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Preface to the Special Issue on Modeling and Data Analysis Methods for the SMILE mission

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Abstract: The SMILE (Solar wind Magnetosphere Ionosphere Link Explorer) project (http://www.nssc.cas.cn/smile/, https://www.cosmos.esa.int/web/smile/mission) is a joint spacecraft mission of the European Space Agency (ESA) and the Chinese Academy of Sciences (CAS) with an expected launch in 2025. SMILE aims to study the global interactions of solar wind–magnetosphere–ionosphere innovatively by imaging the Earth's magnetosheath and cusps in soft X-rays and the northern auroral region in ultraviolet (UV) while simultaneously measuring plasma and magnetic field parameters in the solar wind and magnetosheath along a highly-elliptical and highly-inclined orbit. This special issue is composed of 22 articles, presenting recent progress in modeling and data analysis techniques developed for the SMILE mission. In this preface, we categorize the articles into the following seven topics and provide brief summaries: (1) instrument descriptions of the Soft X-ray Imager (SXI), (2) numerical modeling of the X-ray signals, (3) data processing of the X-ray images, (4) boundary tracing methods from the simulated images, (5) physical phenomena and a mission concept related to the scientific goals of SMILE-SXI, (6) studies of the aurora, and (7) ground-based support for SMILE.

Keywords: SMILE; X-ray imaging; magnetosphere; auroral; ionosphere

The Sun continuously emits streams of particles known as solar wind with an embedded and interplanetary magnetic field into space. Upon reaching near-Earth space, they dynamically interact with the terrestrial magnetic fields and plasma, releasing mass, momentum, and energy of the solar wind into the geospace environment system. The coupling between solar wind, magnetosphere, and ionosphere is a crucial link in the Sun–Earth interaction processes. Studying the dynamics of these coupled regions is essential for a holistic understanding of the Sun–Earth system.

Until now, in-situ observations by a limited number of satellites have been the main way to explore this complicated system. In-situ data provide valuable insights into many localized physical processes, on the microscale or mesoscale, but to reveal the global scenario of such a coupled complex system, based on such sparse localized observations, is extremely difficult if not impossible.

In this context, the European Space Agency (ESA) and the Chinese Academy of Sciences (CAS) have jointly supported a novel space mission: the Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) mission (Branduardi–Raymont et al., 2018), which will be launched in 2025. SMILE will image the region where solar wind directly interacts with the terrestrial magnetic field (around the subsolar magnetopause and the cusps) via the Soft X-ray Imager (SXI); simultaneously, SMILE will monitor the whole auroral region in the northern hemisphere via its UltraViolet Imager (UVI). Solar wind conditions will be detected by the MAGnetometer (MAG) and Light Ion Analyzer (LIA) also onboard SMILE when the satellite is outside of bow shock near the apogee (20 R_E) of a highly elliptical polar orbit. SMILE is a self-standing mission, monitoring large-scale solar wind–magnetosphere–ionosphere interactions by remote sensing, at the same time measuring the driver of the dynamic geospace system, i.e. the solar wind.

The scientific questions that SMILE aims to resolve are: (1) What are the fundamental modes of the dayside solar wind/magnetosphere interaction? (2) What defines the substorm cycle? (3) How do CME-driven storms arise and what is their relationship to substorms?

To ensure that the mission's science requirements will be met, it is essential to conduct reasonable estimations of the expected images, systematically develop the mission's data analysis methods, brainstorm potential scientific understandings derivable from the expected images, and prepare for synchronized ground/space-based detections before the launch of SMILE. These are the main tasks of the SMILE's Modeling Working Group (MWG) and Science

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Working Team (SWT). This special issue presents recent progress of their works.

The following 22 articles cover 7 topics important for the SMILE mission: (1) the instrument designs and performances of the SXI (papers 1–3: Sembay et al., 2024; Hubbard, et al., 2024; Parsons et al., 2024), (2) modeling of the soft X-ray emissions from the magnetosheath or cusps (papers 4–9: Samsonov et al., 2024; Guo J et al., 2024; Yang ZW et al., 2024; Grandin et al., 2024; Jung J et al., 2024; Koutroumpa, 2024), (3) data processing methods (papers 10–11: Zhang YJ et al., 2024; Wang RC et al., 2024), (4) reconstruction of the boundaries from 2D images (papers 12–15: Read, 2024; Kim et al., 2024; Cucho-Padin et al., 2024; Jorgensen et al., 2024), (5) physical phenomena and mission concept related to SMILE (papers 16–18: Hsieh et al., 2024; Echim et al., 2024; Küntz et al., 2024), (6) studies of the aurora (papers 19–20: Ohma et al., 2024; Liang J et al., 2024), and (7) ground-based support for SMILE (papers 21–22: Carter et al., 2024; Zhang JJ et al., 2024).

In the Earth's magnetosheath and cusps, the process of solar wind charge exchange (SWCX) occurs when an electron is transferred from a neutral atom to a high-charged solar wind ion during the interaction and then the ion de-excites, leading to the emission of an X-ray photon (Carter et al., 2010). These X-ray photons can be collected by the wide field of view (FOV) soft X-ray imager onboard SMILE. Based on its Lobster-eye optics, the FOV of SMILE-SXI is designed as 15.5° × 26.5°, sufficient to cover the main region of solar wind-magnetosphere interaction near the subsolar magnetopause. The key mechanical components, instrument modes, performance, and simulations of SMILE-SXI are summarized by Sembay et al. (2024). Utilizing magnetohydrodynamics (MHD) and instrument simulations, they conclude that the subsolar magnetopause location can be derived with a spatial accuracy better than 0.5 R_E (solar wind flux $\geq 4.9 \times 10^8$ cm^{-2} s^{-1}, integration time = 5 minutes), compliant with the science requirement of SMILE. Hubbard et al. (2024) focus on evaluating the instrument background for the Charge-Coupled Devices (CCDs) that form the focal plane array of the SXI, with different radiation shutter door positions at different periods of the solar cycle. The unfocussed instrument background with the shutter door open is estimated as $(8.25 \pm 0.16) \times 10^{-3}$ counts s^{-1} cm^{-2} keV^{-1} during the mission epoch. Galactic cosmic rays are the main contributor to this instrument background. Parsons et al. (2024) provide baseline performance characteristics of the SMILE-SXI flight model CCDs, based on experiments. They report that the performance of the devices meets the SMILE-SXI CCD procurement specifications for the nominal −120 °C operating temperature.

The SMILE mission will be the first to enable a large-scale vision of the dayside magnetopause. Before its launch, an interesting and important question is: What can we reasonably expect to observe in SMILE images? Previous studies have provided predictions via MHD simulations (e.g., Sun TR et al. 2015; 2019; Connor et al., 2021). As the SWCX emissivity is roughly proportional to the proton flux, it is highest in the Earth's magnetosheath and cusps, forming a crescent-shaped region and two bright spots in the X-ray image (as shown by the logo of SMILE). Samsonov et al. (2024) studied an event with the southward IMF turning; using MHD simulations, they validate that the dynamic motion of the magnetopause can be captured by SMILE-SXI. Hybrid simulations help to better reveal some refined structures in the magnetosheath, such as waves and high speed jets (HSJs). Guo J et al. (2024) report that local X-ray emissivity in the magnetosheath can have large amplitude fluctuations (up to 160%). Nevertheless, on an X-ray image derived from line-of-sight integration of local X-ray emissivity, the magnetopause boundary position indicated by maximum X-ray intensity is not significantly affected by fluctuations in the sheath. Yang ZW et al. (2024) studied the magnetopause deformation caused by HSJs under radial IMF conditions. They report that the deformation can reach ~1 R_E in spatial scale and can last for minutes, which enables its detection on SXI images. Hybrid-Vlasov simulation of the X-ray emissions was performed by Grandin et al. (2024). Quantitatively, they estimate the enhancements of X-ray intensity to be 12% for flux transfer events and 4% for mirror-mode waves in the magnetosheath; these are likely to be conservative estimations, as the solar wind flux used in this Vlasiator run was lower than in average anticipated conditions. Jung et al. (2024) developed a user-friendly model of magnetosheath parameters calculated directly from the solar wind inputs: number density, velocity, temperature, and magnetic field. With this parametrized model, which is publicly available, scientists can easily estimate the expected soft X-ray images from any given vantage point. In all the above simulations, the interaction efficiency factor α is a crucial parameter, directly influencing the signal-to-noise ratio of the SXI images. Compiling ACE measurements of the solar wind abundance and atomic data from literature, Koutroumpa (2024) has systematically calculated α values for charge-exchange with H and He under various solar wind types and solar cycle conditions.

The observed X-ray signals of the magnetosphere will be superimposed on some diffusive backgrounds from the universe. Careful removal of background noise helps improve the accurate detection of magnetopause and cusp boundaries in the X-ray images. Zhang YJ et al. (2024) compare two methods to remove the background by analyzing the XMM-Newton observation data: a method based on the ROSAT All-Sky Survey (RASS method), and one based on observation data oriented along the same pointing direction under quiet solar wind conditions (quiet method). They conclude that both methods are robust and reliable. Wang RC et al. (2024) propose to remove background noises by means of an image restoration algorithm based on deep learning. Their idea is to train a patch estimator by selecting noise–clean patch pairs with the same distribution through the Classification–Expectation Maximization algorithm. They demonstrate that applying the image restoration algorithm to noisy X-ray images significantly improves the accuracy of the magnetopause position derived from such images.

The magnetopause and cusp boundaries are 3D, while the observed X-ray image is 2D. Therefore, to better understand the solar wind–magnetosphere interaction via SXI data, it is an important and challenging task to trace the boundaries from X-ray image(s) and do the reconstruction. Several methods have been developed, applicable to different situations (Wang C and Sun TR et al., 2022). Among some of these methods, a hypothesis has been suggested and applied: the apparent peak in the magnetosheath X-ray intensity is aligned with the tangent direction of the magnetopause boundary (Collier and Connor, 2018). Utilizing

MHD simulations, Read (2024) tests the hypothesis for various viewing geometries under different solar wind conditions. Read's analysis concludes that the offset between the two directions is small when the spacecraft is well outside the magnetopause, which implies that some reconstruction methods may have reduced efficiency as the spacecraft gets closer to the magnetopause. Kim et al. (2024) derive the subsolar magnetopause position based on the additional assumption that the magnetopause surface near the subsolar point is almost spherical. The dynamic motion of the subsolar magnetopause is captured with an accuracy of < 0.3 R_E when the solar wind density is >10 cm^{-3}, meeting the scientific requirement. Computed tomography (CT) method can also be used to reconstruct the magnetosheath (e.g., Jorgensen et al., 2022). Cucho-Padin et al. (2024) further introduce a statistically-based estimation approach (maximum a posteriori, MAP), with foundations in tomography, to estimate the spatial distribution of magnetosheath soft X-ray emissivities. The feasibility of this method to derive magnetopause position from two images is demonstrated to be robust, based on various simulation tests. Motivated by the prospect of having multiple soft X-ray imaging instruments in space at the same time, Jorgensen et al. (2024) conclude that the real-time CT reconstruction of the subsolar magnetopause can be achieved with just two satellites that image the magnetosheath from different viewing geometries.

Some physical phenomena related to SMILE are also discussed. To better understand the solar wind–magnetosphere–ionosphere coupling, it will be very helpful to correlate measurements of magnetic field perturbations at geosynchronous orbit with ground measurements of responses to the same solar wind variations. Hsieh and Sibeck (2024) present a systematic survey employing simultaneous solar wind, geosynchronous, and ground based observations. They report that for events with apparent increase in the north/south component of the ground magnetogram, the number of events attributed to variations of IMF B_z and variations of pressure model are nearly equal. A better understanding of how the effects of solar wind variations propagate to the ground and change the magnetic field will be aided by future SMILE observations of the dayside magnetopause and aurora, correlated with ground observations. Magnetopause properties at the flank are compared using MHD simulations, the kinetic Vlasov equilibrium, and in situ observations by Echim et al. (2024). For the general trend of most parameters near the magnetopause, global MHD shows similarities with in situ measurements. Nevertheless, magnetopause thickness in global MHD simulations was found to be one order of magnitude larger than observation, while the kinetic model was in reasonable agreement. As variations of X-ray intensity are expected to reveal the thickness of the magnetopause (Zhang YJ et al., 2023), we can expect significant advancement of knowledge of magnetopause positions and boundary layer properties after the launch of SMILE. To complement SMILE's vision of global imaging, Kuntz et al. (2024) introduce a new mission concept in detail: Line Emission Mapper (LEM), a large-aperture micro-calorimeter-based mission. Anticipated to be launched in 2032, LEM will produce high energy resolution (<2 eV) spectra of the charge exchange X-ray emissions from the magnetosheath, enabling observation of small-scale structures (~0.22 R_E) at high cadence (one detection every 3 minutes).

When energetic particles from the magnetosphere precipitate and collide with the Earth's atmosphere, aurora can be produced. Tracing auroral variations promises to advance our understanding of ionospheric responses and the magnetospheric dynamics that drive the whole system. The UVI onboard SMILE is designed to monitor the northern aurora. Recognizing that the UV cameras are also sensitive to dayglow emissions produced by photoelectrons induced by sunlight, removing background emissions from the auroral emissions is beneficial to the auroral studies. Ohma et al. (2024) demonstrate a data-driven approach that uses robust statistics to model non-auroral emissions; using IMAGE data, they validate the usefulness of this model in removing non-auroral emissions from UVI observations. This method will also be applied to the upcoming SMILE mission. In visible aurora, the 557.7 nm green line is usually the brightest emission line; however, an RGB (red-green-blue) all-sky imager is generally employed, in observations of the aurora and airglow, to capture "true color" images. A reasonable conversion method from RGB data into realistic auroral spectral intensities is thus needed. The approach by Liang J et al. (2024) is established for Transition Region Explorer (TREx) observations and is also applicable to the SMILE all-sky imager that uses a similar RGB camera.

SMILE is going to image at large-scale the magnetosphere and ionosphere; at the same time, a wealth of existing ground and space-based instruments can provide complementary in-situ or regional observations of small or mesoscale structures. Combining these disparate observations to make joint detection of the solar wind–magnetosphere–ionosphere system on a variety of scales is of particular interest to the space science community because such studies promise to provide significant new insights to a broad range of scientific questions. The Ground-based and Additional Science (GBAS) Working Group has been gathering ground-based support for SMILE. Carter et al. (2024) summarize the efforts made by the GBAS working group, including an online data fusion facility and discussions of particular modes for experiments and of observing strategies. Among these ground-based supports is the European Incoherent Scatter Sciences Association's (EISCAT)-3D radar, an advanced ground-based ionospheric experimental device. The joint detection capability of SMILE and EISCAT-3D is analyzed by Zhang JJ et al. (2024).

This special issue presents work in several representative directions that has taken place during the pre-study period of the SMILE mission. Many similar inquiries are still ongoing. The modeling working group is open to all investigators who are interested in scientific inquiries that can be advanced by SMILE.

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