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X-ray astrophysics as secondary science with ESA/China SMILE satellite

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Abstract. We present and discuss the feasibility of X-ray astrophysics with ESA–China *SMILE* satellite designed to investigate the Earth's magnetosphere's dynamic response to the solar wind's impact. We plan to study celestial X-ray targets as a secondary science for the onboard wide-field X-ray telescope SXI and related Czech participation in this mission. The Solar Wind Magnetosphere Ionosphere Link Explorer, or *SMILE*, is a joint mission between the European Space Agency (ESA) and the Chinese Academy of Sciences (CAS). We show that SXI can also provide wide-field imaging of the sky in the soft X-ray region ($E = 0.15 - 3\,\mathrm{keV}$) and observe the long-term activity of cosmic X-ray sources. We show the stability of the orientation of the field of view of the SXI telescope; it will undergo only minor changes during several years of the planned operation. Therefore, observing the long-term soft X-ray activity of cosmic sources, e.g., those in the Magellanic Clouds, will be possible.

Key words: ESA SMILE – SXI – X-ray astrophysics

1. Introduction

ESA–CAS mission *SMILE* is not an astrophysical mission, as X-ray emission also occurs much more nearby, namely in Earth's atmosphere and Earth's magnetosphere (Branduardi-Raymont et al., 2016; Wang et al., 2018; Branduardi-Raymont et al., 2017) and this is the primary mission goal.

SMILE (Solar wind Magnetosphere Ionosphere Link Explorer) is a space mission that aims to measure Earth's global system responses to solar wind and geomagnetic variations (Branduardi-Raymont et al., 2016). It 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.

2. The *SMILE* payload

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

SXI: a telescope with a wide field of view (FOV) (26.5×15.5 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 dayside magnetospheric boundaries' location, shape, and motion. 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.

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 localized 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 analyzer. 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 Lagrangian Point L1 are used. The LIA will include a top-hat-type electrostatic analyzer. The center 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. A 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 an FPGA digital processing unit

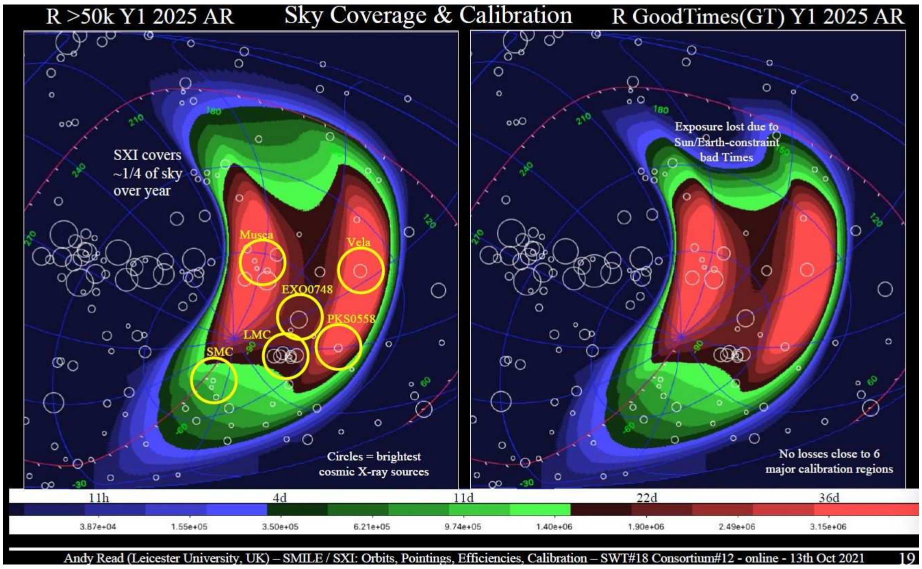

Figure 1. The SXI Sky Coverage and Calibration, the year 2025, simulation by Andrew Read.

with a DC-DC converter. PI: Lei Li, National Space Science Center, Chinese Academy of Sciences (CAS), China.

For X-ray astrophysics, the essential payload is the SXI telescope, as the FOV of this telescope will cover a relatively large fraction of the sky during the mission lifetime with many astrophysical X-ray sources included (Figs. 1 and 2).

Figures 1 and 2 also show the stability of FOV of SXI; it will undergo only minor changes during several years of the planned operation. Therefore, the Magellanic Clouds will be stably observable by this telescope, and observing the long-term soft X-ray activity of cosmic sources located in these galaxies or the directions to their surroundings will be possible (see below for more).

3. Czech Participation in *SMILE*

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. There is essential background in the Czech Republic in the design and the development of wide-field imaging X-ray telescopes based on innovative Lobster-Eye X-ray optics (Hudec et al., 2017b,a, 2015; 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

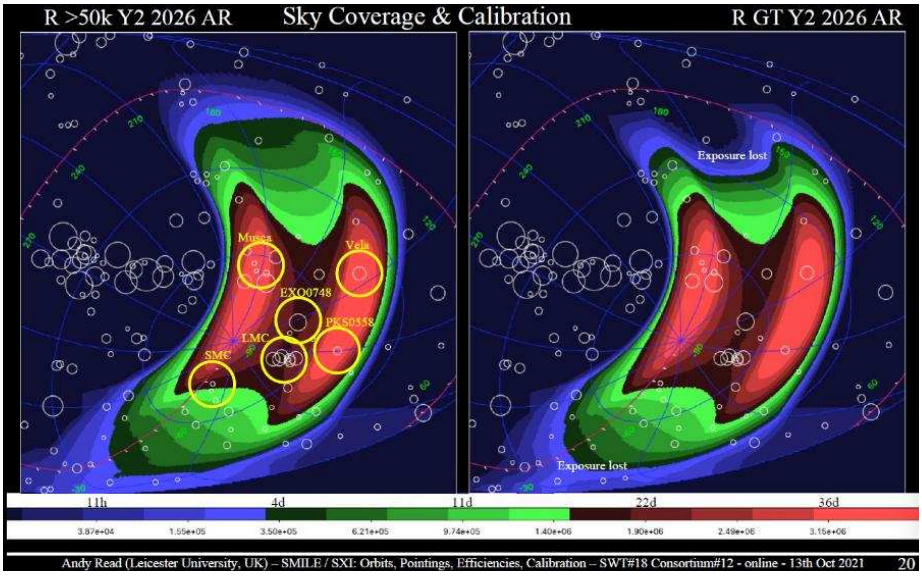

Figure 2. The SXI Sky Coverage and Calibration, the year 2026, simulation by Andrew Read. It is evident that the sky coverage is not very different from the year 2025.

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.

The Czech Technical University represents the leading institution in the Czech Republic in the education of space science and engineering in addition to that participating in numerous space projects [1] so there is a significant potential for the involvement of students, Ph.D. students, and postdocs in the *SMILE* project.

4. Examples of astrophysically important X-ray sources in the SXI FOV

4.1. X–ray binaries

High-mass and low-mass X-ray binaries (HMXBs and LMXBs) contain mass-accreting neutron stars or black holes. Reviews of these systems can be found, e.g., in Lewin et al. (1995) and Lewin & van der Klis (2006). They are promising bright X-ray binaries for SXI/*SMILE*. The examples located in the Magellanic Clouds are listed below.

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

We note that the detectability of the object strongly depends on its activity. In X-ray binaries, the intensity of X-ray emission strongly increases during active states (outbursts, episodes of the high states); often there are no large spectral variations in the soft X-ray band ($E = 0.15 - 3\,\mathrm{keV}$).

Timescales of activity expected to be monitored with SXI/*SMILE* are as follows: (i) state transitions–days (but unpredictable), (ii) outbursts–days to months (usually unpredictable, but cycles are possible) here even bins of 1-day flux can provide valuable information.

Examples of luminous neutron-star or black-hole accretors clustering in the Magellanic Clouds and hence observable by SXI/*SMILE* (Figs. 1 and 2) are listed below:

– LMC X–2: low-mass X-ray binary, neutron star accretor, Z-source (Hasinger & van der Klis, 1989; Agrawal & Nandi, 2020).

– LMC X–3: high-mass X-ray binary, donor of $3.63\,\mathrm{M}_\odot$, black hole of $6.98\,\mathrm{M}_\odot$ (Orosz et al., 2014). The long-term variability – a high amplitude of the factor of about 4 on a 100-200 d time-scale (Cowley et al., 1991).

– SMC X–1: high-mass X-ray binary with the neutron star accreting matter from its early-type companion (Reynolds et al., 1993), strong super-orbital modulation (about 60 days) (Clarkson et al., 2003) (possibly occultation by a precessing and warped disk (Ogilvie & Dubus, 2001)).

– SMC X–2: neutron star+Be binary with orbital period 18.62 d (Schurch et al., 2011), transient X-ray pulsar, luminosity of a rare outburst $5.5 \times 10^{38}\,\mathrm{erg\,s^{-1}}$ in 1-70 keV range, spin period of the pulsar 2.37 s (Jaisawal & Naik, 2016).

4.2. Cataclysmic variables

Cataclysmic variables (CVs) contain the white dwarf accretors. The processes in the transferring matter and the accretion regions on the white dwarf often dominate their emission. In these objects, X-ray emission intensity strongly depends on the X-ray band and the activity state in a given CV (Warner, 1995).

Classical novae in an explosion can represent suitable X-ray transients for observing with SXI/*SMILE*. Nova explosion in the FOV of SXI can result in a bright, very soft X-ray source for days to months. A hydrostatic nuclear burning on the white dwarf surface generates soft X-rays. They represent an active X-ray source from the start of the explosion (visible only later when the ejected nebula cleared as it expanded). In medium X-rays, an interaction of the expanding envelope and density inhomogeneities are represented (Krautter et al., 1996; Warner, 1995).

X-ray luminosity of most CVs enables their detection only if they are in our Galaxy. We expect the CVs detected by SXI/*SMILE* to be usually located in our Galaxy (foreground objects). Nevertheless, the wide FOV of SXI will give an excellent chance to compare their X-ray flux with optical emission in various activity states from the ground-based stations (e.g., AAVSO).

4.3. Supersoft X-ray sources

This unique CV type contains white dwarf accretors that undergo hydrogen burning (even steady-state) of the accreted matter. It often makes them very luminous X-ray sources of very soft X-ray emission, even close to the Eddington luminosity.

These objects have typical orbital periods of several hours, very soft X-ray spectra, and bolometric luminosity (including a very soft X-ray band) at least sometimes at least 10^{37} or $10^{38}\,\mathrm{erg\,s^{-1}}$ (van den Heuvel et al., 1992). Intense soft X-ray emission ($E \leq 1\,\mathrm{keV}$) can be expected (its detectability depends on the interstellar extinction and metallicity of the source) (van den Heuvel et al., 1992).

Table 1. Promising binary supersoft X-ray sources in the fields covered by SXI/*SMILE* in Figs. 1 and 2. The system parameters are given in Greiner (1996).

Object
LMC:
RX J0439.8-6819
RX J0513.9-6951
RX J0527.8-6954
RX J0537.7-7034
CAL83
CAL87
SMC:
1E 0035.4-7230

Vigorous activity in various spectral bands is common in these sources. They are detectable mainly in the Magellanic Clouds in FOV of SXI/*SMILE*. Dense monitoring in a soft X-ray band will enable investigation of the profile of the light curve and its relation on the orbital timescale (several hours or a few days) to the variations on the scale of months or years.

5. Conclusions

The *SMILE* satellite with innovative instrumentation onboard, including a Lobster Eye X-ray telescope, will study X-rays from the magnetosphere. However, the wide-field X-ray images provided by the onboard SXI telescope can be used for X-ray astrophysics as secondary science, as well. Celestial X-ray sources represent important secondary science for SXI, as they will enable a study of the long-term activity of X-ray binary sources by this instrument. A dense coverage will also allow a search for rare and/or unexpected phenomena (also renewing the activity of "sleeping" transients).

A search for the accompanying spectral variations (changes of hardness ratios) and transitions between the states of activity (caused, e.g., by structural changes of the emitting regions) will also be possible.

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