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Recent Progress of the Solar Wind Magnetosphere Ionosphere Link Explorer (SMILE) Mission*

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Abstract The SMILE (Solar wind Magnetosphere Ionosphere Link Explorer) mission is a joint space science mission between the Chinese Academy of Sciences (CAS) and the European Space Agency (ESA), aiming to understand the interaction of the solar wind with the Earth's magnetosphere in a global manner. As of May 2024, the SMILE mission is in phase-D with an expected launch date of September 2025. This report summarizes developments in the mission during the past two years.

Key words SMILE, Soft X-ray Imager, Ultra-Violet Imager, Light Ion Analyzer, Magnetometer

Classified index P353

1 Introduction

The SMILE[1] mission is the first all-around ESA-CAS joint mission in the framework of the Chinese Academy of Sciences (CAS) Strategic Priority Program on Space Science. The mission aims to deepen our understanding of the interaction of the solar wind with the Earth's magnetosphere. The primary scientific objectives of SMILE are to answer three main questions: (i) What are the fundamental modes of the dayside solar wind/magnetosphere interaction? (ii) What defines the substorm cycles? (iii) How do CME-driven storms arise and what is their relationship to substorms?

To answer these questions, SMILE hosts a payload that comprises four scientific instruments: Magnetometer (MAG), Light Ion Analyzer (LIA), Soft X-ray Imager (SXI) and Ultraviolet Imager (UVI). SXI will spectrally image the Earth's magnetopause, magnetosheath and magnetospheric cusps. UVI will capture images of the aurora borealis, LIA will measure the *in-situ* distribution function of the ions, and MAG will measure the *in-situ* vector magnetic field.

SMILE is a single spacecraft mission consisting of two main parts.

(1) A 3-axis stabilized Platform (PF), consisting of a Service Module (SVM) and a Propulsion Module (PM) that provides the spacecraft resources, will raise the orbit from the Launcher insertion orbit to the Highly Elliptical Orbit (HEO). It also hosts the two LIA sensors to enable them to synthesize a full-sky field of view.

(2) The Payload Module (PLM) hosts the other three instruments, SXI, UVI and MAG, the equipment and instrument control unit, and the X-band science data downlink subsystem. Figure 1 shows the SMILE satellite structure.

The joint Mission Preliminary Design Review (M-PDR) was completed successfully in January 2020 in the Netherlands. This was the third critical joint review of

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the SMILE mission, marking the kick-off of Phase-C activities. After two and a half years of phase C including the development and testing of structural and thermal models, electrical models, avionics tests and complete platform qualification, the fourth critical joint review, the Mission Critical Design Review (M-CDR), was successfully completed in Shanghai in June 2023 (see Figure 2), marking the kick-off of Phase-D activities. Since then, the mission has been developing the Flight Models (FMs).

In the previous progress report[2] in 2022, the respective responsibilities of CAS and ESA, as well as the Phase-B study and the early Phase-C study were introduced in detail. In this report, the progress in the last two years, *i.e.* late Phase-C and Phase-D stages is elaborated.

2 Advances in Scientific Research

2.1 A New Mechanism for Driving Planetary Magnetosphere Convection

Plasma convection induced by the interaction between planetary magnetic fields and the impinging solar wind is a fundamental and prominent feature of planetary magnetosphere dynamics. A global-scale pattern of magnetospheric convection in Earth's magnetosphere, known as the Dungey cycle[3], provides a basic understanding of solar-wind-magnetosphere coupling and has been used to explain day-to-day convection processes. In the Dungey cycle, reconnection between the IMF and the magnetosphere drives the convection of open magnetic field lines through the polar cap and magnetotail lobes, whereas nightside reconnection closes this open flux and drives the convection of closed field lines through the magnetosphere and back to the dayside. The dynamics of magnetosphere convection are crucial in the occurrence of geomagnetic storms and substorms. Differing from the Dungey cycle, Dai *et al.*[4] provide direct evidence supporting a scenario whereby reconnection on the dayside enhances the Region 1 and Region 2 current systems, resulting in enhanced convection within the closed magnetosphere towards the dayside as well as the expected convection of open field-lines towards the nightside. This new finding was published in *Nature Communications* with the title of "Global-scale magnetosphere convection driven by dayside magnetic reconnection", and was featured on the homepage and cover of the Nature Communications official website. This important finding provides valuable insights into the mechanisms driving planetary magnetosphere convection, which may be tested by the observation of the upcoming SMILE mission.

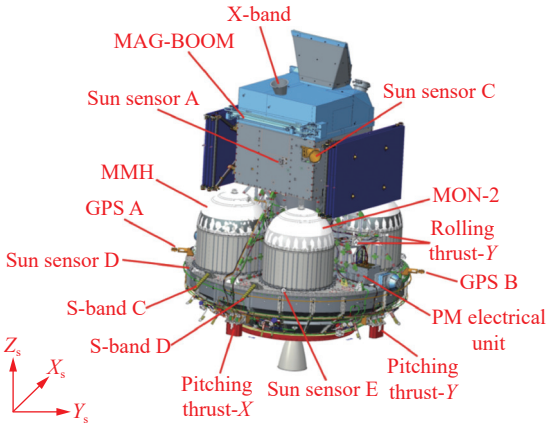


Fig. 1 SMILE satellite structure

2.2 Modelling Working Group

The SMILE Modelling Working Group (MWG) provides modeling supports for the SMILE mission, such as



Fig. 2 SMILE M-CDR group photo in Shanghai

Magneto-Hydro-Dynamical (MHD) model comparison, validation of the SXI requirements and goals, boundary tracing from simulated SXI data, and the development of techniques to reconstruct the 3 D magnetopause from X-ray images. The main progress of MWG has been published recently in the journal Earth and Planetary Physics (EPP) as a special issue[5]. This special issue, comprised of 22 articles, covers the following seven topics: (i) instrument descriptions of the Soft X-ray Imager (SXI), (ii) numerical modeling of the X-ray signals, (iii) data processing of the X-ray images, (iv) boundary tracing methods from the simulated images, (v) physical phenomena and a mission concept related to the scientific goals of SMILE-SXI, (vi) studies of the aurora, and (vii) ground-based support for SMILE.

Guo *et al*.[6] and Yang *et al*.[7] performed hybrid simulations to reproduce refined structures in the magnetosheath, such as waves and High-Speed Jets (HSJs). According to simulation results, although local X-ray emissivity in the magnetosheath can have large amplitude fluctuations (up to 160%), the accuracy of magnetopause boundary detection is not significantly affected while analyzing line-of-sight integration of X-ray emissivity. Deformation of the magnetopause caused by HSJs can reach about 1 R_e in spatial scale and can last for minutes as illustrated in Figure 3 [7]. Their results suggest that the impact of HSJ's may be visible to SMILE.

Jorgensen *et al*.[8] studied the reconstruction method of the subsolar magnetopause from multiple soft X-ray images to be observed by different missions in space at the same time. It is concluded that real-time CT reconstruction of the subsolar magnetopause position can be achieved with images observed by two hypothetical satellites from different viewing geometries.

Careful removal of background X-ray noise is imperative in order to derive the magnetopause position accurately. Zhang *et al*.[9] use two methods to remove the X-ray background superposed on the magnetosheath signal in XMM-Newton data. It demonstrates that both methods are robust and reliable. Wang *et al*.[10] developed an image restoration algorithm based on deep learning to remove background noises and highlight the magnetosheath signals. They demonstrated that the image restoration algorithm significantly improves the accuracy of the magnetopause position derived from noisy X-ray images.

Combining global detection from SMILE with observations from other missions and observatories could be important to understanding the solar wind-magnetosphere-ionosphere coupling system. Zhang *et al*.[11] provide analyses of the joint detection capability of SMILE and the European Incoherent Scatter Sciences Associa-

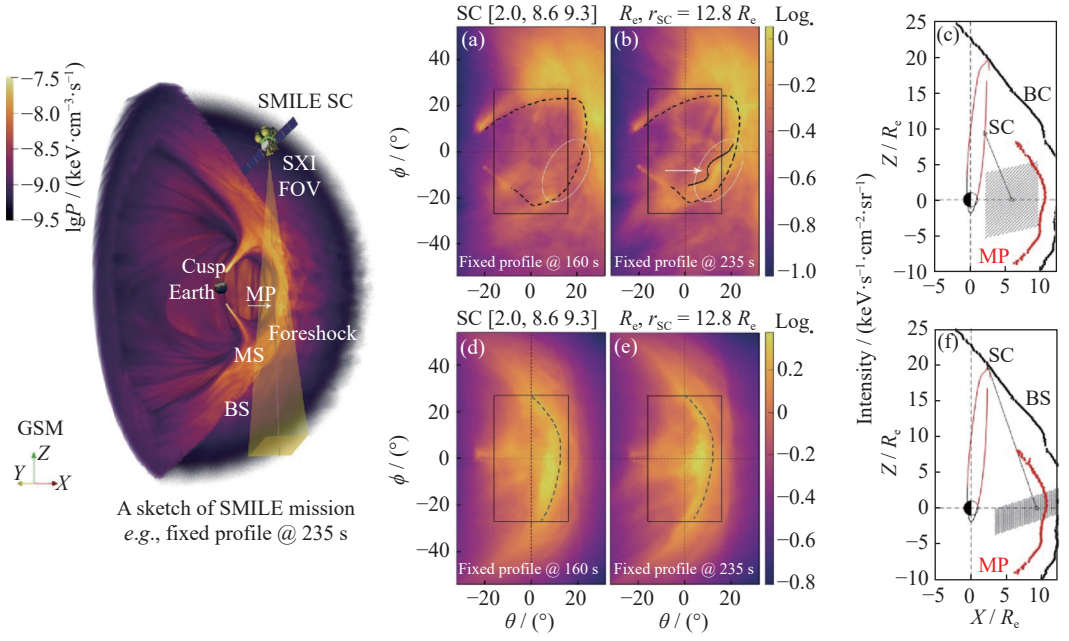


Fig. 3 Deformation of the magnetopause caused by high-speed jets as revealed by the X-ray emissivity (upper panel) and X-ray images (lower panel)

tion's (EISCAT)-3 D radar. Opportunities for joint studies using SMILE and EISCAT-3 D data are presented.

3 Mission Update

3.1 Platform

The PF structure is a stacked structure, including the PM structure comprised of a large Carbon Fiber Reinforced Polymer (CFRP) primary structure and four propellant tanks, and the cubical-shaped SVM structure featuring several honeycomb panels and CFRP frames. There are two solar arrays mounted on the SVM $+Y$ and $-Y$ lateral panels as shown in Figure 4, which are installed and deployed by two solar array mechanisms. The assembly of SVM and PM flight models has now been completed.

3.2 Payload Module

The PLM, hosting the SXI, UVI, MAG, the equipment and instrument control unit and the X-band science data downlink transmitter, has successfully passed CDR in May 2023. Currently, the PLM is on track for integration of the instruments. After receiving the FM of SXI, MAG and LIA as well as QM of UVI, the PLM will complete the last steps of its Assembly, Integration and Tests (AIT) phase.

3.3 Instruments

3.3.1 SXI

SXI will use novel soft X-ray imaging technology to obtain global images of the large-scale structures of the magnetosheath for the first time. This is critical to understand the key features of magnetospheric global dynamics. SXI consists of a main telescope, an SXI electronics box and the front-end electronics. The telescope uses a Lobster-eye technique based on micropore optics to focus the X-rays onto the two very large CCD arrays located on the focal plane. The focal plane is protected from potential radiation damage by a shutter mechanism. Figure 5 shows the SXI Telescope Proto-Flight Model (PFM) during a vibration Test conducted at Rutherford Appleton Laboratory (RAL) Space. SXI is now going through its PFM Qualification and Acceptance Review (QAR) and will be delivered to Airbus shortly thereafter.



Fig. 4 Assembly of the SVM with PM

3.3.2 UVI

UVI will capture global images of the aurora borealis with high spatial resolution. UVI consists of two key sub-assemblies: the optical module (UVI Camera, UVI-C), which is the heart of the instrument; and the electrical control unit (UVI-E). Following programmatic difficulties in 2021, the responsibilities for the development of this instrument, originally led by the Canadian Space Agency, were taken on by CAS with contributions from ESA. This caused a delay in the development of UVI, however, CAS and ESA are doing their utmost to minimize the schedule impact. The UVI-C Qualification Model (QM) has completed delivery acceptance testing, and QM Pre-Shipment Review (PSR) will follow. The QM of UVI is shown in Figure 6. The FM of UVI will

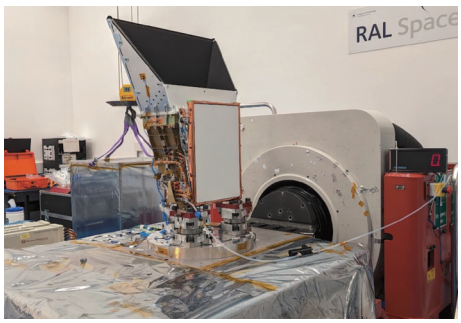


Fig. 5 SXI Telescope PFM during vibration test conducted at RAL Space (credit to S. Sembay, U. Leicester, UK)

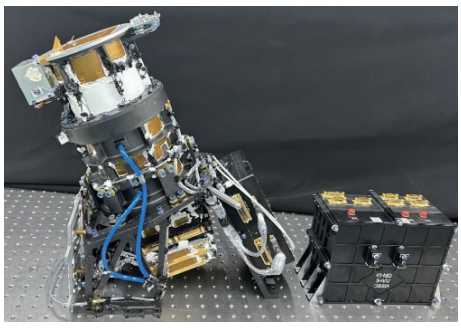


Fig. 6 QM of UVI

be tested at acceptance levels, calibrated, and delivered to ESA by September 2024.

3.3.3 MAG

The MAG instrument will measure the in-situ magnetic field using a digital fluxgate magnetometer system consisting of two individual tri-axial fluxgate sensor heads mounted on a 3-meter-long deployable boom. In March 2024, MAG FM passed the QAR and PSR organized by CAS and ESA. It has now been delivered to Airbus, which is the first instrument of SMILE that has been delivered to ESA. The FM of MAG boom and electronic box are shown in Figure 7.

3.3.4 LIA

Two identical LIA sensors are designed on the basis of a top-cap electrostatic analyzer for large dynamic flux range, wide Field of View (FOV) and high-resolution ion measurement. Since each LIA has 2π FOV, a large 4π FOV for the ion measurement can be achieved overall by the two LIAs. The FMs of LIA have been calibrated at the National Space Science Center (NSSC) and further calibration will take place at the Mullard Space Science Laboratory (MSSL) in August 2024. LIA has now completed its QAR. The FM of LIA are shown in Figure 8.

3.4 Ground Segment

The Ground Segment (GS) of the SMILE mission is jointly established by CAS and ESA. The GS architecture is illustrated in Figure 9 to demonstrate the respective responsibilities and ground-to-space links. The ground segment responsibilities and operation principles for CAS are Science Operations (joint responsibility), Mission Operations, Telemetry, S-band Tracking and Command (TT&C) ground stations, X-band payload data communication station (Sanya as backup). The ground segment responsibilities and operation principles for ESA are Science Operations (joint responsibility), S-band TT&C ground stations (as support to Mission Operations), X-band payload data communication station (s) (DLR station as baseline).

3.4.1 Systems Advances

Since both CAS and ESA GS are used to support multiple satellite missions, the common infrastructure has been already established before SMILE mission. Besides the newly-built Science Application System (SAS), other parts of SMILE GS will be customized from the existing infrastructure, facilities and tools to meet the mission-specific requirements.

The joint GS CDR was completed in June 2022. Since then, efforts have been made in software development. Currently, most software solutions are in the status of coding or updating. The newly-built system SAS also has completed the hardware construction and entered software coding.

3.4.2 GS Activities

GS validation and verification activities define the interface activities between systems.

In Phase C, the interface compatibility tests included: S/C-CCC (Chinese Control Centre) S-Band compatibility test, S/C-ESOC (European Space Operations Center) X-Band compatibility test and S/C-GSS (Ground Support System) TC (Telecommand) test. In Phase D, up to now, the completed interface compatibility tests include S/C- GSS X-Band compatibility test, S/C-CCC S-Band RF compatibility test and S/C-ESOC X-Band RF compatibility test.

Other tests between systems, including GSS/SAS-ESOC interface compatibility test, CCC-GSS interface compatibility test, CCC-ESOC interface compatibility, GSS-ESOC interface compatibility test, S/C-GSS TC test, are scheduled to take place in 2024. After that, the System Operation Validation Test (SOVT) will be conducted during the Spacecraft AIT phase.

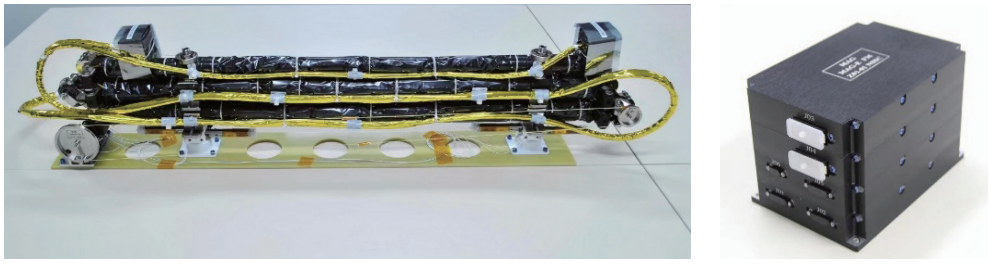


Fig. 7 FM of MAG boom (left) and electronic box (right)

3.5 Launch Vehicle

SMILE will be launched by a Vega-C rocket provided by ArianeSpace. The fit check with the satellite and the Launch vehicle adapter has been conducted at the beginning of 2023 in ESTEC as shown in Figure 10. The mechanical interface with the satellite has been confirmed. In April 2023, ESA signed a launch agreement with ArianeSpace, with a launch window now expected between September 2025 and September 2026.

4 Conclusions

Based on the status of the instruments, PLM and PF CDRs, the joint Mission CDR was completed successfully in June 2023 in Shanghai, which is the fourth joint review of the SMILE mission, marking the kick-off of Phase D activities. Currently, the SMILE mission is going through Phase-D, the final Flight Model (FM) assembly and testing phase. FMs of MAG, LIA, SXI and QM of UVI have been completed and will be integrated on the PLM. The FM of PF is under Assembly, Integration and Tests (AIT) and will be shipped to ESA for integration with the PLM in September 2024. The schedule remains challenging, but all work progresses smoothly. It is expected that the SMILE mission will be launched in the last quarter of 2025.

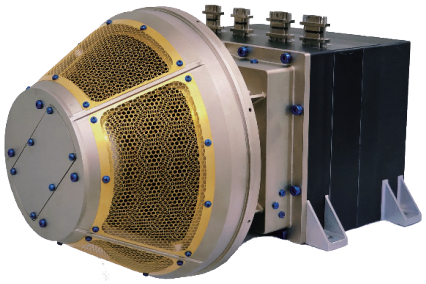


Fig. 8 FM of LIA

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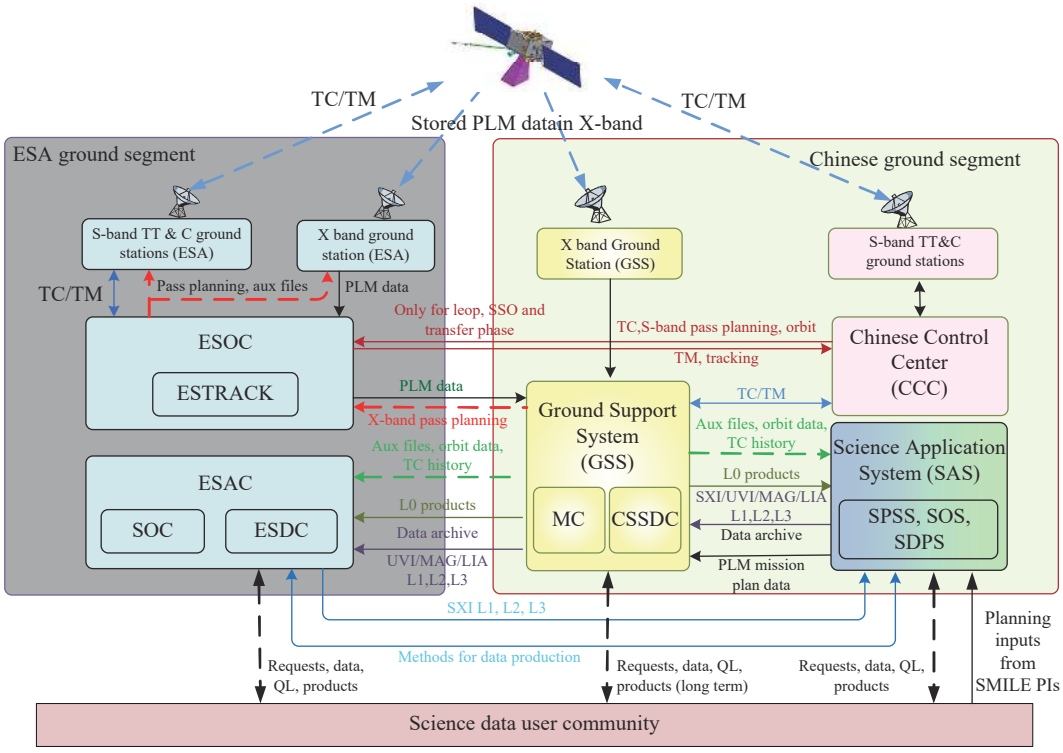


Fig. 9 SMILE ground segment architecture



Fig. 10 Vega-C fit check with satellite in 2023 in ESTEC (Credit to ESA)

Imperial College, Rutherford Appleton Laboratory, Airbus Defence and Space, Arianespace and all involved parties from European side.

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Author Biography



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