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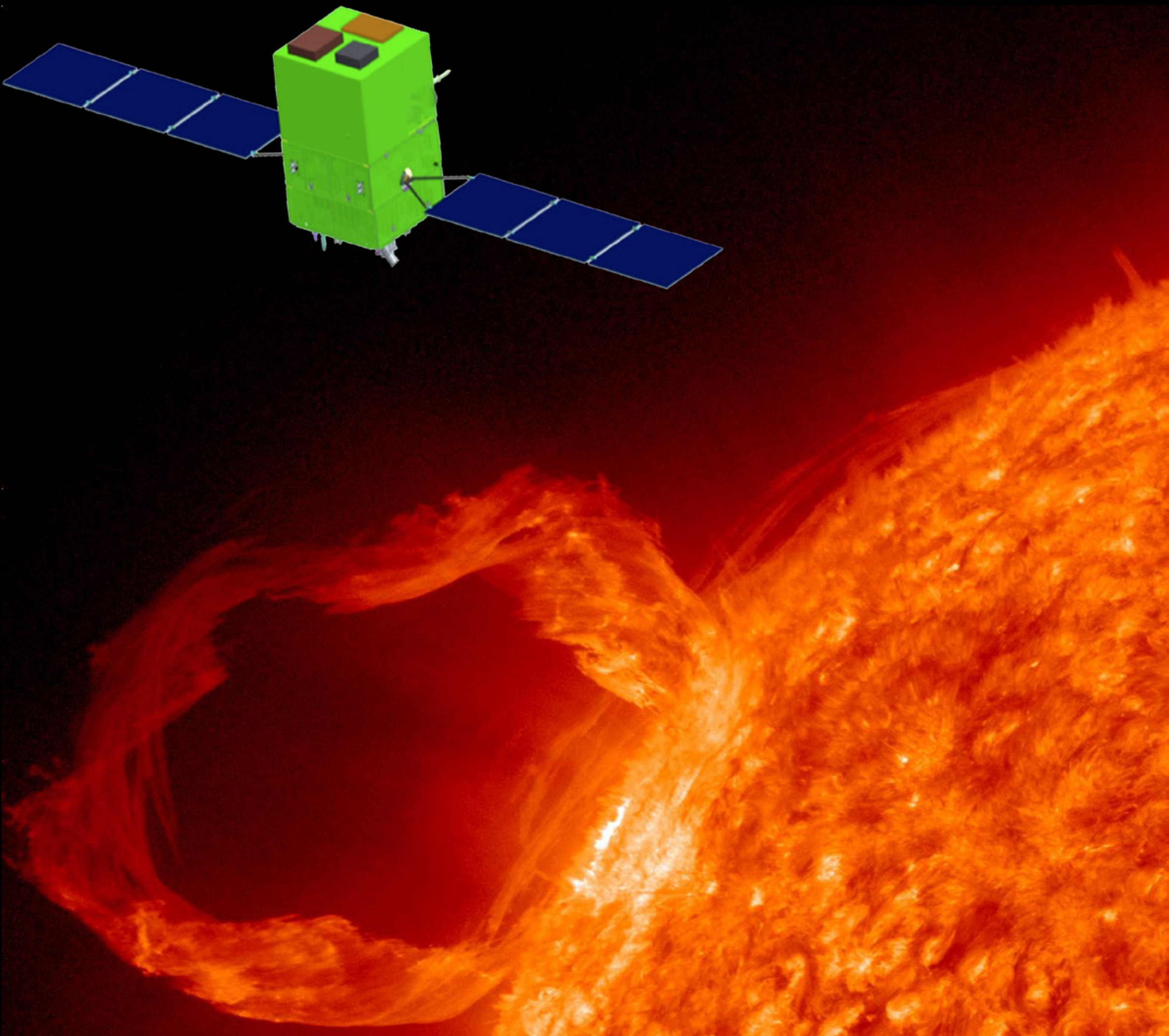
Exploring Solar Eruptions and their Origins



FOREWORD

The International Space Science Institute in Beijing (ISSI-BJ) successfully organized a two-day Forum on "Exploring Solar Eruptions and their Origins" in the framework of the Space Science Strategic Pioneer Project of the Chinese Academy of Sciences (CAS), in Beijing on October 30-31, 2014. ISSI-BJ Forums are informal and free debates, brainstorming meeting, among some twenty-five high-level participants on open questions of scientific nature. In total 27 leading scientists from eight countries participated in this Forum.

The Forum's main aims were to discuss the current status of the research progress on the relationships among magnetic fields, solar flares and coronal mass ejections and to identify relevant results acquired by current missions. The debate mainly focused on the Advanced Space-based Solar Observatory (ASO-S), its key science goals and mission definition, as well as some of the key technological issues. ASO-S is one of the candidate missions for advanced studies in the space science program of the Chinese Academy of Science, with regard to complementary missions.

After starting with recognizing the key scientific objectives for exploring solar eruptions, the Forum continued with an overview of the achievements of current relevant missions like Solar Orbiter and Solar Dynamics Observatory. Furthermore, new possibilities for observations of solar active phenomena were being discussed among the experts, in order to finally review the planed instruments and satellites for ASO-S. The participants recognized the very high scientific value of the mission and raised constructive comments and suggestions on the mission concept, payloads key techniques, and data product. They concluded that the ASO-S mission has complementary objectives to existing or future solar missions, e.g. SOHO, Solar Orbiter, or Interhelioprobe. Therefore, the ASO-S mission is an additional excellent example of how the Chinese Space Science program is innovative and challenging, and complementary to existing missions. This offers significant opportunities for cooperation through mission coordination and scientific analysis that places ASO-S and China in a central position due to its unique objectives and technology. It is also suggested that ASO-S should provide some routine tools to the community or high-level products of magnetic field.

The scientists concluded the very fruitful meeting with defining the mission to be successful with a broad international interest. This TAIKONG magazine provides an overview of the scientific objectives and the overall design of the ASO-S project, including spacecraft and instrumentation discussed during the Forum.

I wish to thank the conveners and organizer of the Forum Weiqun Gan (PMO, CN), Säm Krucker (FHNW, CH / UC Berkeley, US), Haimin Wang (NJIT, US), Yihua Yan (NAOC, CN). I also wish to thank the ISSI-BJ staff, Sabrina Brezger, Lijuan En, and Xiaolong Dong, for actively und cheerfully supporting the organization of the Forum. In particular, I wish to thank Weiqun Gan and Li Feng, who with dedication, enthusiasm, and seriousness, conducted the whole Forum and the editing of this report. Let me also thank all those who participated actively in this stimulating Forum.

Prof. Dr. Maurizio Falanga
Beijing
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Front Cover

This image artistically illustrates ASO-S observing the eruptions of the Sun.

INTRODUCTION

A two-day forum on the mission of the Advanced Space-based Solar Observatory (ASO-S) was held at the International Space Science Institute in Beijing (ISSI-BJ). Approximately thirty scientists and engineers from China, France, Germany, Italy, Russia, Switzerland, UK and USA attended this meeting. The forum was sponsored by ISSI-BJ with some support from the Purple Mountain Observatory, Chinese Academy of Sciences.

Solar flares and coronal mass ejections (CMEs) are the two most powerful eruptive phenomena on the Sun. The energies of these eruptions are believed to originally come from the solar magnetic field. The forum overviewed latest research progress on the solar magnetic field, solar flares, and CMEs, which are the major scientific objectives of ASO-S. The forum also had intensive discussions on the optimization of the scientific objectives and payloads, synergy between ASO-S and other ground and space observations, and potential international cooperation in the future.

The primary concept of the ASO-S mission was proposed in 2009 or earlier. It partially inherited the Sino-French joint Small Explorer for Solar Eruptions (SMESE) mission. The concept's phase A study was finished in March 2013. ASO-S is currently undergoing scientific and engineering background studies (phase B) from January 2014 to December 2015, in the framework of the Space Sciences Strategic Pioneer Project of the Chinese Academy of Sciences. If selected, engineering implementation is expected to start in 2016. Aiming at the 25th solar activity maximum, ASO-S is planned to launch in 2021.

This TAIKONG magazine presents an overview of the ASO-S mission, its major scientific objectives, the three payload elements onboard, and the outcome from the discussions during the forum

MISSION OVERVIEW

ASO-S could be the first Chinese solar space observatory, if selected in 2016. It is a small or middle-scale mission to understand the physical processes involved in solar eruptions, especially solar flares and CMEs. **Table 1** gives an overview of the mission.

ASO-S MISSION SUMMARY	
Top level scientific objectives	• Simultaneously observe non-thermal images of flares in hard X-rays, and formation of CMEs, to understand the relationships between flares and CMEs. • Simultaneously observe full-disc vector magnetic field, energy build up and release of solar flares, and the initiation of CMEs, to understand the causality among them. • Observe the response of solar atmosphere to eruptions, to understand the mechanisms of energy release and transport. • Observe solar eruptions and the evolution of magnetic field, to provide early warning and physical clues for forecasting space weather.
Payloads	• FMG: Full-disc vector MagnetoGraph • LST: Lyman-alpha Solar Telescopes • HXI: Hard X-ray Imager
Mission profile	• launch vehicle: Long March 2D • Orbit: solar synchronous orbit - Altitude: 720 km - Inclination: 98.2 degree
Spacecraft platform	• candidates: SAST1000 or ZY-1
Data downlink	• 220 GB/day
Launch year	• 2021
Mission duration	• > 4 years

Table 1: ASO mission overview.

SCIENTIFIC OBJECTIVES

A solar flare is detected as a sudden flash of brightness observed over the solar surface or at the solar limb. Solar flares can affect all layers of the solar atmosphere. The plasma temperature can reach tens of millions of Kelvins. Electrons, protons, and heavier ions are accelerated to relativistic energies and produce radiation across the electromagnetic spectrum at wavelengths from radio waves to gamma rays. Ionization produced by flare emissions may produce radio blackouts and disrupt communications.

A CME is a large-scale release of mass and magnetic field from the Sun. This process is a major cause of geomagnetic storms. Flares are often associated with CMEs, however, a causal relationship has not been established. The energies of these eruptions are believed to come from the solar magnetic field, with comparable amounts appearing as radiation and mass motions. Therefore, the simultaneous observations of the solar magnetic field, solar flares, and CMEs, are of particular importance in the study of their relationships.

The ASO-S mission is specifically proposed to understand the physical processes involved in solar flares, CMEs, and the solar magnetic field evolution. Its major scientific objectives could be abbreviated as '1M2B': one magnetism plus two bursts (flares and CMEs). **Figure 1** is an artistic view of a solar flare, a CME, and a possible associated magnetic field configuration.

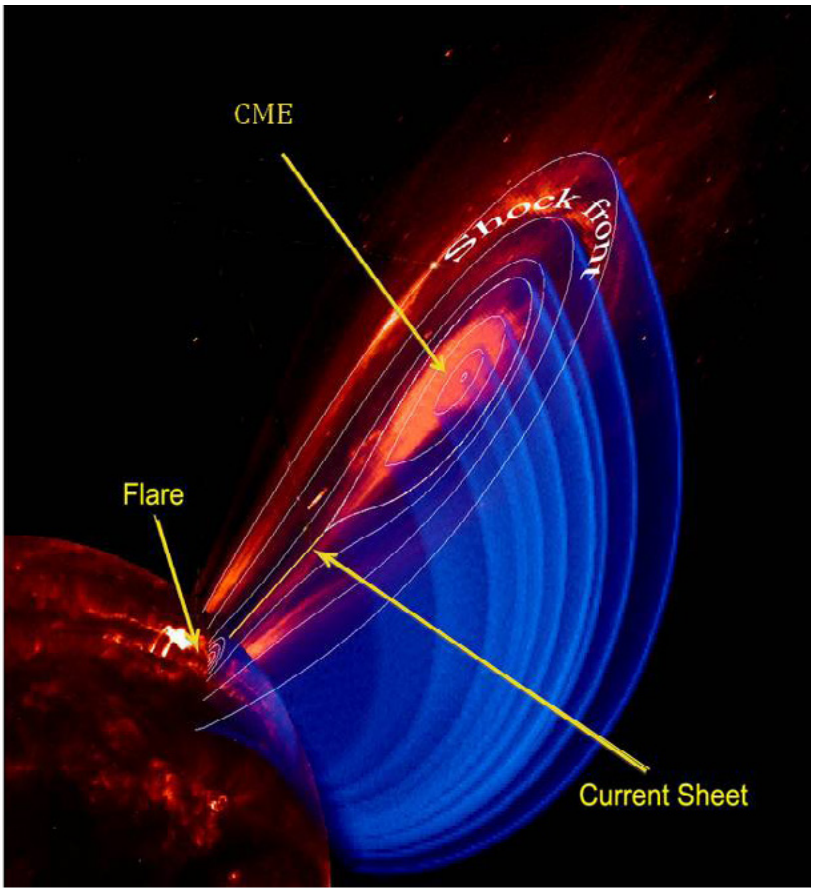

Fig. 1: An artistic view of a solar flare, a CME, and a possible magnetic field configuration in white (modified from NASA's Solar Sentinels STDT report).

In this complicated development, we can discern four major observational goals:

1) Simultaneously observe non-thermal images of flares in hard X-rays, and the formation of CMEs, to understand the relationships between flares and CMEs.

The origin and initiation of solar flares and CMEs remain unsolved and are still a hot topic in solar physics. It is generally accepted that flares originate locally, but CMEs can originate either in small scale or in large scale. The relationship between flares and CMEs is still in debate. Is there any cause-effect relationship between flares and CMEs? Does a flare trigger a CME or *vice-versa*, or is there no link between them? Statistically there is a rough 70% link. Why are some flares accompanied by CMEs, and others not, and how is this behavior determined? The Sun has an activity cycle of 11 years. It is predicted that cycle 25 would eventually start from 2020 and peak around 2022 to 2025. Close to the solar maximum, the occurrence of flares and CMEs is more frequent. ASO-S is planned to launch in 2021 and to make imaging observations of the source region of these two types of eruptions in white light, UV, X-ray, and γ-ray. ASO-S will be able to follow the eruptions from the photosphere to the corona and from their initiation to full development.

2) Simultaneously observe full-disc vector magnetic field, energy build up and release of solar flares, and the initiation of CMEs, to understand the causality among them.

A consensus has been reached that solar flares and CMEs are driven by

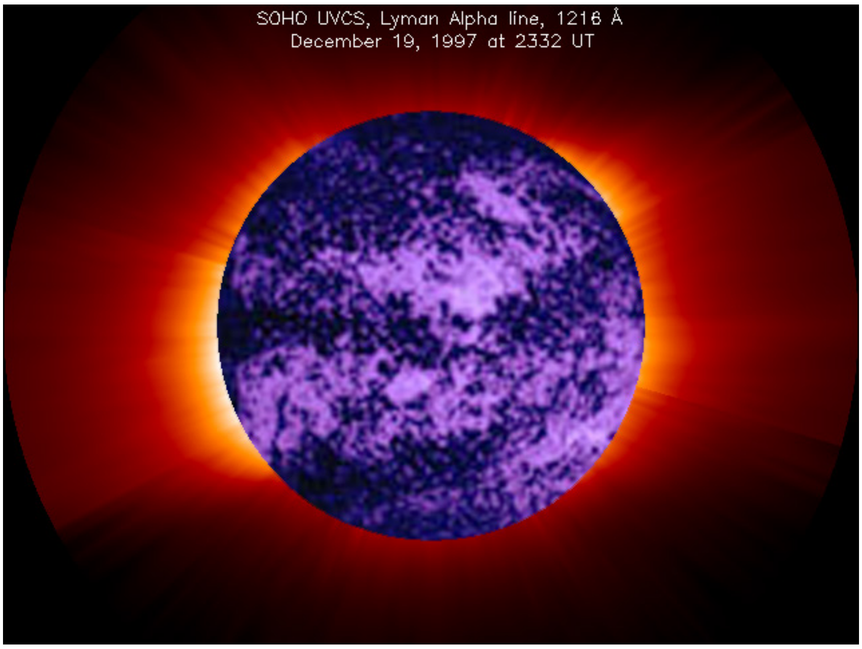

Fig. 2: Possible mode of Lyman-alpha observations of LST. The coronagraph image taken by SOHO/UVCS (UltraViolet Coronagraph Spectrometer) is similar to the future observations of LST/SCI, and full disk image observed by MSSTA (Multi-Spectral Solar Telescope Array) is in analogue to the future observations of LST/SDI.

the magnetic field, and the energy involved in these two eruptions comes from gradual build-up of stresses (the "non-potential energy") stored in the coronal magnetic field. The question 'What magnetic configuration is favorable for producing flares and CMEs?' remains to be one of the most important issues in solar physics. For example, the following questions need to be answered. What roles do the magnetic field shearing and magnetic flux emergence play to store the pre-flare energy and to trigger eruptions? What quantitative relationship can we establish between the magnetic field complexity and the productivity of CMEs? Are CME triggered locally (e.g., by magnetic reconnection) or globally on a large scale (e.g., by ideal MHD instabilities or loss of equilibrium)? The full-disk vector magnetograph onboard ASO-S will provide detailed information on the magnetic context of eruptions. HXI is dedicated for flare observations, LST for CME observations. Simultaneous observations of solar magnetic field, solar flares, and CMEs will help us to disentangle the relationships among them, and most importantly to establish quantitative relationships between the magnetic field and the eruptions.

3) Observe the response of solar atmosphere to eruptions, to understand the mechanisms of energy release and transport.

When flares and CMEs occur, huge numbers of energetic electrons and ions are accelerated. These accelerated particles can travel swiftly in the direction of the magnetic field, penetrate the lower

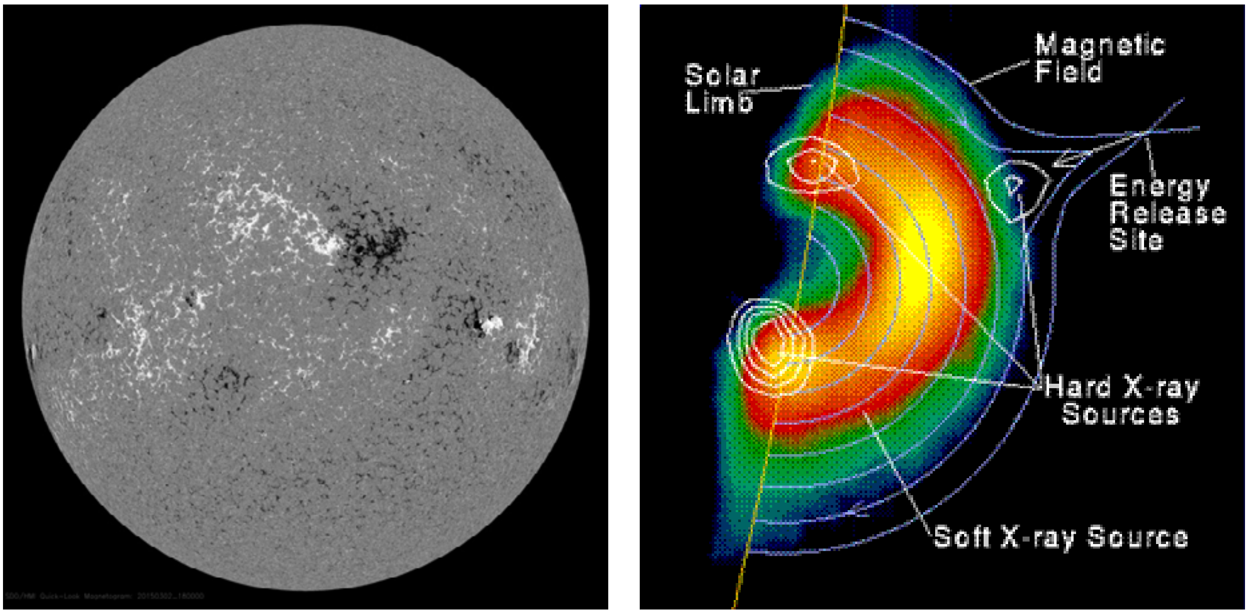

Fig. 3: Left: a full disk magnetogram observed by HMI. FMG will be a successor of HMI. Right: Magnetic field topology and X-ray sources of a flare. The magnetic field can be derived from FMG observations, and hard X-ray sources can be obtained from HXI measurements after the launch of ASO. (The image is adopted from the RHESSI website.)

Instrument	Mass (kg)	Size (mm)	Power (W)	Data rate(GB/day)
FMG	85	1200×600×450	55	140
HXI	50	1200×400×400	70	5
LST	60	880×600×420	80	75
Structure	25			
Sum	220		<250	220

Table 2: Weight, size power requirements and data rate of the three payloads..

atmosphere, and heat the plasma there. ASO-S is designed to observe the lower corona, chromosphere, and photosphere simultaneously. The observations in X-ray and γ-ray can reveal properties of accelerated electrons and ions. Thus the energy transport process during the eruptions in the solar atmosphere can be understood. The diagnostics of the energy transport is a key to understand the energy release process, and to reveal the properties of the energetic particles escaping from the Sun. Meanwhile, contrary to H-alpha line studies, Lyman-alpha line has seldom been studied before. The pioneering systematic observations of the Lyman-alpha line will bring us an almost completely new window.

4) Observe solar eruptions and the evolution of magnetic field, to provide clues for forecasting space weather.

The space environment near the Earth is greatly influenced by flares and CMEs, which are two most intensive phenomena in the Sun. From flare observations by ASO-S, we can predict the arrival of energetic particles a few ten minutes in advance. From the CME observations by ASO-S, we can determine their morphology and propagation direction, then predict the arrival of a CME at the Earth tens of hours or a few days in advance. If we can obtain the relationships between the magnetic field and the eruptions from observations made by ASO-S, the predictions can be made even earlier according to the magnetic field quantities.

Figures 2 and **3** present a demonstrative observation of ASO-S in the future.

PAYLOADS

To fulfill the scientific objectives, three payloads are proposed: a full-disc vector magnetograph (FMG), a Lyman-alpha solar telescope (LST), and a hard X-ray imager (HXI). An overview of the mass, size, power requirement and data rate of three payloads can be seen in **Table 2**. An outline sketch of the ASO-S configuration appears in **Figure 4**.

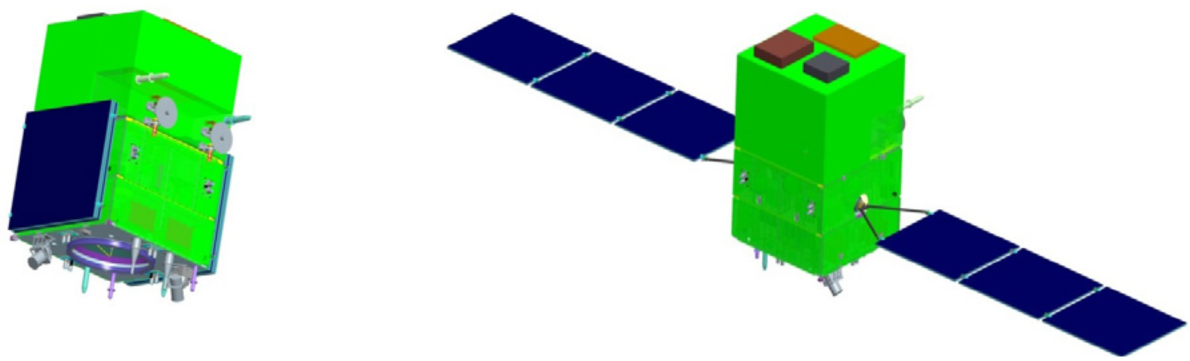

Fig. 4: Sketch of the ASO-S configuration.

• Full-Disc vector MagnetoGraph

FMG measures the magnetic fields of the photosphere over the entire solar disk. Compared with the magnetograph onboard Hinode, FMG has a much larger field of view and higher time cadence. Comparing to the magnetographs onboard SDO and SOHO, FMG has a simpler observation mode and a higher measurement precision. The main performance parameters of FMG and the corresponding parameters of the magnetograph of PHI (Polarimetric and Helioseismic Imager) onboard Solar Orbiter are listed in **Table 3**. FMG consists of an imaging optical system, a polarization optical system, and a CCD image acquisition and processing system. Its optical system is delineated in **Figure 5**.

• Hard X-ray Imager

HXI aims to image the full solar disk in the high-energy range from 30 keV to 300 keV, with good energy resolution and high time cadence. It is designed for flare observations. The principle of HXI is the same as HXT (hard X-ray telescope) on board YOHKOH using indirect imaging of spatial modulation. Unlike HXI and HXT, another high energy imaging mission RHESSI adopts the indirect imaging technique by rotational modulation. STIX (Spectrometer Telescope for Imaging X-rays) onboard Solar Orbiter takes the indirect imaging of spatial modulation as well. The key parameters of HXI and STIX are summarized in **Table 4**. The telescope structure including collimators, detector, and electronics box, etc., is presented in **Figure 6**.

• Lyman-alpha Solar Telescopes

To observe CMEs continuously from solar disk to a few solar radii, another payload LST will be on board. It comprises three telescopes observing in Lyman-alpha and white light: SDI (solar disk imager), SCI (solar coronagraph imager), and WST (full-disk white-light solar telescope) for the purpose of calibration. WST can also be used to observe white-light flares, a fundamentally important aspect of flare physics. SDI works in the same wavelength band as the HRI (High Resolution Imager) of EUI (Extreme Ultraviolet Imager) onboard Solar Orbiter; And SCI shares some common features with METIS (Multi Element Telescope for Imaging and Spectroscopy) onboard Solar Orbiter. The key parameters of these four instruments are presented in **Table 5**.

The hydrogen Lyman-alpha line is the brightest line in the UV and is formed all through the chromosphere and the bottom of the transition region. Comparing with the conventional white-light coronagraph images, Lyman-alpha coronagraph observations will provide new discoveries of CMEs. The light ray-tracing diagrams of the SCI and SDI are delineated in the left and right panels of **Figure 7**, respectively.

ORBIT, SPACECRAFT PLATFORM AND ALTITUDE CONTROL

ASO-S has a solar synchronous orbit at an altitude of ~ 700 - 750 km. The selection of the altitude takes into account both the particle background along the orbit for HXI

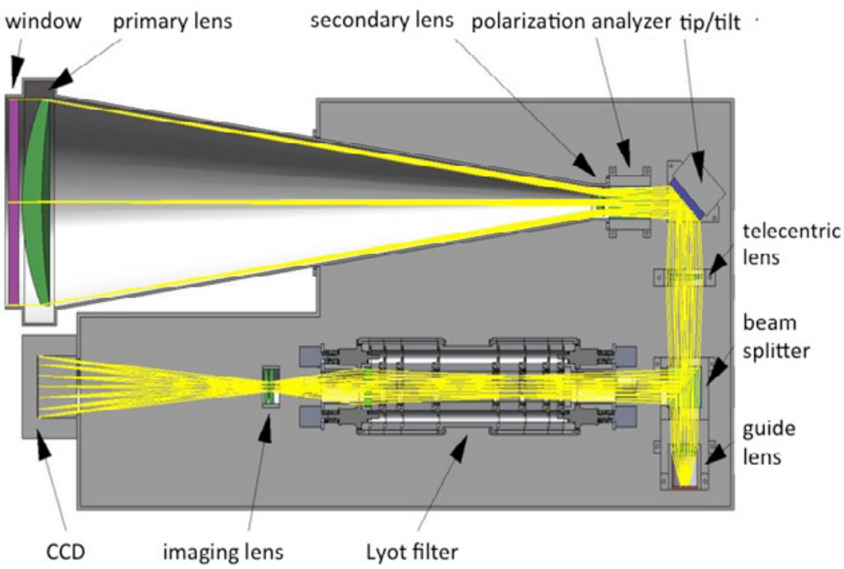

Fig. 5: Optical system of FMG.

	FMG	PHI/HRT	PHI/FDT
Wavelength	Fe I 532.4nm	Fe I 617.3±0.06nm	Fe I 617.3±0.06nm
Accuracy	B_{LOS}≈5G	B_{LOS}<10G	B_{LOS}<10G
Spatial resolution	0.5″	~200 km at 0.28 AU	~730 km at 0.28 AU
Temporal resolution	2 minutes	45-60s	45-60s
Field of view	33′	16.8′*16.8′	2.1°

Table 3: Key performance parameters of FMG and PHI. (HRT: high resolution telescope; FDT: full disk telescope)

and the scattered light level for LST. It has an inclination angle of around 98°.

- One candidate of the satellite platform is the FengYun series SAST1000 from Shanghai Academy of Space Technology. Another is ZY-1 from China Academy of Space Technology.
- The altitude control uses the three-axes stability technology. The platform attitude pointing accuracy is designed to be ≤ 0.01°, measurement accuracy ≤ 1″, stabilization accuracy ≤ 0.0005°/s. The payload attitude pointing accuracy is designed to be ≤ 20″, and stabilization accuracy ≤ 0.25″/30s for FMG and 1-2″/10s for LST.

DISCUSSION AND RECOMMENDATION

During the two-day forum, there were many insightful discussions. They are classified into three following categories:

1. MISSION CONCEPT

The participants intensively discussed the synergy between ASO-S and Solar Orbiter. Thanks to the different orbits of the two missions, stereoscopic studies can be made. For instances, FMG and PHI can work together to solve the 180° ambiguity problem of transverse magnetic field in a novel and extremely attractive manner; HXI and STIX can be used to study the anisotropy of energetic electrons and the 3D geometry of flare loops; LST and EUI/METIS can reveal the 3D context of the features observed in Lyman-alpha, such as prominences. The remote-sensing instruments onboard Solar Orbiter have only a limited duty cycle, while the observations made by ASO-S will be able to monitor the Sun with much higher data rate. Together also with the Russian mission Interhelioprobe and many ground-based telescopes, scientists can benefit hugely from multi-perspective, multi-wavelength observations of commonly observed phenomena.

ASO-S plans call for a launch in around 2021 for selection at the end of 2015. Some of the participants worried about such a tight schedule and expressed that some delay is completely acceptable. However, after comprehensively considering the status of key technology, the participants found that the time scheme is attainable. For FMG, the team has worked on the magnetograph for tens of years, and the key technology is already there. For HXI, the team has done a good part of work. Further through international collaborations, the PI of STIX onboard Solar Orbiter was confident that the key technology of HXI could be solved in time. LST inherits the Lyman-alpha telescope

	HXI	STIX
Energy range	30-300 keV	4-150 keV
Energy resolution	3%@662keV	~1 keV, less at higher energies
Angular resolution	< 6″	7″
Field of view	1°	2.5° for spectroscopy, 1.5° for imaging
Temporal resolution	0.5 s	Up to 0.1 s
Effective area	100 cm^2	~6 cm^2

Table 4: Key parameters of HXI and STIX.

	LST/SCI	METIS	LST/SDI	EUI/HRI
Wavelength	121.6±10nm	visible: 580-640nm HI Ly α 121.6±10nm	121.6±5nm	H I Ly α 121.6nm 17.4 nm
Field of view	1.1 – 2.5 R	1.4 -2.9 $R_\odot$ (0.27 AU) 2.1 -4.35$R_\odot$ (0.4AU)	0.0 – 1.2 $R_\odot$	1000″*1000″
Spatial resolution	4.6″	20″(2*2 binning)	1.12″	1″
Temporary resolu-tion	4 - 10s	Visible: 5 min UV/EUV: 15-20 min	1-5s	can reach sub second

Table 5: Key parameters of LST/SCI, METIS, LST/SDI, and EUI/HRI.

designed for the Sino-French mission SMESE. It was proposed about 10 years ago. Therefore, we have already accumulated some experience from the SMESE mission and can also benefit from the techniques applied to Lyman-alpha telescopes onboard other missions, e.g., SOHO. Dr. Jean-Claude Vial suggested us to make good use of the time before the last round of the mission selection. All the participants expressed that even if a few years delay happens, there is no major influence on the scientific goals of ASO-S.

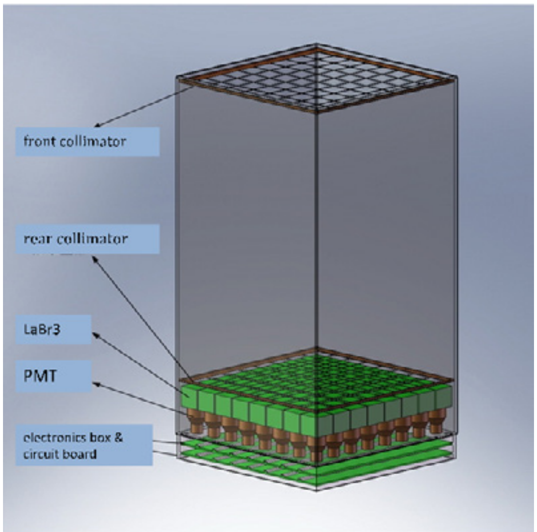

Fig. 6: Design of the HXI structure.

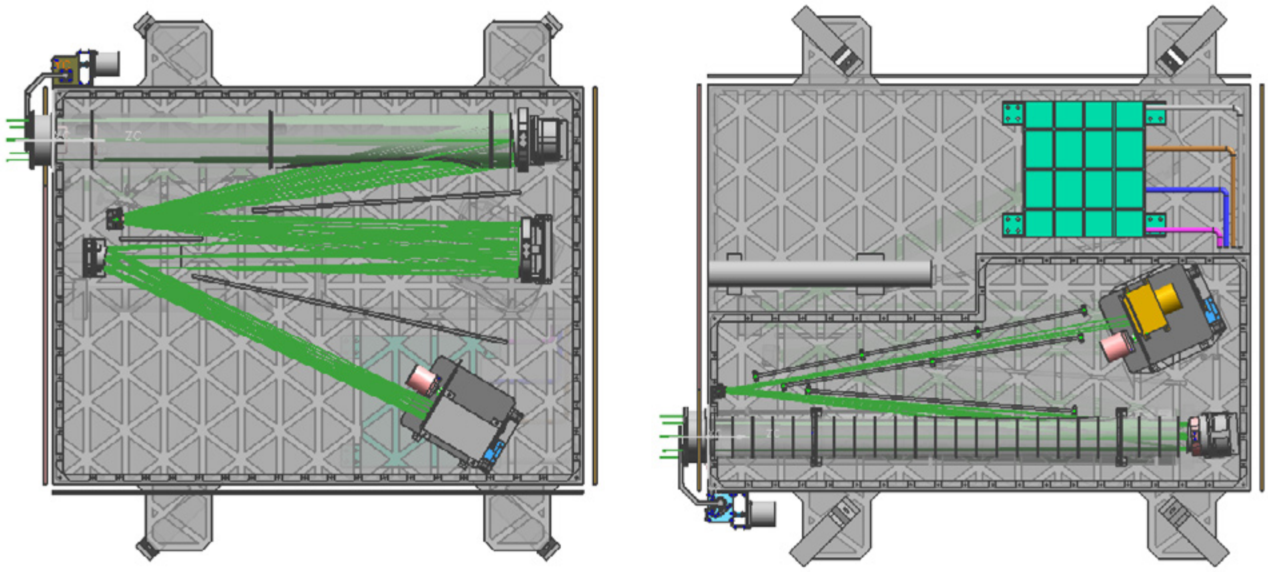

Fig. 7: Ray-tracing diagrams of SCI (left) and SDI (right).

2. PAYLOADS KEY TECHNIQUES

The participants extensively discussed the key technologies involved in payloads.

• FMG

The key techniques of FMG discussed include: data acquisition and real-time onboard processing, image stabilization, temperature control (or compensation), and oil sealing. In order to get higher accuracy, FMG uses multi-frame-add mode. In normal mode of observation, 512 frames (half for left and half for right) will be collected for one magnetogram. Such huge data absolutely need real-time onboard data acquisition and processing. On the other hand, within 32s (for obtaining 512 frames) the pointing should be stabilized at least within half pixel, say 0.″25. For a birefringent-filter-based magnetograph, temperature control accuracy of filter should be better than 0.01°C. All of these issues should be paid more attention at this key stage of the project.

• HXI

The main discussions on HXI are about the energy range, absolute calibrations, cross talk problem between different subcollimators, background measurement, etc. It is found that the upper limit of the energy band of 300 keV is better than 150 keV that STIX has. Another new aspect of HXI is the high time cadence, which makes the image with tens of milliseconds possible. This is really new, since such a time is just the order of magnitude for the electrons travelling from the top of the loop to the footpoints, and HXI can for the first time resolve these motions. A big issue for hard X-ray telescopes is the calibration. The HXI team and STIX team plan to sit together in the future to compare the absolute values observed by HXI and STIX. The gain calibration was also briefly discussed. Proper alignment of front and rear subcollimator pairs needs to be done to avoid the cross talk problem and to ensure the optical performance. To measure the background, one can remove the grids in front of some detector elements.

• LST

LST led to quite a number of discussions. The FOV of LST onboard ASO-S is more beneficial in observing the inner corona than METIS onboard Solar Orbiter. The cleanness of the spacecraft is very crucial to Lyman-alpha measurements. Another fundamental issue for coronagraphs is to decrease the stray light, especially that from the first mirror. It is recommended to quantify the stray light as a function of radial distance. It is also recommended to add a white-light channel to increase the science outcome of LST, by implementing filter wheels in the optical path. The participants also suggested including a capability for measuring Lyman-alpha polarization to obtain the horizontal component of the coronal magnetic field, and the possibility of a Lyman-alpha spectrometer to retrieve more physical quantities. As a result, the LST team will seriously consider these possibilities and envisage the technical feasibility. During the meeting, the contrast of Lyman-alpha images and the contribution of geocorona to the Lyman-alpha signal were also discussed.

3. DATA PRODUCT

Another aspect is the data product. It is suggested that ASO-S should not only provide measurements but also some routine tools to the community. In particular for FMG, the team was asked to provide high-level products of magnetic field. Borrowing the experiences from HMI, the high-level product may include the extrapolated coronal magnetic field, the 180-degree disambiguation of the transverse field in the photosphere, and surface flow maps. Probably in the future, the Q-maps quantifying the magnetic topology could be included as well. It is better to start preparation for work early in the program.

SUMMARY

The participants reached an agreement after this two-day meeting: ASO-S has well-defined scientific objectives and will measure fundamental and important parameters of solar magnetic field, solar flares, and CMEs. The mission is not overloaded and still is ambitious. It has focus and is in good balance between the advanced scientific objectives and resources. Therefore, the mission is very probable to be successful. The director of Kiepenheuer-Institute for Solar Physics in Germany Prof. Oskar von der Luehe stimulatively asked the ASO-S team to "go for it"! And in the future, some workshops will be set up to work on the calibration of hard X-ray telescope on different missions, etc. It is also planned to frame ASO-S into the NASA's Living with a Star Program.

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