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ESA SMILE and Czech Participation

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SMILE (Solar wind Magnetosphere Ionosphere Link Explorer) is a space mission which aims to measure Earth's global system responses to solar wind and geomagnetic variations with innovative instrumentation, e.g. wide–field X-ray telescope of Lobster–Eye type, on board. It is a collaborative project of the European Space Agency (ESA) and the Chinese Academy of Sciences (CAS). The SMILE international consortium involves the Czech Technical University in Prague and the Czech teams are expected to contribute to the project, mainly to the science and software related to the X–ray telescope. The aim of this short paper is to provide an outline of SMILE and in particular of the Czech participation to this mission, with emphasis on observation of celestial X-ray sources as SMILE secondary science.

KEYWORDS:
space vehicles: instruments; X-rays: general; Sun: solar-terrestrial relations; Earth

1 | INTRODUCTION

In X–ray astronomy and astrophysics, we usually deal with X–ray imaging and spectroscopy of celestial galactic and extragalactic X–ray sources supplemented by solar and solar system X–ray observations. Consequently, most of past and recent X–ray satellites focused on these fields. However, X–ray emission occurs also much more nearby, namely in Earth atmosphere and in Earth magnetosphere (Branduardi-Raymont et al., 2016; Branduardi-Raymont, Wang, & Smile Collaboration, 2017; Wang, Escoubet, & Branduardi-Raymont, 2018).

Now we have the 1st space mission with innovative wide–field imaging X-ray telescopes addressing the X-ray imaging of Earth magnetosphere in the development. SMILE is a space mission which aims to measure Earth's global system responses to solar wind and geomagnetic variations (Branduardi-Raymont et al., 2016). SMILE (Solar wind Magnetosphere Ionosphere Link Explorer) will investigate the dynamic response of the Earth's magnetosphere to the impact of the solar wind in a unique manner, never attempted before: it will combine soft X-ray imaging of the Earth's magnetopause and magnetospheric cusps with simultaneous UV imaging of the Northern aurora. For the first time we will be able to trace and link the processes of solar wind injection in the magnetosphere with those acting on the charged particles precipitating into the cusps and eventually the aurora. SMILE will also carry in-situ instrumentation to monitor the solar wind conditions, so that the simultaneous X-ray and UV images can be compared and contrasted directly, and self-sufficiently, with the upstream driving conditions. With its unparalleled payload SMILE will provide answers to many of the open questions in solar-terrestrial relationships in a thoroughly novel way.

SMILE was put forward in March 2015 in response to the European Space Agency and Chinese Academy of Sciences (CAS) joint call for a small-size space mission. Out of 13 missions originally proposed, SMILE was the one chosen for an initial study phase during the summer of 2015. An initial study of the whole mission was carried out by ESA and CAS at their Concurrent Design Facilities during October 2015, and the conclusion is that the mission was feasible, with no show stoppers. In early November 2015 SMILE was formally selected by the ESA Science Programme Committee. The mission has been adopted by ESA as of March 2019. Launch is expected to take place at the end of 2023.

2 | THE SMILE SCIENCE

As already mentioned, the SMILE mission focuses on the study of the response of the Earth's magnetosphere to the impact of the solar wind (Branduardi-Raymont et al., 2016; Sun et al., 2018). Consequently, the key science questions for SMILE can be summarized as follows: (i) What are the fundamental modes of the dayside solar wind/magnetosphere interaction? (ii) What defines the substorm cycle? (iii) How do Coronal Mass Ejections (CME) driven storms arise and what is their relationship to substorms?

In addition to that, SMILE will determine when and where transient and steady magnetopause reconnection dominates. Dayside reconnection causes plasma to flow antisunward through the mangetopause boundaries, the cusps, and over the polar caps. Reconnection can persist for long periods, or be bursty and patchy. It is unclear whether steady reconnection occurs when the plasma beta is low (when the incoming Interplanetary Magnetic Field (IMF) pressure dominates), and whether unsteady reconnection happens when the converse is true, during high plasma beta conditions. SMILE will test this hypothesis by determining the location and evolution over time of the magnetopause boundary. SMILE will also measure the proton cusp spot latitude, extent in longitude and the proton cusp spot intensity. Measurements of the proton cusp will be used to determine whether the magnetopause has experienced compression, spatially constrain the X-line (the region over which magnetic reconnection occurs) and determine whether steady or bursty reconnection has happened.

The trigger that leads to substorm onset remains controversial. Southward turnings of the Interplanetary Magnetic Field (IMF) are required to add energy to the magnetotail lobes. However, the precise nature of how the energy is loaded into the tails and how this precedes a period of enhanced geomagnetic activity is an area of much controversy. A substorm may start after the magnetotail is squeezed by an increase in solar wind dynamic pressure. Alternatively, a northward turning of the IMF may trigger a substorm. Some substorms have been observed with no obvious external drivers. SMILE will track the evolution of a substorm. SMILE will monitor the loading of energy at the dayside magnetopause through to the response of the cusps and the subsequent changes in the size of the open field line region of the polar cap. SMILE will also test whether other modes of magnetospheric behaviours, such as Steady Magnetospheric Convection (when the size of the open-flux region of the polar cap does not change) and Saw-tooth events (a fast expansion and contraction of the open cap), are manifestations of the same process as substorms, but under different external driving conditions.

SMILE will follow the development and evolution of the CME-driven storms. The largest geomagnetic disturbances are often associated with CME-driven storms, and they present the largest space-weather threat to world-wide infrastructure. SMILE will determine whether these CME-driven storms are a sequence of substorms. SMILE will also consider the questions: how long does a substorm last, and how and why does a substorm stop? Does this happen when the reserves of stored magnetic energy in the mangetotail have been exhausted? Or does a substorm stop when changes occur in the upstream solar wind? A combination of conditions may be required for the complete cessation of a substorm, and therefore the relative importance of each factor must be considered.

SMILE will answer these questions using its novel approach of simultaneously: (ii) Measuring the input solar wind driving conditions, (ii) Determining the location and shape of the magnetospheric boundaries, and (iii) Determining the global nature and properties of the auroral oval (Sun et al., 2018).

2.1 | The magnetospheric X–ray emission mechanism: Solar Wind Charge Exchange (SWCX)

In contrast to most investigated X-ray emission processes in X–ray astrophysics, the emission mechanism of the Earth magnetospere has been recognized only recently and is based on the charge exchange emission which occur when ions interact with neutral atoms or molecules; one or more electrons are transferred to the ion into an excited state (Sun et al., 2019). In the subsequent relaxation of the ion (with the charge now reduced by the number of electrons captured), a cascade of photons may be emitted.

X-ray emission from Solar Wind Charge Exchange (SWCX) recombination occurs in planetary atmospheres, comets, interplanetary space, and in the Earth's exosphere, while evidence for extrasolar charge exchange emission has been observed in supernova remnants, galaxies and galaxy clusters. Consequently, the heliophysics, planetary science, and astrophysics communities all have an interest in SWCX.

SWCX emission could be used to image the Earth's magnetosheath. The magnetosheath is the area near the Earth where the magnetic field, embedded in the solar wind plasma, is confronted by the Earth's magnetic field. This results in the magnetosphere; a cavity of Earth–confined plasma which protects the Earth from the harsh conditions within the solar wind. This picture, however, is not static as the Earth system responds quickly to changes in the solar wind density and velocity (Sun et al., 2018).

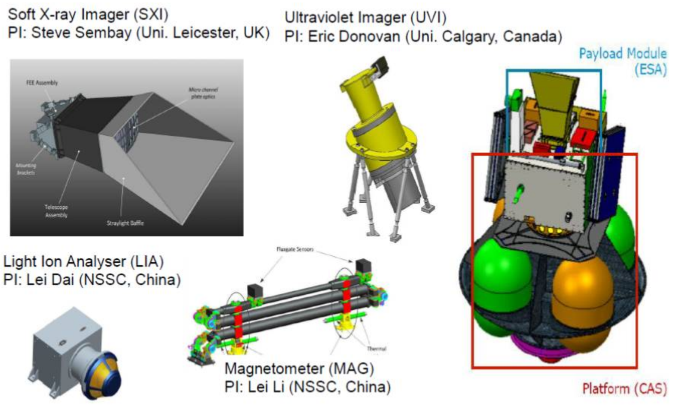

FIGURE 1 The SMILE payload.

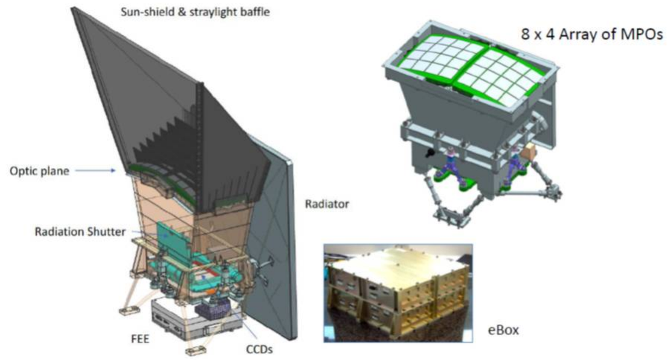

FIGURE 2 The SXI wide–field soft X–ray telescope onboard SMILE.

3 | THE SMILE PAYLOAD

The following instrumentation forms the payload for SMILE satellite (Branduardi-Raymont et al., 2016) (Fig. 1).

SXI: a telescope with a wide field of view FOV (26.5 x 15.5 degrees) Lobster–eye X–ray optic based on microchannel plate technology and CCD detector at the focal plane (Sembay et al., 2016). The SXI will observe the location, shape and motion of the dayside magnetospheric boundaries. X-rays in the Earth's exosphere result from the charge exchange interaction between ions in the solar wind and neutrals such as hydrogen in the Earth's exosphere and interplanetary space. PI: Steve Sembay, University of Leicester, UK (Fig. 2).

UVI: a wide field of view optic sensitive to the Lyman-Birge-Hopffman band of ultraviolet radiation (120–190 nm). Filters and coatings will be used to suppress day glow. The UVI will observe the polar cap, and measure the location and width of the auroral oval. It will also observe transient and localised brightenings that occur on the auroral oval edges. PI: Eric Donovan, University of Calgary, Canada.

LIA: a wide field of view proton and alpha particle analyser. This will determine the basic moments of the solar wind and magnetosheath ion distributions, such as velocity, density, temperature and the heat flux vector. These measurements, taken simultaneously with the UV and X-ray images, obviate the concerns of arrival times and spatial extents when external solar wind monitors at the distant Langrangian Point L1 are used. The LIA will include a top-hat-type electrostatic analyser. The centre plane of the field of view will be parallel to the ecliptic, to ensure that the solar wind and average plasma sheet flow directions remain within the field of view. Larger dynamic range will be obtained using a variable geometric factor system. PI: Lei Dai, National Space Science Center, Chinese Academy of Sciences, China.

MAG: a dual-redundant digital fluxgate magnetometer, with two tri–axial fluxgate sensors connected by a boom to a spacecraft-mounted electronics box. The accompanying electronics unit consists of a FPGA digital processing unit with a DC-DC converter. PI: Lei Li, National Space Science Center, Chinese Academy of Sciences (CAS), China.

3.1 | The SMILE operational orbit

SMILE is planned to be launched from Kourou, French Guyana, with ESA launcher VEGA-C or Ariane 6-2. The Mission Operations Center will be run by CAS; both organizations will jointly operate the Science Operations Center.

SMILE will operate in a highly elliptical and highly inclined orbit . The orbit takes SMILE a third of the way to the Moon at apogee (20 RE or 127 000 km) – two orbits are being considered, depending on the launcher, one with 70 degrees inclination. and the other with 98 degrees inclination (Fig. 3). This type of orbit enables SMILE to spend much of its time (about 80%, equivalent to nine months of the year) at high altitude, allowing the spacecraft to collect continuous observations for longer periods of time. This orbit also limits the time spent in the high-radiation Van Allen belts, and in the two toroidal belts.

4 | CZECH PARTICIPATION IN SMILE

CTU (Czech Technical University) in Prague and Rene Hudec are the SMILE SXI consortium members. The Czech participation is based on very long experience with imaging X–ray telescopes and monitors in the Czech Republic with emphasis on wide field X ray monitors Lobster Eye type.

[0]http://sci.esa.int/jump.cfm?oid=59199

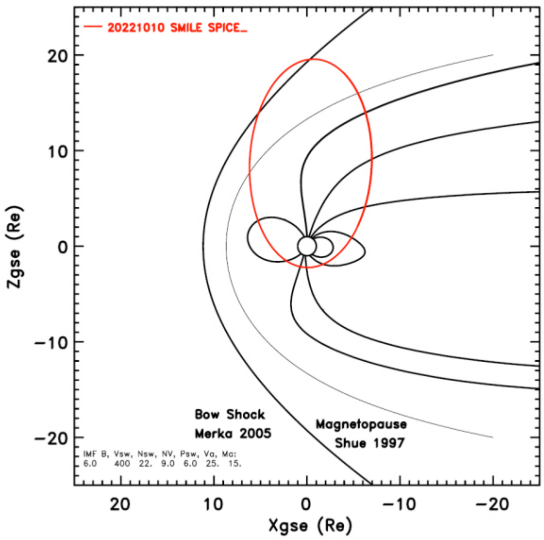

FIGURE 3 The expected SMILE operational orbit. The axes units are in Earth radii (Re). Picture courtesy ESA.

There is essential background in the Czech Republic in the design and the development of wide–field imaging X–ray telescopes based on the innovative Lobster–Eye X–ray optics (Hudec, Pína, & Inneman, 2017; Hudec, Pina, Inneman, & Tichy, 2015; Hudec, Sveda, et al., 2017; Pina et al., 2014).

The expected Czech contribution is based on scientific and data evaluation software and data analyses, with emphasis on the SXI telescope. The data and scientific analyses for celestial X–ray sources passing through the SXI FOV, also the secondary science with SXI data, represent another potential interest of the Czech team.

Two SMILE meetings were held in Prague, namely a SMILE session at Prague AXRO conference in December 2015 with presentations of SMILE PIs negotiating details on Czech participation, and SMILE project meeting in July 2016.

The Czech Technical University represents leading institution in the Czech Republic in education of space science and engineering in addition to that participating in numerous space projects [1] so that there is large potential for the involvement of students, PhD students and post docs in the SMILE project. Astronomical Institute of the Czech Academy of Sciences represents another important Czech Institution expected to participate in the project.

More details on the expected scientific contribution to SMILE, namely the secondary science aspects, are given in the next section.

[1] https://www.fel.cvut.cz/en/research/space-activities.html

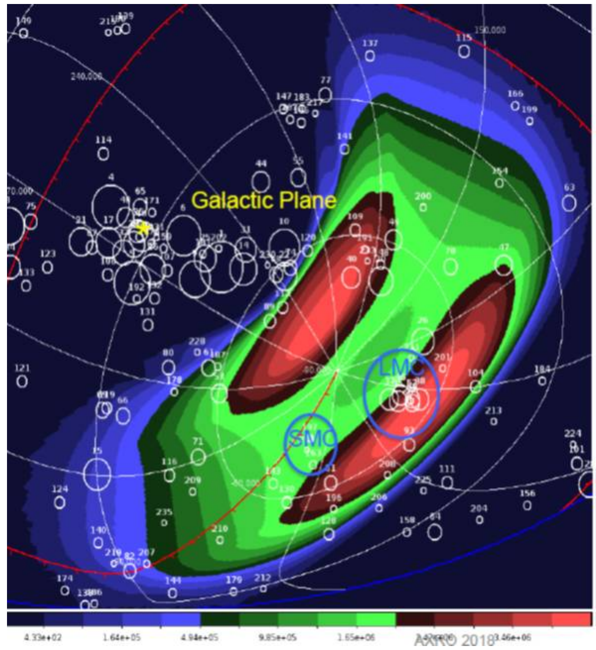

FIGURE 4 Many bright X-ray sources including many well-known calibration sources and IACHEC1 standard candles (1ES0102, N132D, PKS2155, Zeta Puppis, AB Dor, LMC X-2, LMC X-3, Vela Pulsar) are expected to pass through the SXI FOV. Analysis of all RASS (ROSAT All-Sky Survey) sources > 2 cps (counts per second) (237) over full year of SXI observations is shown on the picture: Only occurrences of more than 6 sources in the SXI FOV when observing the LMC are shown.

4.1 | Secondary science with SMILE

We propose that observing of activity of cosmic sources like X-ray binaries will be secondary science of SMILE. Because it is planned to observe the field around the ecliptic pole, the Magellanic Clouds containing many X-ray sources of various types will be included in the field of view of SXI (Fig.4).

We argue that SXI, observing with an effective energy range of 0.15—2.5 keV, can be used for monitoring of the long-term activity of X-ray binaries, containing the neutron star or the black hole accreting matter from a close companion (e.g. via Roche-lobe overflow of the donor, wind from the donor, or periastron passages of the donor) (see (Lewin, van Paradijs, & van den Heuvel, 1995) for a review).

Their X-ray spectra are continuous (often thermal emission from the inner part of the accretion disk + comptonized emission). The X-ray flux of most of these X-ray binaries peaks near energy $E \approx 1-2$ keV, so they can be detected and monitored with SXI. This instrument will detect mainly thermal emission of the inner disk region embedding the compact object in X-ray binary.

Several known and observable X-binaries are located right in the Magellanic Clouds. A series of observations with SXI can provide the X-ray light curves of this activity. These systems aften show strong variability of X-ray flux with time. Because their variability is strongest on the timescale of days, months and years, even combining the SXI data into the 1d-bins to increase the signal-to-noise ratio can be made.

We argue that SMILE can obtain useful observations of cosmic sources especially if we constrain ourselves on the states of activity of persistent X-ray sources (intense X-ray emitters all the time). In addition, because of the assumed long observing time of SXI, also a search for the outbursts of transient sources whose phases of activity are recurrent (especially if the epochs of the high X-ray emission last for months) will be promising targets for SXI.

We show an example of the light curve of a cosmic X-ray source which can be expected from the observations with SXI/SMILE. For this purpose, we made the X-ray light curve of SMC X–1. It consists of the 1-day means of data from the X-ray monitor MAXI/ISS (Matsuoka et al., 2009). MAXI can observe in the 2–20 keV band. These observations can be separated into several bands. We chose the 2–4 keV band which partly overlaps with the one of the proposed SXI/SMILE. The X-ray light curve of SMC X–1 is displayed in Fig.5a.

SMC X–1 is X-ray binary with the neutron star accreting matter from its early-type companion star (Reynolds, Hilditch, Bell, & Hill, 1993). Its orbital period is 3.8927 days (Schreier, Giacconi, Gursky, Kellogg, & Tananbaum, 1972). This object also shows strong super-orbital modulation on a timescale of about 60 days (Clarkson et al., 2003; Gruber & Rothschild, 1984). It can be explained by occultation by a precessing and warped disk using models of (Ogilvie & Dubus, 2001; Wijers & Pringle, 1999). The cycle-length of this modulation in SMC X–1 is unstable, with several strong recurrent excursions (Hu, Mihara, Sugizaki, Ueda, & Enoto, 2019).

We selected a time segment of 1000 days, which can be an approximation of the expected time of the operation of SXI. We can see the big variations of flux on the timescale of weeks. They recur with the timescale of about 55 days (Fig.5a). The data points with the remarkably low fluxes during the bumps represent the orbital modulation of SMC X–1, not an observing noise.

The histogram of fluxes of SMC X–1 in Fig.5b, representing a series of 18 bumps, shows a broad, asymmetric peak near flux 0.05 photons cm^{-2} s with a significant tail toward high flux. The broad peak near flux 0 photons cm^{-2} s shows that SMC X–1 can even become temporary undetectable in some minima of the super-orbital modulation.

Fig.5c shows a comparison of two epochs of activity from Fig.5a. Neither the lengths nor the peak fluxes of these individual bumps remain the same.

We show that SXI/SMILE will be able to obtain new observations of the long-term activity of X-ray binaries in the soft X-ray band. It will be even possible to extend this coverage to a very soft X-ray band (even below $E < 1$ keV), not accessible to most previous or current observings on the long time scales (months, years). Since it is possible to divide the SXI observations into several energy bins, it will be also possible to show the hardness ratios of the activity.

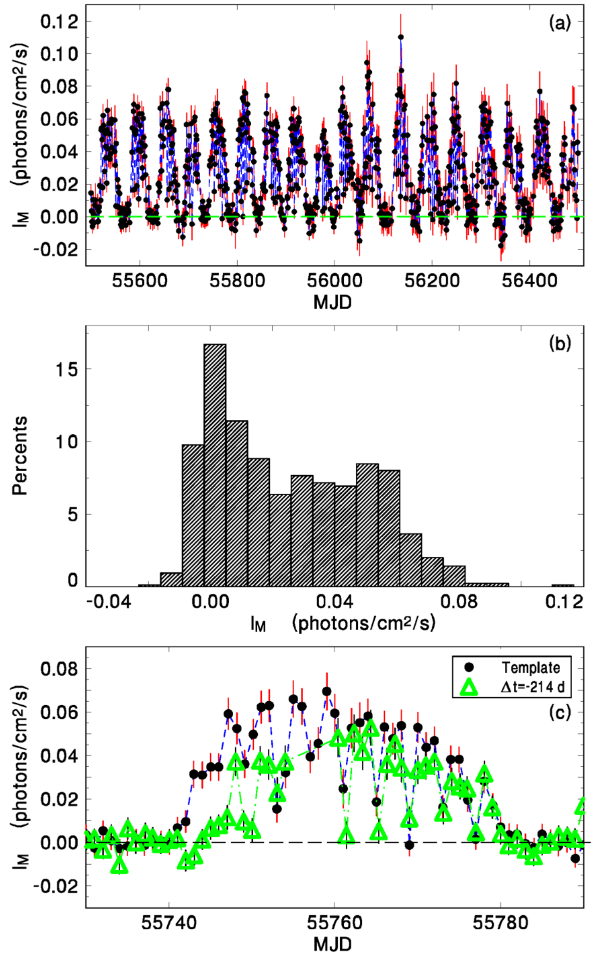

FIGURE 5 (a) X-ray light curve of SMC X-1 in the 2-4 keV band (the 1-day means of data from MAXI/ISS).This band partly overlaps with the one of the proposed SXI/SMILE. The points are connected by a line to guide the eye in the complicated light curve. (b) Histogram of fluxes of SMC X-1. (c) Comparison of two epochs of activity (bumps) from panel (a). The light curves are aligned according to the decaying branches of these bumps.

5 | CONCLUSIONS

The SMILE satellite with innovative instrumentation on-board including a Lobster Eye X-ray telescope will study X-rays from the magnetosphere. SMILE will trace and link processes of solar wind injection with those acting on charged particles precipitating into the cusps and the aurora. There will be outreach potential as well: The possibility of captivating the public to science (magnetic field) so far invisible. The project is based on cooperation with China: SMILE is a showcase, building on Double Star experience. The observation of celestial X-ray sources with SXI, discussed in this paper, is expected to represent the SMILE secondary science.

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Conflict of interest

The authors declare no potential conflict of interests.