Fig. 2), the physical processes underlying CMEs have, even after more than 30 years of study, not been fully revealed due to the limitations of the available observations. This resulted in the situation that space weather forecasting is still in its infancy. We have to admit that predicting even the most dramatic energetic solar transients such as flares and CMEs is still beyond our capabilities. The basic questions are as follows:

(1) Progenitors and precursors

What are the CME precursors? How is the energy and mass stored in the pre-eruption structures? Solar energetic transients, i.e., flares and CMEs occur rather unwarnedly, and we have not yet identified unique signatures that would indicate an imminent explosion and its probable onset time, location, and strength.

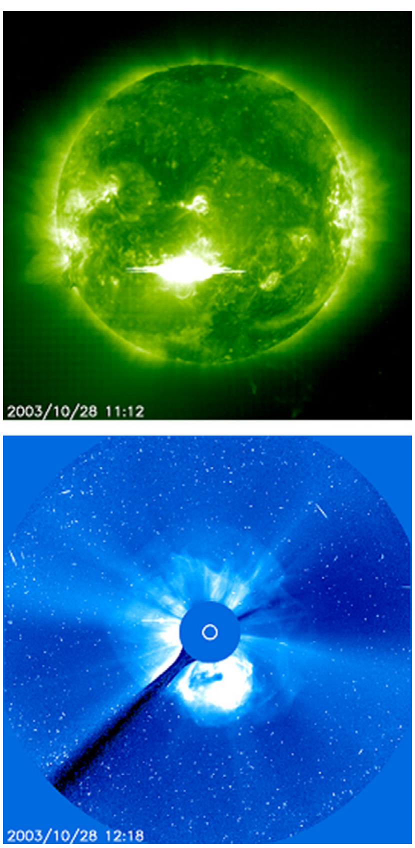

Fig. 2. One of the most dramatic space weather disturbances in the past solar cycle was caused by the X17 flare and the halo CME of 28 October 2003, as seen by the SOHO instruments EIT (top), and LASCO C3 (bottom). This spectacular event caused major disturbances of space weather and affected the Earth system in various ways: charged particles were accelerated to near-relativistic energies, such that they could penetrate spacecraft skins and disturb electronics, e.g., the CCD cameras on SOHO and other satellite instrumentation, an extremely fast interplanetary shock wave was initiated that reached the Earth only 19 h later, a severe geomagnetic storm (Dst −363 nT) was launched, with bright aurora even all over Europe and the US, several technical systems on Earth orbiting satellites and on ground were affected.

(2) CME initiation

How is an eruption triggered from such a structure? How and where does the magnetic reconnection actually take place? What is the relation between flares and CMEs?

(3) CME evolution and transport

How is the energy released from the magnetic field? How is the mass about 10^{15}–10^{16} g mass of plasma supplied to CMEs? How are the CMEs accelerated? How are the CME ejecta transported in collisionless magnetized plasma? How are the particles accelerated? We do not understand why the frequently observed pattern, i.e., three distinct structures that are seen in the white-light coronagraph images, disappears in the magnetic clouds, which are considered as the backbone of ICMEs – the interplanetary counterparts of CMEs.

All these basic questions concern the universal processes which control the origin, evolution, and propagation of CMEs.

Since the high speed streams of the solar wind may result in recurrent magnetic storms, fast solar winds also influence the space weather conditions. The origin of the solar wind is still a basic issue of the space physics (Fisk, 2003; Tu et al., 2005; Marsch, 2006). Some universal process, such as magnetic reconnection, non-collisional plasma heating and acceleration, are also considered as key processes which control the solar wind origin. In the paradigm suggested by Tu et al. (2005), the solar wind originates in corona funnels with mass and energy supplied by the magnetic reconnection of loop structures inside the network cell driven by the supergranule convection. In the paradigm of Fisk (2003), the large loops across the network cell play an important role. The real processes of the solar wind origin also need to be identified from the future observations.

2.1.2. Required novel measurements

To answer the question of which theoretical model can best describe the real CME processes on the Sun, we need to test the different model assumptions and results with observations. However, this is difficult to do with the present observational data. The major difficulties in CME studies come from the three following observational limitations.

First, the CME phenomenon was mainly observed by white-light coronagraphs (with the solar disk being occulted) and by EUV imagers (with the solar disk images being obtained in coronal EUV lines) like LASCO and EIT on SOHO. It is difficult to trace the CMEs' dynamic evolution continuously from the source on the disk to the corona by using just these two types of observations. Only in some cases, when the source region was on or near the solar limb, could the EIT and LASCO C1 images together be used to identify the source region without making an extrapolation (Zhang et al., 2001, 2004). These authors found that CMEs have their important acceleration phase within the first few solar radii. Unfortunately, LASCO C1 has only been working during the period from January 1996 to June 1998, when the Sun was in a relatively quiet period, and therefore not many CMEs could be traced in this way. Second, almost all previous CME observations on the solar disk and in the corona have been made without using spectral diagnostics and with by no means adequate temporal resolution. Thus, no information about the line-of-sight velocity of the source structure was simultaneously available. Third, the magnetic field vector in CME structures nor in the corona in general cannot yet be measured. Therefore, the CMEs' magnetic topology and in particular its changes due to reconnection processes as assumed in some models can still not be verified observationally. These three observational limitations have in the past made it difficult to identify clearly the source signal and initiation process of CMEs. To make a breakthrough in the study of CMEs the following novel measurements are proposed for KuaFu-A.

(1) To identify the precursors and source regions of CMEs

It is necessary to identify on the Sun the unique signatures indicating eruptive magnetic activity and the associated outbursts of radiation (photons and particles), and moreover to determine most precisely onset time, location, and strength of such activity. This applies especially to CMEs which were recently shown by Tripathi et al. (2004) to be closely related with bi-polar active regions (AR), concerning, e.g., their intrinsic magnetic helicity, source location on the Sun, and frequency distribution over the solar cycle. The basic ultraviolet radiation characteristics of eruptive arcades should be observed, as they can be used as tracers of the plasma dynamics in the CME source regions. To monitor exploding ARs, or prominences that are prone to instability, and subsequently the post-eruptive arcades is an important new science objective for KuaFu-A.

(2) To get information on the line-of-sight velocity of the source structures

Once a notable outbreak has actually been observed, it is still hard to predict whether the ejected gas clouds will reach the Earth at all, and at which time, and what their geo-effects will be. Of crucial importance is to determine the direction in which an eruption is originally pointed, since only one out of ten CMEs hits the Earth. Space-based coronagraphs keep providing spectacular views (see Fig. 2) of erupting gas clouds but show only their projections on to the plane of the sky and cannot be used to infer directly the CME radial propagation velocity. CMEs pointed along the Earth–Sun line appear as "halos" around the occulted disk in a coronagraph field of view (Howard et al., 1982). Complementary disk observations are required for deciding whether a halo CME is pointed towards or away from Earth. The scientific value of coordinated observations has been demonstrated repeatedly, since the set of modern solar telescopes on the Solar and Heliospheric Observatory (SOHO) spacecraft went into operation in early 1996 (Domingo et al., 1995). The disk images taken by the EUV imaging telescope (EIT) at a sufficiently high time cadence allow the almost continuous detection of flare explosions and filament eruptions (Delaboudinière et al., 1995), which may give some information to determine the related CME ejecta moving towards the Earth.

Measuring directly the upward speed of possible eruptive prominences and ARs through the Doppler effect, with both high spatial and temporal resolution, is of crucial importance for the understanding of mass supply to CMEs, precursors of CMEs and early phases of their acceleration. Of course, all this requires spectroscopic capabilities.

(3) To get information of the corona magnetic vector

Polarization measurements of Lyman-alpha will provide information on the transition region and coronal magnetic field vector.

(4) To track continuously solar disturbances from their solar source region to the outer corona

The instruments of the large angle and spectrometric coronagraph (LASCO) observe the CME evolution in the corona above the solar limb in a range from 1.1 Rs from Sun center out to 32 Rs (Brueckner et al., 1995). Recently it was shown that on the basis of LASCO data the CME propagation time to 1 AU can be derived with reasonable certainty (Schwenn et al., 2001, 2005; Schwenn, 2006). Beyond 32 Rs the ejecta clouds can only be traced by radio wave observations during their travel from Sun to Earth (Reiner et al., 1998). However, the previous observations cannot provide continuous image to track a CME event from its source to the ejecta in the interplanetary space. To identify the dynamic processes a continuous tracking is important.

We now turn to discuss the requirement on the location of the spacecraft for the above suggested novel measurements. The success of SOHO suggests that a long-lasting space weather surveillance mission should be done, with a spacecraft being stationed at the L1 Lagrange point around 1.5 million kilometers ahead of the Earth. The second main objective of a spacecraft located at this point is to sample the properties of the solar wind well before it hits the Earth's magnetosphere. From the arrival at L1 to the onset of a geomagnetic storm there is usually a time delay of one to several hours. Thus, an early warning may allow to take precautionary measures.

STEREO will give a continuous heliographic survey of the 3-D corona along the whole Sun–Earth line from two distant viewpoints. However, such ideal constellations will last only few years (Sheeley et al., 1985) and further missions are needed in the future.

2.1.3. The first-ever observations provided by KuaFu-A

KuaFu-A will identify the spatial and temporal processes leading to a CME by means of combined observations of (1) earliest signatures of chromospheric flaring or eruption, (2) transient dynamics of transition region and lower corona, (3) timing of hard X-ray, Gamma-ray, and non-thermal radio emissions, and of high-energy particle fluxes, (4) initiation, propagation, and interaction of CMEs, (5) density distribution and magnetic structure, (6) flow patterns, and (7) waves.

These measurement requirements lead to the proposed suite of instruments on KuaFu-A, which will be equipped with (1) EUV/FUV disk imager (EDI), including a Lyman-alpha disk imager and the spectral radiance measurements (MOSES for KuaFu), (2) coronal dynamics imager (CDI), including a Lyman-alpha coronagraph, (3) radio burst instrument (RBI), (4) solar wind instrument package (SWIP), (5) solar energetic particle sensor (SEPS), and (6) hard X-ray and gamma-ray spectrometer (HXGR). The detailed description of these instruments will be given in Section 3.

These measurements on KuaFu-A will give the following number of "firsts":

(1) The first-ever continuous imaging of the source regions of solar eruptive events in the Lyman-alpha line with high spatial and temporal resolution

Lyman-alpha is a strong VUV line that is optically thick, and thus will be more sensitive to the variations of atmospheric structures, e.g., during a filament eruption. Since quiescent prominences are comparatively dense and cool magnetic structures, they prominently radiate in vacuum ultraviolet lines, like in the well-known Lyman-alpha emission line of hydrogen at 121.6 nm, but they have in this line never been routinely be imaged at high spatial (one second of arc, or below 1 Mm) and temporal (1–10 s) resolution. Of course, these comments equally apply to ARs. Only fragmented observations were produced by rocket-borne instruments (e.g., TRC, VAULT, SwRI/LASP MXUVI), and by TRACE with a limited FOV and low spectral purity due to a large continuum contribution (Handy et al., 1999). KuaFu will continuously provide high-resolution Lyman-alpha images with spectral purity. These line radiance measurements with high spatio-temporal resolution will support and be essential for studies of such dynamic features in the lower solar atmosphere as the network, spicules, cold loops, quiescent and eruptive filaments, flares and post-flare loops, and will be very complementary to the low-corona observations in the Fe XII line at 19.5 nm. Gary et al. (1987) already made measurements of the fibril structures in Lyman-alpha on rocket flights. Their results indicated how important it is to use this line, e.g., for exploring the magnetic shear at heights ranging from the photosphere to the transition region.

(2) The first-ever simultaneous imaging, using the 30.4 nm (He II), of the plasma flow velocity on the solar disk

A traditional imager can track the evolution of the source regions of solar eruptions, but does not provide line-of-sight velocity information, while a slit spectrograph can provide velocity information, but it takes a long time to build up an image, and thus one may easily miss the detailed evolution of an eruption. The new KuaFu instruments will provide high-resolution images simultaneously, that can be used to deduce the flow velocity as an eruption occurs on the solar disk. For example, the instrument will be able to detect where is the source region of a CME is, e.g., by detecting which dimming region is related to outflow of material. For Earth-directed CMEs, the He II spectro-imager will be able to measure velocity and hence acceleration accurately. This will give us clues to understand the CME trigger mechanism. Moreover, for quiescent and eruptive filaments, it will also be able to measure the twist in the erupting flux rope as well as the early phases of an eruption occurring low in the atmosphere.

(3) The first-ever continuous recording of the polarization of Lyman-alpha line

KuaFu will make continuous measurements of the polarization of Lyman-alpha line in order to reveal the magnetic topology in the CME pre-eruptive structures. This measurement will help us to identify how the CME energy is stored in the magnetic field and how it is released.

(4) The first-ever continuous tracking of CMEs from the disk source out to 15 Rs

The continuous tracking of CMEs will be facilitated by using the Lyman-alpha disk imager up to 1.1 Rs, together with the Lyman-alpha coronagraph from 1.1 to 2.5 Rs and the white-light coronagraph from 2.5 to 15 Rs. At the same single wavelength of Lyman-alpha, it is easier to trace an eruption from the solar disk to beyond the solar limb out to 2.5 Rs. This continuity will be very important for identifying the source region, learning about the relationship between surface activity and CMEs, and studying the CME initiation and its subsequent evolution in the corona.

The Lyman-alpha disk image and He II spectrograph will also help to identify the scenario of the solar wind origin suggested by Tu et al. (2005) or by Fisk (2003).

There are important synergies with other missions. The complementary instruments of KuaFu, Solar Orbiter and Sentinels will in combination offer unique perspectives and new vantage points for global solar and heliospheric research. Specifically, these missions together will enable us to study the 3-D evolution and morphology of CMEs in an unprecedented way. The Solar Orbiter (Marsch et al., 2002) launch is planned for 2015, and the Sentinels mission is presently planned by NASA for launch in about the same time frame. Solar Orbiter will, while being in a close orbit around the Sun on the far side and eastern and western sides of the Sun, and even outside of the ecliptic plane, together with KuaFu-A allow us to do novel, simultaneous multi-point observations of the solar disk and off-limb corona. To identify the CME source regions KuaFu observations need to be combined with ground-based and space-borne magnetic field observations.

2.2. Frontier geospace science objectives: the mechanism of magnetic storms and the global MIT coupling, the sub-storm initiation, and system-level geospace science

We now turn to discuss the new science objectives of KuaFu-B1 and KuaFu-B2. These two satellites are designed to observe how the Earth's magnetosphere responds to solar activities. The major phenomena regarding these regions are the magnetospheric substorms and storms. The orbital arrangement of KuaFu-B provides the possibility of continuous global aurora and ring current imaging, and an excellent platform for high-latitude and high-altitude in situ observations. KuaFu-B will quantify how energy derived from the solar wind powers the magnetospheric and ionospheric current systems and convection, leading to the aurora, particle energization, enhanced ionization, and Joule heating.

2.2.1. The basic science issues of the storms in geospace

Based on numerous single-point in situ measurements and remote sensing carried out in the past half century, a comprehensive view of geospace response to the solar storms has evolved. The energy of ICMEs carried in the solar wind may get into the magnetosphere through dayside magnetic reconnection. Some of the energy is directly dissipated in the magnetosphere-ionosphere system, while a large part of the energy is first stored in the magnetotail as magnetic energy and then episodically released and deposited in the auroral ionosphere and inner magnetosphere via the magnetospheric substorm process which typically unfolds over several hours. In some cases the energy may be released over a longer period, say 20–40 h, having a series of effects on the inner magnetosphere, such as the enhancement of the ring current intensity. The later phenomenon is called a geomagnetic storm. Both storms and substorms are manifestations of the gobal magnetospheric convection. This convection varies from steady, almost laminar flow to bursty rapid flows called Bursty Bulk Flows (see e.g., Erickson and Wolf, 1980; Angelopoulos et al., 1992; Yahnin et al., 1994). Understanding geospace as a complex coupled system means understanding mass and energy transport, and energization, transport and loss via precipitation of plasma. If we recognize substorms, storms and related convection processes as the most important dynamic features of the geospace response to the solar driver, we must in turn recognize the importance of the related universal fundamental processes, such as magnetic reconnection, particle acceleration and magnetic flux transfer and release (Alexeev, 2003; McPherron, 1979, 1991; Gonzalez et al., 1994; Tsurutani et al., 1997).

If we are working towards a system-level understanding of the geospace response to the solar driver, it is useful to attack the problem within the well-developed paradigms of the substorm, storm, magnetosphere–ionosphere–thermosphere (MIT) coupling, and the new paradigm of natural complexity as applied to geospace phenomena. While the first three are old problems, they are clearly system-level ones, wherein the universal processes referred to above play important and possibly even central roles. The evolving field of natural complexity is developing somewhat orthogonally to the historically reductionist approach taken in addressing the substorm, storm, and MIT coupling. The basic questions need to be answered are as follows.

(1) Substorm initiation

Substorms consist of three phases: growth, expansion, and recovery. Substorm expansion initiation manifests a global interaction between the mid-tail, inner-tail and the ionosphere. There are two major paradigms for answering the related outstanding questions such as the location of the initial onset, causal link between tail magnetic reconnection (MR), aurora breakup and cross-tail current disruption (CD). The near Earth neutral line (NENL) paradigm insists that mid-tail MR ($\sim$25 Re) first takes place to release the stored magnetic energy; the MR generated fast flows then transport the energy to the inner tail and cause the CD and aurora breakup (Baker et al., 1996, 2002; Baumjohann, 2002). On the other hand, the near Earth current disruption (NECD) paradigm argues that instabilities in the near-Earth tail ($\sim$10 Re) first cause current disruption, which then yields the aurora breakup and launches a rarefaction wave to trigger MR and fast flows in the mid-tail (Lui, 1996, 1991). A synthesis scenario of MR and CD has also been suggested (Pu et al., 1999, 2001). Despite many years of study this controversy remains unsolved. The related outstanding questions are as follows: where is the location of the expansion initial onset, and what is the mechanism that triggers the onset? How are the tail MR, aurora breakup and CD causally linked, and what is the role of the global interaction between the mid-tail, inner-tail and the ionosphere? How are the particles energized and injected in the inner magnetosphere? And how are energetic electrons accelerated and precipitated to the ionosphere to cause aurora breakup?

In the next few years we can expect significant progress on the substorm problem as a consequence of the imminent THEMIS mission. THEMIS may elucidate the time sequence of large-scale processes clarifying for example the relative timing of CD and formation of the NENL and some other key problems. THEMIS will unfold, however, largely without the benefit of global auroral and ring-current observations until when KuaFu is launched. KuaFu, together with THEMIS, will bring closure to the key question of whether substorms are triggered by solar wind disturbances (when THEMIS is in its dayside configuration), and the role the substorm plays in the evolution of the ring current and in the magnetic storm.

(2) The mechanism of magnetic storms

The mechanism of magnetic storms is another outstanding question. Akasofu (1968) suggested that a storm develops as a result of a superposition of successive "substorms". Other studies support that storms are a direct consequence of the solar wind electric field, without the need for substorm actions. The worldwide depression of the magnetic field horizontal component in storms is due to the enhanced westward ring current. However, after several tens of years' studies one still does not fully understand how the storm ring current is formed and maintained. It is suggested that enhanced convection during a long-lasting southward IMF period can sufficiently intensify the ring current (Gonzalez et al., 1994; Kamide et al., 1998). Meanwhile, magnetosphere–ionosphere (MI) coupling may create strong electric fields that significantly modify the ring-current morphology during the main phase of storms (e.g., Brandt and Goldstein, 2005). The related questions are as follows: How does the central plasma sheet (CPS) feed plasma into the ring current? What is the role of the substorms in the storm? What is the inter-relationship between the ring current and the electric field of the inner magnetosphere? How does the storm ring current grow and decay? KuaFu will bring synoptic continuous observations of the storm-time ring current and global auroral distribution to bear on the storm. We will for the first time have observations of the ionospheric projection of the CPS that span entire storms, allowing us to explore how the CPS feeds the ring current, and potentially how CPS electrons are staged for ultimate transport to the radiation belts.

(3) Global magnetosphere–ionosphere–thermosphere coupling

Magnetosphere, ionosphere, and thermosphere (MIT) form a closely-coupled, interacting system. MIT coupling during substorms and storms powers a huge amount of energy into the high-latitude ionosphere–thermosphere (IT), and hence is of fundamental importance for understanding how the solar storms affect the entire geospace environment. MIT coupling is controlled by multi-scale interactions and proceeds through temporal/spatial processes such as parallel electric field and field-aligned currents (FACs), particle precipitation and outflow and plasma waves (Kamide and Baumjohann, 1993). Regarding the geospace energy pathways that lead to the mid-latitude IT storms we have the following unsolved questions. What are the energy sources and their effects on various geospace sinks, such as the IT system, ring current and plasmasphere? How important is precipitation in the thermospheric energy budget? What are the impacts of precipitation and Joule heating in modifying the mid-latitude ionosphere and atmosphere? For the coupling through the FACs we have the following questions. What is the role of ionospheric conductivity in substorms and its influence on ionospheric electric fields, currents, FACs and aurora structures? How do the FACs affect the MI coupling between the two hemispheres? These IT questions are central to the NASA LWS program, and cannot be credibly addressed without long duration unbroken sequences of global auroral images.

(4) Natural complexity in geospace

Traditionally, geospace science has been carried out with a largely reductionist view. That is, events unfold in a very causal fashion. For example, the substorm onset is viewed as a direct consequence of a sequence of events. On the one hand, enhanced reconnection leads to stretching of the magnetotail, and a northward turning of the IMF precipitates the expansive phase onset. In this point of view, the substorm is considered as a driving processes. On the other hand, it is possible that a transient dissipation looks as if energy, built up over an hour or so, is dissipated explosively over tens of minutes. In this point of view, the substorm is considered as an unload process. It is clear that bringing the techniques of natural complexity to the study of geospace processes will allow us to better understand geospace dynamics. Does the magnetosphere exhibit self-organized criticality? How does the spectrum of spatial and temporal structures respond to changes in the solar driver? Can we ultimately predict the size and hence space weather impact of disturbances like the substorm?

To address these and other questions, researchers are starting to explore, for example, large data sets of global auroral images, or the spectrum of sizes of substorm injections (see e.g., Uritsky et al., 2006a,b; Liu et al., 2006,). At the heart of complexity is analysis of the distributions of fluctuations of dynamical properties. Clearly long time series of multi-scale observations are of tremendous importance to this endeavor. KuaFu will provide unbroken time series of global auroral observations. In conjunction with various ground-based imaging programs, this will allow, for the first time ever, the continuous observation of the spectrum of auroral spatial scales across virtually all relevant scales from tens of meters to thousands of kilometers. Together with KuaFu-A observations, we will have ability to study how the spectrum of fluctuations responds to changes in the solar driver.

2.2.2. The required novel measurements

The primary reason why the fundamental processes have not yet been understood, even after half a century of space observations, is that most of the observations were made by help of single-point in situ measurements. The magnetosphere is a huge volume of space, containing many different plasma regimes, and even multi-point in situ measurements can only provide limited coverage. The present understanding of the geospace response to the solar storms is mainly based on statistical studies with the data obtained from single-point in situ measurements. Since the changes from case to case of the events are very large, the statistical results can just give an overall picture, but not the real physical processes. Global perspectives are still needed to change our understanding from the outline in a statistical average sense (space climatology) to an instantaneous view of large-spatial-scale magnetosphere dynamics (space weather). Therefore, global imaging including EUV, FUV, and ENA is the key tool and an effective way of remote sensing system-level magnetospheric dynamics, and our best (albeit 2-D) way to study geospace as a coupled system (Williams, 1990; Williams et al., 1992; Donovan et al., 2007).

The POLAR and IMAGE UV imaging programs have made tremendous scientific contributions to our understanding of the global features of magnetospheric storms and substorms, steady magnetospheric convection, and MI coupling in general. These data are now routinely used in conjunction with plasmaspheric (EUV) and ring current (ENA) images to track the spatio-temporal evolution of the global geospace system (see for example Brandt and Goldstein, 2005). UV auroral imagers remotely sense the ionospheric projection of the central plasma sheet (CPS) (see, e.g., Frey et al., 2001), and provide information about the pressure distribution in the inner CPS and inclination of the magnetic field in the inner magnetosphere (see, e.g., Wing and Newell (1998) and Donovan et al. (2003)). The auroral imaging spectrograph provides estimates of polar cap size, energy deposition on a global scale, and observations of time evolving dynamic auroral structures (see e.g., Elsen et al. (1998), Germany et al. (1994), and Henderson et al. (1998)). More importantly, the combined proton and electron auroral observations allow us to quantify the effects of precipitation on ionospheric conductivity, the relationship between convection, large-scale currents, and the aurora, and to track storm-associated auroral disturbances down to mid latitudes. From these auroral imagers the ionospheric signature of dayside reconnection, the injection of CPS plasma into the ring current and the conjugate and non-conjugate features of the polar aurora have been identified (see e.g., Phan et al., 2003; Østgaard et al., 2003, 2004; Liu and Donovan, manuscript in preparation).

ENA imaging like that carried out on IMAGE is also important for study the MIT coupling. ENAs are produced in the Earth's atmosphere via a charge exchange mechanism between singly charged energetic ions and the cold neutral atoms of the exosphere. Since they are not affected by ambient electric and magnetic fields, directly propagating ENA particles can be used to image and to remotely diagnose the plasma populations in the neutral gas in which the ENA are created. Thus they, in effect, provide a means to make the active magnetospheric plasma visible. The ENA data confirm that M–I coupling creates strong electric fields that significantly modify the morphology of the main phase ring current (e.g., Brandt and Goldstein, 2005). Also, it was possible to observe plasma sheet dynamics during substorms out to ~15 Re. From storm onset, the ENA fluxes from the plasma sheet were found to typically increase by an order of magnitude over some 30 min. The fluxes were subsequently restored to their original level during the substorm recovery phase.

The combination of global and continuous ring current ENA and auroral observations provides means for retrieving ionospheric conductance and pressure-driven currents that modify the electric field of the inner magnetosphere and form the core part of MI-coupling. With the conductance estimated from FUV images, simultaneous observations of the morphology of the ring current can impose invaluable constraints in the matter of modelling global MI-coupling.

Clearly, however, the previous imaging of magnetosphere is not complete. For fully understanding the physical processes this kind of observations need to be greatly improved. As Donovan et al. (2007) point out, there are a number of technical firsts in global auroral imaging that are now well within our collective grasp (even within the context of a single mission such as KuaFu) that would greatly enhance our ability to carry out system-level geospace research. In brief, all previous global imagers have been on single-satellite missions with orbits that sustained no more than ~10 h of continuous imaging. While serendipitous alignments of Polar and IMAGE, and side-on global views from Polar provided some conjugate auroral imaging (see the Østgaard et al. papers referred to above), there has never been a systematic attempt to carry out conjugate auroral imaging from space. Multi-channel imagers have repeatedly attempted to isolate narrow parts of the LBH spectrum to allow for the use of ratios and intensities to infer characteristic energies and energy fluxes, although out of bandpass leakage has limited progress on this front. While temporal resolution in global imaging has been good (30 s to 2 min being typical), spatial resolution has never truly been better than 100 km. With KuaFu-B, we intend to advance on each of these fronts, in ways that facilitate new science sketched out in Section 2.1.1.

(1) Long-term continuous imaging of global aurora and ring current

In order to determine the dynamical evolution of a geomagnetic storm which lasts several days, continuous imaging 24 h a day and 7 days a week (now often called "24×7") is required. No mission has yet been able to follow a storm from beginning to end due to the lack of continuity. The time resolution for identifying the chronological and causal link of various substorm and storm phenomena is a time scale of minutes (looked at globally). Thus, to properly address the storm–substorm relationship, that continuous imaging must have temporal resolution of 1 min or better. Further, to address the relationship between the CPS and ring current (and other inner magnetospheric populations), we need to separate the electron and proton aurora. Finally, for quantifying energy deposition and effects on conductivity on the time-scales of storms, we must have appropriate spectral isolation of the electron aurora in at least two separate channels.

(2) Global conjugate aurora imaging

Global conjugate imaging will be particularly valuable for studying the aurora breakup produced by substorms, poleward boundary intensifications (PBIs) as a direct consequence of distant tail reconnection and cusp aurora from high lobe reconnection during northward IMF. Conjugate imaging may also help to study how the polar cap regions and polar ionospheres are coupled through the FACs and how the global aurora responds to storms. Through identifying the locations of substorm aurora breakup on two hemispheres, we could get information how the field lines in the onset region are twisted by IMF and where the cross-tail current is disrupted near the equator. Moreover, by examining the consequences of differential conductivity at opposite ends of flux tubes one could assess the role of conductivity in initiating expansive phase onset and other dynamic processes. Global conjugate imaging will also help to explore when diffuse and discrete auroral forms are conjugate and when they are not. With conjugate imaging, most of the scientific issues pertain to how the global system responds to rather rapid processes like substorm expansion, bursty bulk flows, and solar wind pressure pulses. Thus, the objective here is to provide a systematic program for conjugate imaging, which does not need to be carried out 24×7.

(3) Imaging across all relevant spatial scales

There are technical and even fundamental limitations to the spatial resolution that can be obtained with a global imager. On the technical side, greater resolution demands larger CCDs, bigger bandwidth, and ultimately a larger aperture given a target imaging cadence. On the fundamental side, given a ~20 km thick emitting region, for sources away from nadir, the spatial resolution is limited by the thickness of the emitting layer. Even with these limitations, however, it is clear that with current technology and a reasonable frame rate, we could do better than the best global imagers have done so far. Placing a number on this, an average resolution at auroral and polar cap latitudes of ~30 km is a reasonable target (T.S. Trondsen, private communication). This would be a significant improvement over the best previously obtained global average resolutions, which are ~70 km or more.

With global imaging at 35-km resolution with continent-scale networks of All-Sky Imagers which have resolutions of around ~1 km, and narrow-field-of-view auroral telescopes which have resolutions of 10 s of meters, we would have the first-ever opportunity to image simultaneously across all relevant spatial scales. KuaFu (see below), together with ground-based programs such as THEMIS, NORSTAR, PENGUIn, and MIRACLE, offers the very real opportunity of achieving this technological objective.

2.2.3. The orbit and measurements of KuaFu-B1 and B2

Long-term continuous imaging of the aurora distribution in one hemisphere and part-time conjugate imaging on the two polar regions can be achieved with two satellites. The two spacecraft should be relatively phased on identical (coplanar) elliptical polar (90° inclination) orbits so that when one is at apogee, the other is at perigee. The relatively slow passage through apogee and quick passage through perigee mean that at all times at least one of the two spacecraft will be near apogee (see Fig. 3).

The orbit must be significantly elliptical so that each satellite spends a large enough fraction of its orbital period near apogee. This is necessary for achieving the 24×7 continuous aurora coverage, but we point out the competing need that perigee should be high enough to facilitate conjugate imaging with the wide field of view (FOV) imager. For a given apogee and perigee that allows 24×7 viewing, the precession of the line of apsides then limits the duration of continuous viewing. Based on our calculations and considerations of resolution, we have decided to argue for an orbit of 7×1.8 Re (radial from origin), with a 90° inclination, subject to radiation dosage issues. This gives us a roughly 13-h orbit, which will allow for 2.5 years of continuous viewing of the northern hemisphere auroral zone.

We now turn to describe the measurements to be made by KuaFu-B1 and B2. The imaging complement

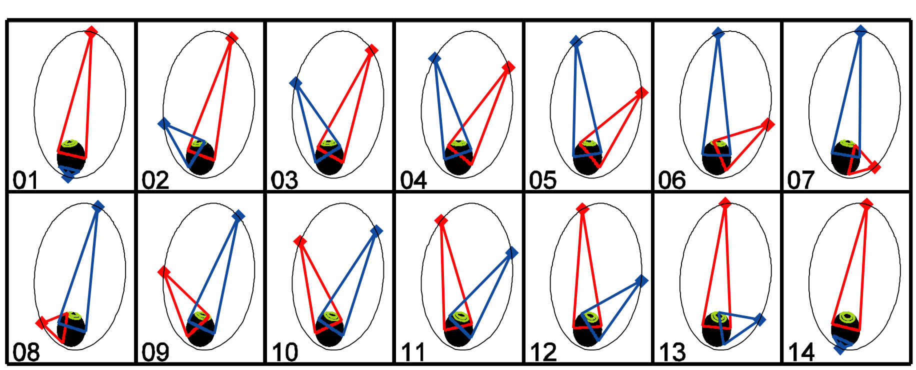

Fig. 3. Fourteen snapshots of two satellites relatively phased on identical polar orbits so that when one is at apogee the other is at perigee. An auroral oval, at appropriate latitudes, is indicated in green, and the part of the globe visible to each spacecraft is indicated with the red and blue cones. Note that, at all times, the entire oval and polar cap are within view of one, the other, or both satellites. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of each KuaFu-B satellite will be the same. Each satellite will be instrumented with two UV auroral imagers, an auroral imaging spectrograph, and an ENA imager. The ultraviolet auroral monitoring camera (UVAMC) will build on the heritage of the Canadian Viking, Freja, Interball and IMAGE WIC instruments. UVAMC will be designed to allow for global observations of the electron aurora with spectral resolution of the Lyman–Birge–Hopfield (LBH) long and short bands and global observations of the proton aurora (via Doppler-shifted hydrogen Lyman-alpha emissions). This new instrument will provide wavelength separated LBH electron auroral observations with a spatial resolution of about 30 km and 30 s over the global auroral distribution. Furthermore, it will image even dim aurora (∼20 Rayleigh features).

Each satellite will also be identically instrumented with a Wide Field Auroral Imager and a Neutral Atom Imager. The former is a novel instrument designed to make global auroral images at low altitudes of the orbit. Combined with the auroral images observed by the two UV auroral imagers at the high altitudes of the orbit we will obtain conjugate auroral observations. The Neutral Atom Imager is for observing the energetic neutral atoms (ENAs).The ENA data can provide insights into circumstances in the ring current responsible for stimulating those magnetic storms/substorms that underlie various aspects of space weather.

2.2.4. The first-ever observations provided by KuaFu-B1 and B2

KuaFu-B will play an essential role in the overall KuaFu program of geospace science and space-weather exploration. With the new constellation, the systematic conjugate auroral observations, the better global spatial resolution from the imagers, the best-yet wavelength separation, and the stereoscopic ENA imaging of the ring current while the RBSPs, THEMIS, and ORBITALS make multiple cuts through the ring current, this component of the mission will quantify energy and mass transport in the inner magnetosphere and energy deposition in the ionosphere and thermosphere, thus studying the geospace consequences of the varying solar inputs which will be studied by KuaFu-A. As well, KuaFu-B will address exciting stand-alone science questions related to MI-coupling, mass and energy transport in the CPS and inner magnetosphere, multi-scale processes in geo-space plasmas, and natural complexity. KuaFu-B1 and B2 will provide following five first-ever observations:

(1) The first-ever 24×7 global imaging of the northern hemisphere

This has never been done in any wavelength. We will do this with two electron channels (LBHL and LBHS) and the spectroscopic imager (i.e., the proton aurora) and ENA imager. With these observations the complete storm development and decay can be tracked.

(2) The first-ever systematic conjugate auroral imaging

IMAGE working together with Polar gave only a few periods of conjugate imaging. KuaFu-B will do this more systematically, with ∼45 min per orbital period (13 h) of conjugate observations. This will provide numerous conjugate observations of substorm onset, storm sudden commencement, and snapshots through all phases of magnetic storms.

(3) The first-ever high temporal and spatial resolution of imaging

All the imagers on KuaFu-B1 and B2 have 30 s temporal resolution. The global electron auroral observations have 35 km spatial resolution. They are better than the imagers on IMAGE which had 2 min temporal resolution and the electron auroral imager on IMAGE which had ∼75 km spatial (or larger) resolution.

The high-resolution aurora imaging is necessary to allow accurate timing of all expansion signatures since the time response in the initiation of substorm expansion onset is only tens of seconds. Aurora overlapping views ranging from global scales down to tens of meters will be provided by combining the global imaging of electron aurora with simultaneous mesoscale all-sky imaging and telescopic imaging.

(4) The first-ever global time-evolving maps of the characteristic energy and energy flux of the electron aurora

The global electron aurora observations on KuaFu-B1 and B2 will have better wave-band separation of the LBHL & LBHS than previously achieved, allowing better specification of the characteristic energy than previously obtained. The characteristic energy and energy flux will help to estimate the energy output during substorms and storms and to explore how the auroral acceleration mechanism relates to, and even feeds back to, magnetospheric dynamics.

(5) The first-ever real description on magnetic and ionospheric coupling

This will be done based on the combination of the 3-D ring current and 2-D aurora measurements. KuaFu-B1 and B2 may make stereoscopic imaging of the ring current with ENA observations. The 3-D ring current measurement will have been accomplished by TWINS, but without simultaneous aurora observations. ENA observation on KuaFu will also benefit from multiple frequent cuts through the ring current from THEMIS, and the RBSPs. This allows for calibrating the ring-current images with in situ data and produce calibrated 3-D ring current images.

2.3. The basic science issues in the Sun–Earth relations: the complex global behavior of disturbances in the Sun–Earth system

The Sun and the Earth are a connected system within which magnetic fields, plasmas, and energetic particles are interacting simultaneously on multiple temporal/spatial scales. On the Sun, the photosphere, chromosphere and the corona are coupled through the magnetic field. In the Earth's environment, the magnetospheric plasmas, radiation-belt energetic particles and ionosphere/thermosphere all interact organized by the Earth's magnetic field. Through reconnection of the Earth magnetic field with the interplanetary magnetic field, some field lines originating at the Sun directly connect with the Earth's field lines, with one foot-point on the Sun and the other one in the Earth's polar regions. Following these open field lines the solar energetic protons and electrons, as well as the solar wind particles, can directly penetrate into the Earth's upper atmosphere and deposit their energies there.

The first Sun–Earth relation event was reported 147 years ago (Tsurutani et al., 2003). The Carrington's flare was found followed by an extremely big Earth magnetic storm. However, the Sun–Earth relation is not yet fully understood. To explore the complex and global (system level) processes in the Sun–Earth system is an exciting new frontier in Sun–Earth science. This new research thrust is clearly described in the web site of the Sun–Earth Connection division under NASA (http://sec.gsfc.nasa.gov/sec_science.htm): "Understanding the Sun, heliosphere, and planetary environments as a single connected system is the goal of the SEC division... Our challenge now is to explore the full system of complex interactions that characterize the relationship of the Sun with the Solar System". In this subsection, we highlight the KuaFu mission objectives as they relate to exploring complex global behavior of the coupled Sun–Earth system.

2.3.1. The basic science issues in the Sun–Earth relation system

(1) How is the mass and energy transported from the solar wind into the Earth magnetosphere?

The geo-effectiveness of a disturbance in the solar wind depends crucially on plasma density and speed, and particularly on the orientation of the interplanetary magnetic field (IMF). Only in the case the IMF has a strong southward component, i.e., opposite to the Earth's field, a process called "magnetic reconnection" will occur and eventually trigger a major geomagnetic storm with all its consequences (see, e.g., Tsurutani and Gonzalez, 1997). The most dramatic southward swings of the IMF occur usually in the compressed plasma that is piled up by interplanetary shock waves launched by major CMEs, and in the so-called "magnetic clouds" often imbedded in the ejecta (Burlaga et al., 1981; Wei et al., 2003). Flux Tube Transfer Events are considered as signatures of reconnection and of mass and energy transfer.

However, the energy transfer from the solar wind to the magnetosphere is a very complicated process. The reconnection in the magnetopause is considered to take place in a small-scale region, whereas the energy transfer takes place in a large-scale region. The related physical processes are far from being understood. The related questions to be answered are as follows: How does the ICME drive the geospace storms? How is the solar wind energy transferred into the magnetosphere? How is the energy converted and dissipated in the magnetosphere (or MIT system)? Is it a driving process or unload process? The previous studies on these issues are mainly based on an energy-budget estimate using the magnetic indices such as Dst, AE, and ϵ. The Dst and AE are derived from the ground-based magnetic records, and ϵ is calculated with the solar wind parameters measured at L1 point. Many statistical correlations were found between the solar wind parameters and these indices. However, these indices cannot describe the real physical processes which control the coupling phenomena.

(2) How are the related universal processes self-organized?

The disturbances in the Sun–Earth system are controlled by several universal processes, including the generation and evolution of magnetic structures, boundaries, flows and transients, and the transfer and coupling of energy. The former includes solar (stellar) flares, CMEs, substorms, storms, and bursty bulk flows. The latter contains sudden energy release, reconnection and acceleration and heating mechanisms (for a reference please read The International Heliophysical Year website). Most of these universal processes are multi-scale coupled and controlled by natural self-organized processes. It is an exciting topic to identify how the magnetic field and field-aligned currents organize the different plasma regimes in the Sun–Earth space as a single dynamic system. To fully understand these universal processes the space observations should concentrate on exploring the complex global behavior of the entire Sun–Earth system.

(3) How to understand the related multi-scale phenomena?

Space storms in both the solar corona and the Earth's magnetosphere including CMEs, magnetospheric substorms and storms are all multi-scale phenomena. They all involve large-scale magnetic structures and are related with huge mass and energy releases from the solar atmosphere or the Earth's magnetosphere. On the other hand, it is believed that small-scale magnetic reconnection plays an important role in these processes. Furthermore, changing of large-scale magnetic structure, such as the emerging of magnetic flux in the solar atmosphere and the transport of magnetic flux from the dayside to the tail lobes in the Earth magnetosphere may relate to, and even drive, the small-scale reconnection.

2.3.2. The required measurements

In order to understand the energy transfer processes, the self-organized processes and the multi-scale phenomena, new space exploration is required to measure the instant global behavior of the Sun–Earth system. For exploring the global behavior of disturbance in the Sun–Earth system, the solar observations and the geospace observations should be combined. SOHO was designed to exploit synergies with Cluster. However, the latter gives only in situ measurements and cannot provide information about global behavior. Polar and Image provided imaging observations, but not continuously. Twins concentrates on the ring current but not on aurora observations simultaneously. A complete continuous imaging on both the Sun and the magnetosphere are badly needed.

2.3.3. *The first-ever observations provided by the KuaFu project*

The novel combination of KuaFu-A and KuaFu-B1 and B2 will give the first-ever simultaneous and continuous end-to-end imaging of the Sun–Earth system.

KuaFu will make continuous global instantaneous observations of these processes. KuaFu will provide data, mainly images, describing globally the complete chain of disturbance for each case from the solar chromospheres to the Earth polar ionosphere. The novel combination of measurements includes observing the origin and development of CMEs by imaging the top chromosphere, transition region, lower corona and distant corona; observing the ICME-produced shock waves by receiving the shock-produced radio waves; observing the CME-produced magnetic clouds by local measurements of the solar wind plasma and magnetic field. The timing and intensity of the solar storms are determined by observing X-rays, gamma-rays, and high-energy particles. The global responses of the geospace to solar storms, such as the energy and mass release during substorms and storms are observed by round-the-clock imaging of the aurora activities and the ring current, and by local measurements of energetic particles. Fig. 4 gives an illustration of KuaFu measurements concerning the global Sun–Earth system.

A study based on the combination of KuaFu observations with the recently developed global 3-D simulations will provide better insight into the underlying physical processes, as mentioned in Section 2.3.1. The space weather events from the Sun to the Earth recently have been modelled by 3-D simulation, coupling several state-of-the-art codes (e.g., Luhmann et al., 2004; Groth et al., 2000; Wang et al., 2006). In comparison with the observations by spacecraft SOHO, ACE, Wind, Polar, and IMAGE, these simulation models have been successful, especially in qualitatively reproducing the processes of the CME, ICME, substorm, and aurora activity. However, since several key processes, such as the CME initiation, the evolution of CMEs from their source to the distant corona, the evolution of the structure of a CME to the structure of an ICME, the mass and energy transfer from the solar wind to the magnetosphere, the total energy output of the substorm and storm and the conjugate aurora activity have not yet been covered by these observations, and some artificial assumptions had to be introduced into the model. Hence, these simulations do not represent the phenomena quantitatively, especially for the start time and intensity of the storms in the geospace. The KuaFu mission will provide the desired data related to all above-mentioned processes and thus provide clues and put stricter constraints and clues on the numerical models. The data to be collected by KuaFu-A will serve as continuous input to computer models used for forecasting the resulting phenomena in the magnetosphere-ionosphere system, in the Earth atmosphere, and at the Earth's surface (Linker et al., 2003). KuaFu-B1 and B2 will provide data for testing the model

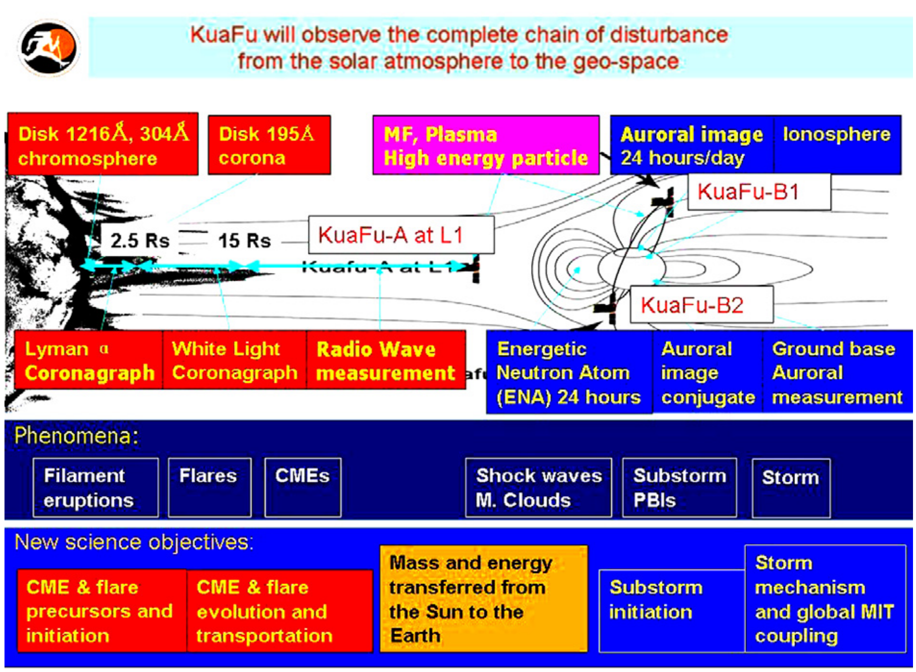

Fig. 4. KuaFu will observe globally the complete chain of disturbances from the solar atmosphere to geospace.

results. This will certainly improve the Sun–Earth space weather modelling and help in understanding the processes which control the energy transfer, their self-organization, and the related multi-scale phenomena.

3. Payload of KuaFu-A and observations of solar disturbances

The goals of the KuaFu-A mission, as pointed out above, motivated our choice of instruments for the minimum payload:

(1) An EUV disk imager (EDI) is needed to survey the Sun for coronal structure and activity evolution, especially for imminent and ongoing prominence eruptions, optical flares and post-CME effects (EIT waves and dimmings). Images should be taken in the 19.5 nm wavelength range for the hot corona (like the "green" images from EIT on SOHO) and with less priority at 30.4 nm for the chromosphere. The EUVI telescope (see http://projects.nrl.navy.mil/secchi/instruments.html) on STEREO can serve as a guideline. Images with at least 1024×1024 pixels of 2.6 seconds of arc in size should, like on EIT, be taken every 5 min or faster, depending on the available telemetry. Modern image compression software should extensively be used to bring down the telemetry rate to acceptable numbers.

(2) A far ultraviolet (FUV) channel at the Lyman-alpha wavelength of 121.6 nm is added as the second channel of the EDI instrument, using a very similar design as the EUV filtergraph. The FUV telescope on KuaFu-A will provide high-resolution and continuous Lyman-alpha images. It will indeed provide images of the chromosphere and lower transition region, containing the dense filaments or prominences that are prone to eruption and may dash at Earth. This observation is very complementary to the low corona observation in Fe XII.

(3) A multi-order solar EUV spectrograph (MOSES for KuaFu) would take high-resolution images in the EUV wavelength and simultaneously measure the flow velocity accurately as an eruption occurs on the solar disk. It would be a slitless imaging spectrograph at 3 spectral orders ($n = \pm 1$, 0) in the He II 30.4 nm line ($T \sim 80000$ K). This type of instrument has recently been developed and tested via a rocket flight (see http://solar.physics.montana.edu/MOSES/). With the current design we will be able to measure flows with an accuracy of 20 km/s, which is sufficient in order to measure the large-scale eruptive features that are so important to understand space weather.

(4) A coronal dynamics imager (CDI) would survey the extended corona from about 2 to 15 solar radii from disk center. CDI is a white-light coronagraph capable of following coronal evolution and observing all types of CMEs. As a guideline (see http://projects.nrl.navy.mil/secchi/instruments.html), the COR2 telescope of the SECCHI instrument on STEREO can be considered. Images with at least 1024×1024 pixels of 40 seconds of arc should be taken every 10 min or faster. Modern image compression software should extensively be used to bring down the telemetry rate to acceptable numbers.

(5) A Lyman-alpha coronagraph is proposed to bridge the gap between the disk imagers and the externally-occulted coronagraph which is limited to 2.5 solar radii. The field of view extends from 1.15 to 2.5 solar radii. The Lyman-alpha coronagraph will allow us to connect the coronal structures and trace the transient events (mostly CMEs) from their sources on the disk to the outer corona. The expected high spatial resolution images at high spatial resolution of all structures will map the distribution of the coronal density (and therefore the mass) and will further give access to the topology of the magnetic field above the photosphere, at least up to one solar radius above the limb.

(6) A radio burst instrument (RBI) is needed to observe radio Type III bursts caused by accelerated electrons on their way from a flare/CME site out into space. The frequency range should reach from about 10 kHz to 20 MHz. For direction finding of radio bursts on the 3-axis stabilized KuaFu spacecraft an antenna system like SWAVES (see http://wwwlep.gsfc.nasa.gov/swaves/swaves.html) on the STEREO mission is recommended. It consists of 3 deployable monopole antenna booms of 6 m length each.

(7) A solar energetic particle sensor (SEPS) should measure the fluxes of energetic particles accelerated at flare sites and at shock fronts. Ion energies of up to 100 MeV/nucleon and electron energies up to 7 MeV should be covered, with a modest spectral resolution. Instruments of this type have been used on many space missions. The SEP telescopes of the IMPACT instrument on STEREO could serve as a guideline (see http://sprg.ssl.berkeley.edu/impact/instruments/index.html). The time resolution should be of the order of 1 min.

(8) A solar wind instrument package (SWIP) should be able to observe the solar wind variability (stream structure, corotating interaction regions, Alfvénic fluctuations, shock waves, magnetic clouds). SWIP should include a plasma ion detector (separating protons and helium ions), and a magnetometer. A solar wind electron instrument is not required for this mission and would cause unnecessary complications. Time resolution for the plasma sensors should be about 1 min, for the magnetic field sensor of the order of a few seconds. SWIP can be mounted on an expandable boom, in order to minimize magnetic disturbances. Magnetic cleanliness of the whole spacecraft is not a stringent requirement for this particular mission. As a guideline for SWIP, the ROMAP (see http://rzv048.rz.tubs.de/forschung/projekte/roslan/romap/) instrument recently launched with the Rosetta mission can be considered.

By intention, we did not list specific numbers for instrument mass, power and telemetry in this very early phase of the mission. All instruments should run in a fully autonomous way and should not require routine mission operation activities. The KuaFu spacecraft must be a 3-axis stabilized platform. It should be stationed in a circular orbit around the L1 point, like SOHO and ACE. Continuous telemetry is highly desirable. Storing data on board and dumping them later can also be envisaged, provided a "beacon mode" allows continuous transmission of selected data that are essential for real-time space weather survey.

4. Payload of KuaFu-B1 and KuaFu-B2 and observations of geospace response

As stated above, the instrument complement for each KuaFu-B satellite will be identical. The primary technical objective for KuaFu-B is to provide, for 24 h a day and 7 days a week, global observations of the northern hemispheric auroral distribution, with spectral and temporal resolution sufficient to meet our scientific and space weather objectives. The baseline instrument package for each satellite will be the following:

(1) UV auroral monitoring cameras (UVAMCs) meet the primary technical requirement of KuaFu-B. The RAVENS UV auroral monitoring cameras (UVAMCs) will continuously monitor auroral morphology in the far ultraviolet, simultaneously covering both the dayside and nightside portions of the Earth's northern polar regions. Facilitated by the unique KuaFu orbital viewing geometry, the required temporal and spatial coverage is achieved by means of highly sensitive, 20° field-of-view wideband far-ultraviolet imagers mounted on each of two spin-stablized satellites. The secondary technical requirement of the UVAMC is to provide a global view of the flow of energy between the Earth's magnetosphere and ionosphere. This is accomplished by employing two such wideband far ultraviolet auroral imagers on each satellite, both controlled by the same electronics unit, but each looking at a slightly different wavelength region. The proposed wavelength regions are 140–160 nm (LBH short) and 160–180 nm (LBH long), allowing the estimation on a per-pixel basis of incident energy flux as well as average energy of precipitating particles (Germany et al., 1994). To achieve the required spectral resolution (i.e., to provide high in-band transmission and adequate suppression of out-of-band emissions), modern narrow-band, far-ultraviolet filters developed for the Ultraviolet Imager (Torr et al., 1995; Zukic et al., 1993) will be utilized. The heritage of these instruments is the series of University of Calgary UV auroral imagers (Viking, Freja, Interball, and the IMAGE WIC instrument which was a re-engineered Freja flight spare) (http://aurora.phys.ucalgary.ca) modified to increase the number of reflective elements in order to effectively use the spectral performance of the filters.

(2) A proton spectrographic imager (PSI) is in principle identical to the IMAGE SI12 spectrographic imager instrument (Mende et al., 2000). Imaging auroral Lyman-alpha emissions, the PSI provides the Ravens mission with continuous global maps of the hydrogen component (121.8 nm) of the terrestrial aurora. The novel imager design keeps spectral separation and imaging functions independent from each other; i.e., 2-D images are produced on a detector, spectrally filtered by the spectrographic part of the instrument. Doppler-shifted Lyman-alpha is imaged, while geocoronal cold Lyman-alpha (121.567 nm) is rejected. The imaging spectrograph (actually, an "imaging monochromator") is an all-reflective Wadsworth configuration in which a grill arrangement blocks most of the geocoronal emission (transmitting less than 2%). The detector is a photon-counting device utilizing the cross-delay line principle and stacked microchannel plates.

While the KuaFu-B baseline instrument package (1 and 2 above) will allow us to meet our scientific objectives, KuaFu-B would provide an excellent platform from which to carry out energetic neutral atom (ENA) and extreme ultraviolet (EUV) imaging of the ring current and plasmasphere, respectively. These additional imaging capabilities would enhance the primary overall mission objective of studying the solar input and geospace response. Further, while not central to the KuaFu mission objectives, in situ detectors on the two KuaFu-B satellites would provide an important complement to other planned geospace missions such as THEMIS and the Radiation Belt Storm Probes. For these reasons, we will be exploring the inclusion of some or all of the additional instruments on KuaFu-B:

(3) A neutral atom imager (NAI) onboard KuaFu-B will allow us to characterize the global picture of the magnetosphere. It will image the energetic neutral atoms (ENA), produced by the interaction between the energetic ions in Earth's magnetosphere with cold neutral atom populations. In its producing process, an ENA moves off from the collision point on a ballistic trajectory, with initial velocity equal to that of the parent ion immediately before the collision. Therefore, information about the ions' velocity distribution is preserved in the ENA distribution, and the ENAs can be sensed remotely since they are no longer confined by the magnetic field as the parent ions were. Thus, the ENA imaging technique enables quantitative, global-scale measurements of energetic magnetospheric ion populations from a remote observing point (see Williams et al., 1992; Henderson et al., 1997).

(4) An extreme ultraviolet (EUV) imager will allow imaging of the plasmasphere via resonant scattering of solar photons from plasmaspheric He^{+} (see Williams et al., 1992; Sandel et al., 2001). Combined ENA, EUV, PSI, and UVAMC observations would allow for an essentially complete specification of the spatio-temporal evolution of the coupled CPS, ring current, and plasmaspheric system.

We note that KuaFu-B1 and -B2 will be on polar elliptical orbits that are well suited for in situ observations of high-latitude processes. Although the primary objective in developing the KuaFu-B satellite pair was in fact geospace imaging, in situ observations from satellites on such orbits (Polar is one example) are an essential component of a systematic exploration of energy and mass transport through geospace. All of the high-altitude missions that are currently planned for in situ probing of geospace (THEMIS, MMS, RBSPs, GOES, ERG, etc.) are in nearly equatorial orbits. Thus, during the KuaFu timeframe there is no mission currently planned (other than KuaFu) that could provide these essential in situ observations. For this compelling reason, we decided to expand our instrument complement beyond what we originally envisaged in order to include a baseline set of high-altitude high-latitude in situ observations. We note that the in situ instruments are not the same for both satellites, except for the fluxgate magnetometer. We have elected to use different payloads because of mass constraints, and to maintain a relatively simple mission profile.

(5) A fluxgate magnetometer (FGM) will be an important contribution to KuaFu-B. The magnetometer will provide accurate, high-time-resolution measurements of the magnetic field vector in the magnetosphere. A major potential source of uncertainties for magnetic field measurements in space is background fields due to the spacecraft at the location of the magnetometer sensors. A comprehensive magnetic cleanliness program has to be implemented, to ensure that any disturbance caused by the spacecraft is minimized. (http://www.iwf.oeaw.ac.at/english/welcome1024-e.html).

In addition, KuaFu-B1 will carry the additional in situ instruments:

(6) The imaging energetic particle spectrometer (IEPS) will provide fast 3-D angular distribution of energetic particles (electrons and ions) in the range 20–1000 keV, which are responsible for the majority of the ring-current energy. The IEPS will contribute to the KuaFu aim of determining the flow of energy in the Sun–Earth system by providing critical in situ and remote sampling of ring-current evolution, direct measurement of storm/sub-storm energization, determination of the polar cap open/closed field line boundary, and measurement of the particles that deposit their energy into the ionospheric D region.

(7) The KuaFu-B agile plasma pitch-angle (KAPPA) instrument, is designed to support the KuaFu-B imaging instruments by measuring the precipitating sub-30 keV plasma electrons (and perhaps ions) which produce auroral luminosity detected by the KuaFu-B imagers. KAPPAs in situ measurements will be used to ensure correct identification in auroral imaging data of the polar cap boundary, between open and closed magnetic flux, thus contributing to the assessment of the time history of dayside and nightside reconnection processes. KAPPAs direct measurements of particle energy flux will also be needed to calibrate auroral luminosity measurements in different wavebands, so as to allow estimation of global auroral energy deposition.

(8) The ion mass spectrometer (IMS) can measure 3-D velocity distributions of ions with mass per charge composition determination. The energy range of ions is from a few eV to ∼30 keV. The scientific objectives of IMS are as follows: Investigation of the interaction between the solar wind and the magnetosphere by observing differences in conjugate auroral morphology arising from different IMF conditions; Study of the degree to which the ionosphere influences substorm development and auroral energy flow; Measurement of the energy flow into and out of the ionospheric auroral and polar regions and monitoring of the ionospheric and magnetospheric responses to that energy flow.

KuaFu-B2 will carry the following additional in situ instruments:

(9) The high-energy electron directional measurement (HEEDM), high-energy proton directional measurement (HEPDM), and particle energy flux measurement (PEFM) are three instruments in one package. HEEDM measures MeV electrons in 3 energy bins in 3 directions, HEPDM measures 5–80 MeV protons in 4 energy bins in 3 directions, while PEFM measures particles in the interior of the satellites. Multi-direction measurements of high energy particles can serve for scientific objectives such as investigation on variations of the radiation environment during the Sun–Earth activities, the precipitation of the energetic particles during active periods, the evolution of the radiation belts and construction of the models of them, and the sources and acceleration mechanism of the energetic electrons. Combining the three instruments one can do experiments for comparison of the radiation strength inside and outside the satellites to study the linkage of the radiation to the satellite effects.

(10) The tri-band beacon (TBB) on board KuaFu-B2 will be a three-frequency radio beacon to provide transmissions at VHF, UHF and L-band. The instrument is designed to measure the ionospheric total electron content (TEC) and derive the ionospheric electron density profiles by the computerized ionospheric tomography (CIT) technique, to investigate the ionospheric scintillation and irregularity, to measure the vapor content in the troposphere, and to help in positioning of the satellite (orbit).

5. Conclusions

The KuaFu Space Weather Explorer mission is being proposed as: (1) The first mission that aims at space weather science and provision of simultaneous, long-term, and synoptic observations of the complete chain of disturbances from the solar atmosphere to geospace; (2) The first non-interactive observations of the global response of geospace to solar disturbances; (3) The first continuous imaging of the source region of solar eruptive events in vacuum ultraviolet lines.

KuaFu observations will support the continuous surveillance of the governing processes of the connected Sun–

Earth system as an integrated entity and support space weather forecasting and monitoring. KuaFu will also support fundamental research that will identify the unique signatures indicating solar eruptive events, elucidate coupling relations between phenomena related to the disturbance propagation from the Sun to geospace, and quantify the effects of physical processes of energy transfer from solar input to geospace sink (colloquially referred to in the solar terrestrial community as "Sun to Mud"). There will be significant synergies between KuaFu and other ILWS missions. KuaFu-A and Solar Obiter and Sentinels together will offer unique perspectives and new vantage points for 3-D global solar and heliospheric research. KuaFu-B will provide the only global auroral imaging planned during RBSP, MMS, and the later stages of THEMIS. KuaFu-B will also complement worldwide networks of ground-based instruments, allowing the most specification of the ionosphere–thermosphere electrodynamic and thermodynamic response to space weather processes. KuaFu is essential to the overarching ILWS objectives.

We complete this paper with a philosophical statement about where we are in the history of our field. In order to understand the energy transfer processes, the self-organized processes and the multi-scale phenomena, new space exploration is required to measure the instant global behavior of the Sun–Earth system. The scientific exploration of the Sun–Earth system has unfolded in three phases:

(1) In the first phase, the space exploration was aimed at finding the composition of the Sun–Earth system, such as the solar photosphere, solar corona, solar wind, magnetic cloud, bow shock, magnetopause, plasma sheet, radiation belt, etc. These observations established phenomenological and cartographic descriptions of the Sun–Earth space plasma system.

(2) In the second phase, near-Earth space exploration was aimed at observing the correlations and interactions between two phenomena or even two parameters, for example, between CMEs and flares, northward turnings of the IMF and substorms onset, and changes in particle populations to global wave fields. This phase started in the later decades of the last century, and there is some left to do along these lines. This kind of observations led to discovery of the general transportation way of mass and energy, in which the detailed physical processes we are now trying to understand.

(3) Even in the midst of this second phase, space exploration is already entering the third phase. The purpose of the exploration in this phase will be to concentrate on exploring the complex global behavior of the whole Sun–Earth system. This goes well beyond causal relationships between pairs of processes and will invoke 3-D simultation. Imaging will be the major tool for global observations.

The following recent observations may be considered as in the second phase. Synergies between SOHO and Cluster, or Cluster and IMAGE, or Geotail and Polar have been capitalized on to clarify causal relationships between what are usually pairs of physical processes. The missions such as the RBSPs, THEMIS, MMS will much more explore key processes much more completely than they have been to date.

KuaFu will be a typical mission in the third phase. Our objective with KuaFu is to enable true system-level geospace science for the first time. Our synoptic observations will by themselves lead to scientific firsts. More importantly, however, our observations will enable observations of the entire system from the Sun, through the solar wind with KuaFu-A, direct in situ observations quantifying processes of interest with the planned mission lineup of the RBSPs, MMS, THEMIS, and others, right through to the consequences in the ring current, ionosphere and thermosphere with KuaFu-B. In this way, KuaFu will, together with other planned ILWS missions, usher in a new era of Sun–Earth system research.

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