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About the Authors

The SCF Lab is a space infrastructure belonging to the INFN and located in the Frascati National Laboratories (Rome). It is devoted to INFN's space research programmes and AIT/AIV activities. The laboratory itself is a clean room, where all the activities take place. Amongst the many accomplishments of the SCF_Lab, it is worth noting the following (published in *Advances in Space Research*):
- Creation of the new industry-standard space test of laser retroreflectors for the GNSS and LAGEOS, www.sciencedirect.com/science/article/pii/S0273117710007052.
- Thermo-optical vacuum testing of Galileo In-Orbit Validation laser retroreflectors, www.sciencedirect.com/science/article/pii/S0273117716300503.
- INRRI-EDM/2016: the first laser retroreflector on the surface of Mars, www.sciencedirect.com/science/article/pii/S0273117716305890.
- Thermo-optical vacuum testing of IRNSS laser retroreflector array qualification model, www.sciencedirect.com/science/article/pii/S0273117717303411.
- Performance analysis of next-generation lunar laser retroreflectors, www.sciencedirect.com/science/article/pii/S027311771730412X.

Further material and information are easily accessible through the webpage at www.lnf.infn.it/esperimenti/etrusco. NASA authors are JPL employees who are members of the InSight mission team. ASI authors have managed the institutional interface with NASA and aided in the qualification campaign. ASI and INFN are respectively Associate Member and Affiliate Member of NASA's SSERVI.

A Novel and Global Way to Explore Solar-Terrestrial Relationships: *SMILE*

[By G. Branduardi-Raymont (Mullard Space Science Laboratory, UCL, UK), and C. Wang (National Space Science Center, CAS, China).]

As humans we are poised to understand how the Sun creates the heliosphere, and how the planets interact with the solar wind and its magnetic field. In particular, we want to establish how the Earth's global system responds to the impact of the solar wind and to geomagnetic variations.

This is not just scientific curiosity–it also addresses a clear practical problem. As our world becomes ever-more dependent on complex technology–both in space and on the ground—society becomes more exposed to the vagaries of space weather, the conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of technological systems and endanger human life and health.

The interaction between the solar wind and the Earth's magnetosphere, and the geospace dynamics that result, act as fundamental drivers of space weather. Understanding how this vast system works requires knowledge of energy and mass transport, and coupling between regions and plasma and neutral populations. This interaction has been and is investigated by a fleet of magnetospheric space missions dedicated to in situ measurements of particle and magnetic field parameters; these provide a detailed but local knowledge of the physical processes working on the microscale. What we still miss is a global view of the interaction, and the ability to quantify its global effects. This information is the key missing link for developing a complete understanding of how the Sun gives rise to and controls the Earth's plasma environment and space weather.

SMILE (*Solar wind Magnetosphere Ionosphere Link Explorer*) is a scientific mission which will address these issues 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. Moreover, self-sufficiently from its highly elliptical polar orbit, *SMILE* will make in situ measurements of the solar wind and magnetosheath plasma which will be compared and contrasted with the simultaneous imaging data[1].

Remote sensing of the magnetosheath and the cusps with X-ray imaging is now possible thanks to the relatively recent discovery of solar wind charge exchange (SWCX) X-ray emission, first observed at comets, and subsequently found to occur in the vicinity of the Earth's magnetosphere[2]. SWCX occurs when highly charged ions of the solar wind interact with exospheric neutrals, acquire an electron, are left in an excited state and then decay emitting soft X-ray lines of wavelengths characteristic of the de-exciting ion. Consider the impact of a Coronal Mass Ejection from the Sun arriving at the Earth (Figure 1). It will compress the magnetosphere and for favourable conditions of magnetic field orientation solar wind plasma will penetrate in the magneto-sheath and produce SWCX X-rays in its encounter with exospheric neutrals. The higher the particle density, the larger the emission flux; hence dayside magnetosheath and magneto-spheric cusps are the regions brightest in SWCX X-rays.

The ultimate consequences of the CME impact and plasma injection are geomagnetic storms and particle precipitation in the aurorae, which are the footprints of this whole interaction and produce bright UV emission. *SMILE* will allow us to investigate the full chain of events that drive Sun–Earth relationships, i.e. phenomena such as dayside magnetic reconnection, the magnetospheric substorm cycle and CME-driven storms.

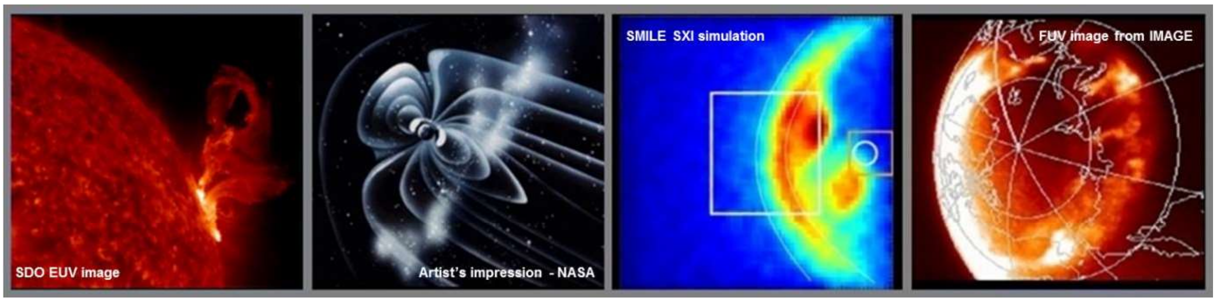

Figure 1: From left to right: A Coronal Mass Ejection from the Sun impacts on the Earth's magnetosphere and plasma penetrates into the magnetosheath; soft X-rays are generated and mapped by the *SMILE* Soft X-ray Imager; ultimately the footprints of the precipitating plasma are monitored by the *SMILE* UV Imager

SMILE scientific motivations

It is well known that the structure and dynamics of the magnetosphere are mainly controlled by magnetic reconnection: this takes place between the magnetic field carried in the solar wind with the terrestrial one, and allows the solar wind to enter the magnetosphere when the directions of the fields are opposite (Southward for the solar wind). The interactions involved have been explored by many in situ measurements at the microscale level and the basic theory of magnetospheric circulation is well established. However, the reality of how this complex interaction takes place on a global scale, and how it evolves, is still not understood. Examples of questions in need of answers, and ways in which *SMILE* can help to find them, are:

- When/where does transient and steady reconnection dominate? It is thought, but still to be clearly demonstrated, that steady re-connection occurs for low β, the ratio of the plasma pressure to the magnetic pressure. There could also be direct dependence on solar wind parameters. Answers could come from correlating in situ data with the position and motion of the magnetopause from SXI mapping, and from the observations of cusps and auroral brightenings.
- What defines the substorm cycle? What changes in solar wind conditions trigger substorms and determine their evolution? Changes in Interplanetary Magnetic Field (IMF) orientation? Or in solar wind dynamic pressure? Seasonal effects? With *SMILE* we can look for changes in the Bz and By IMF components and compare with variations seen in the imaging data.
- How do CME-driven storms arise? Are CME-driven storms sequences of substorms? Observation of repeatable sequences of locations for magnetic boundaries could answer this.

How did we get to *SMILE*?

SMILE was formally put forward in March 2015 in response to a European Space Agency (ESA) and Chinese Academy of Sciences (CAS) joint call for a small-size space mission. The joint Announcement of Opportunity established the principle that the proposed missions had to be based on an East-West collaboration throughout their life, from design, to implementation, flight operations and science exploitation. Our previous European-US collaboration which aimed to realise X-ray imaging of the dayside magnetosheath had already proposed in response to ESA calls for a medium and a small mission. The novelty this time was the participation of Chinese partners with whom we established early contacts and with whom we developed the preliminary design and the proposal for the mission.

Out of 13 missions originally proposed to ESA and CAS, *SMILE* was the one chosen for an initial study phase during the summer of 2015. The initial study of the whole mission was carried out by ESA and CAS at their Concurrent Design Facilities during October 2015, and the conclusion was that the mission is feasible, with no show stoppers. In early November 2015 *SMILE* was formally selected by the ESA Science Programme Committee. We are now in Phase B study, with the objective of reaching mission adoption in 2018. Launch is expected to take place at the end of 2021.

Scientists and engineers from the UK, China, Canada, several European countries and the US are collaborating to make *SMILE* a reality.

SMILE payload

With *SMILE* 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 creating the aurora. The science delivered by *SMILE* will have a profound impact on our understanding of the way the solar wind interacts with the Earth's environment, and will pave the way to future space weather monitoring and forecasting satellites for which *SMILE* is an important scientific precursor.

In order to achieve its scientific objectives *SMILE*'s payload comprises: the Soft X-ray Imager (SXI), which will map spectrally the Earth's magnetic boundaries, magnetosheath and polar cusps; the UltraViolet Imager (UVI),

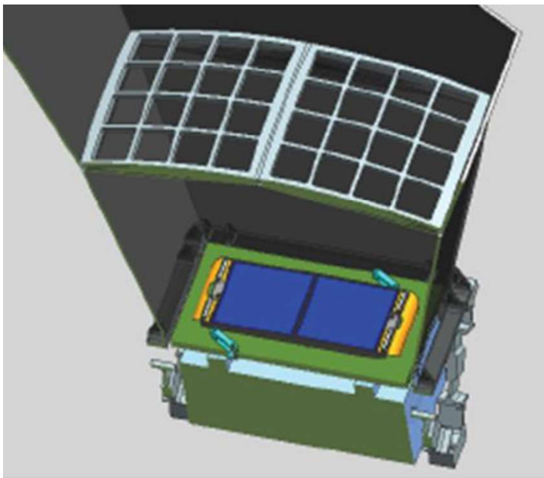

Figure 2: CAD drawing of the *SMILE* SXI as viewed from the top. Clearly visible are the micropore optic (MPO) arrays (mounted in the grid-like structure at the top), protected from stray light by the baffle (black) extending further out. X-rays are focussed onto CCDs (blue) at the focal plane at the bottom of the (black) optical bench, 30 cm below the MPO

dedicated to imaging the auroral regions; the Light Ion Analyser (LIA) and the MAGnetometer (MAG), which will establish the solar wind/magnetosheath properties simultaneously with the imaging instruments.

Soft X-Ray Imager (SXI)

The SXI is a wide FOV Lobster-eye telescope (Figure 2) employing light weight (< 1 kg) micropore optic (MPO) to achieve soft X-ray imaging with large spatial coverage (16o x 27o FOV) and adequate spatial resolution (few arcmin) over the energy range 0.2 – 5 keV. At the telescope focus are charge-coupled devices (CCDs) providing quantum efficiency (~60% at 250 eV) and energy resolution (~50 eV FWHM at 500 eV) sufficient to map the SWCX X-ray emission and characterise the solar wind ionic population generating it. The CCDs need to be cooled to about -100°C in order to operate efficiently in the X-ray regime in photon counting mode, and this can be achieved by the use of a passive radiator.

Simulations of the modelled X-ray emissivity, the expected SXI count and processed images are shown in Figure 3. In order to avoid stray light from the Sun and the bright Earth penetrating the focal plane the SXI incorporates an optical/UV filter and a ~ 0.7 m long baffle (which is visible in Figure 2, giving a view of the SXI from the top, and in Figure 6, showing *SMILE* in its flying configuration).

The SXI instrument development is led by the University of Leicester, UK (PI: Steve Sembay). Institutes from the UK and several European countries (Austria, the Czech Republic, Hungary, Norway, Spain, Switzerland) participate in the Consortium building the SXI. Scientific, technical and software support is provided by the US and Ireland.

Ultra Violet Imager (UVI)

The UVI is a four mirror reflective telescope (10^o x 10^o FOV) able to image the whole Northern aurora oval at 150 km resolution. The imager bandpass of 160 – 180 nm is selected by appropriately coating the optical surfaces and the detector, with a factor of > 10^{16} rejection in the visible. The detector is an image intensifier comprising a photocathode, microchannel plates for electron multiplication, a phosphor and a CMOS sensor.

The UVI, shown in Figure 4, is the responsibility of the University of Calgary, Canada (PI: Eric Donovan) with the participation of the University of Liege (Belgium) and CAS.

In situ package: Light Ion Analyser (LIA) and Magnetometer

The in situ package on board *SMILE* comprises the Light Ion Analyser (LIA) and the magnetometer (MAG) instruments. Both are developed by CAS/National Space Science Center (NSSC), China (LIA PI: Lei Dai, MAG PI: Lei Li).

The LIA (Figure 5 Top) is a top-hat analyser for protons and α particles, measuring their density, velocity and temperature and working in the energy range 50 eV – 20 keV, with a 360^o FOV in azimuth, reaching +/-45^o in elevation by use of deflector plates.

MAG (Figure 5 Bottom) is a fluxgate-type magnetometer measuring both strength and direction of the local magnetic field. Its two sensors will be mounted on a boom some 2.5 m long, and separated by 0.8-1 m; the boom is

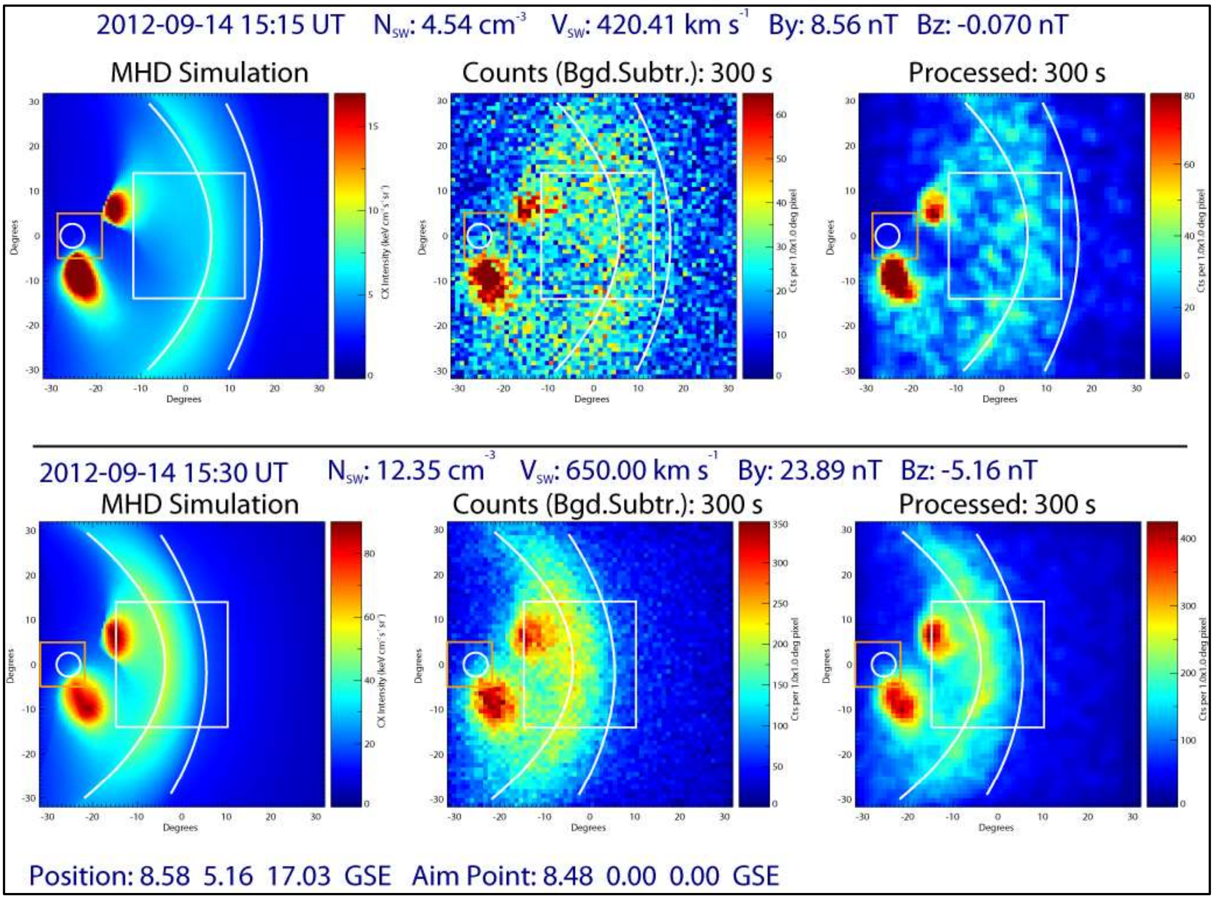

Figure 3: Simulated dayside magnetosphere X-ray emissivity before (top) and after (bottom) the arrival of an interplanetary shock. The figure shows original MHD simulation data (left), the predicted SXI counts (centre) and the images processed in order to highlight the magnetic boundaries (right).

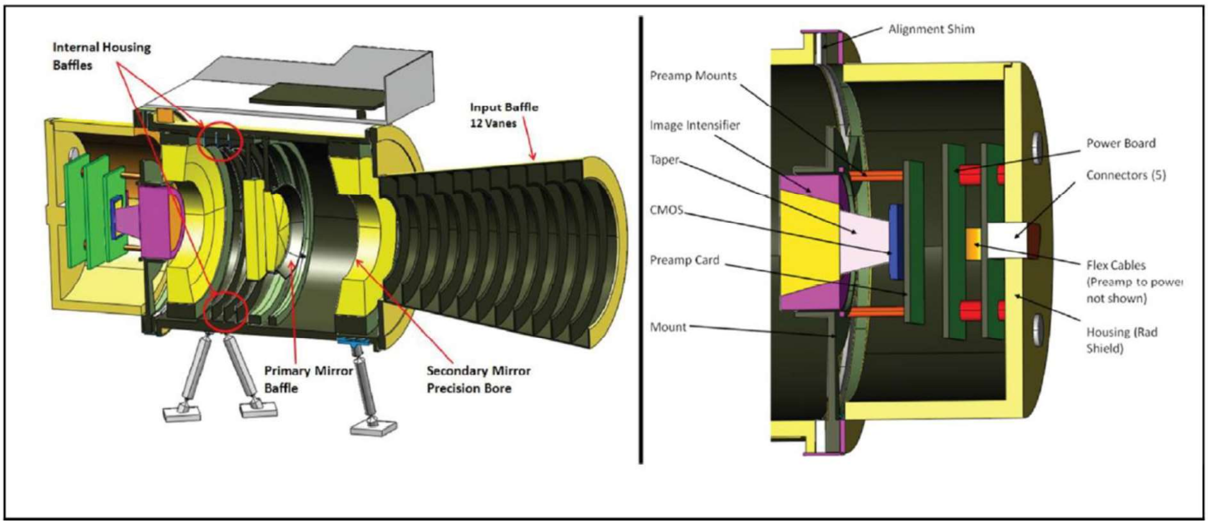

Figure 4: Schematic view of the UVI highlighting the stray light baffle, mirrors and detector layout

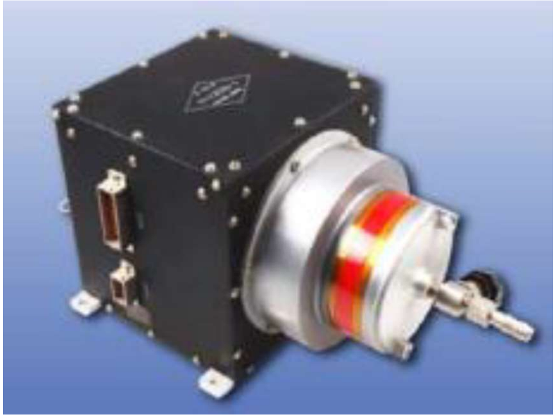

Figure 5: Top panel: Example of the type of solar wind ion detector (flown on *Chang'E-1/2*) that will be adopted for the LIA on *SMILE*. Bottom panel: Example of fluxgate magnetometer (both from CAS/NSSC)

seen in its deployed configuration in Figure 6.

An image of the *SMILE* spacecraft in its flight configuration, including the propulsion module which will inject it into its operational highly elliptical polar orbit, is shown in Figure 6. The provision of the *SMILE* elements is shared between CAS, ESA and national agencies, reflecting the truly collaborative nature of this mission. CAS provides the Propulsion Module, the Service Module, the spacecraft Prime Contractor, mission operations (with ESA contribution) and the Chinese instruments. ESA provides the Payload Module (the interface plate between the Service Module and theinstruments and the sub-systems required to collect and download the scientific data—see Figure 6), the launcher and facilities for spacecraft integration and testing in Europe. The European/Canadian instruments will be provided by ESA member states and Canada. Science operations will be shared among the hardware institutes, ESA and CAS.

Two possible approaches to launch (scheduled for the end of 2021) are being considered: *SMILE* could be passenger in a dual launch on a Soyuz or Ariane 6 rocket, or could be launched on its own on Vega C. After spending some days or a few months (depending on the launch approach) in a low-Earth parking orbit, *SMILE* will be injected by its propulsion module into a highly elliptical, high inclination (70o – 90o) orbit currently baselined to have a period of ~50 hour and apogee altitude of ~19 Earth radii; this allows ~41 hour of SXI and UVI operations above an altitude of ~50,000 km, selected in order to avoid radiation damage to the SXI

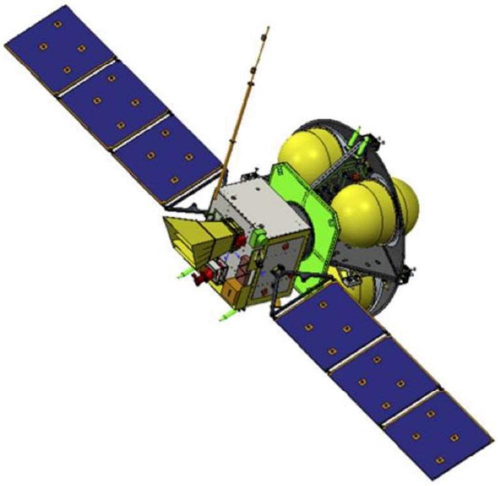

Figure 6: *SMILE* in flight configuration with unfolded solar panels. The Service Module (light blue) is mounted above the Propulsion Module (tanks in yellow). Clearly visible is the SXI with its baffle (yellow) located in the centre of the Payload Module interface plate (at the top of the Service Module, light blue), together with the UVI (red) and the LIA (green). The 2 MAG sensors are mounted on the extended boom. [Image credit: Shanghai Engineering Center for Microsatellites, China]

CCDs during van Allen belt passages near perigee (when the CCDs will be protected by closing a door mounted at the bottom of the baffle). LIA and MAG will make measurements for most of the orbit.

Summary and looking ahead

In summary, *SMILE* will turn what is an unwanted variable background 'noise' for soft

X-ray astronomical observations pointing along line of sights crossing the Earth's magnetosheath into a novel diagnostic tool of the conditions of geospace under the vagaries of the solar wind. *SMILE* will work in synergy with other space missions, current and forthcoming, probing the microscale (such as MMS, Cluster, Solar Orbiter, Solar Probe+, THOR), and with ground based observatories in the polar regions, to lead to a comprehensive understanding of solar-terrestrial interactions.

Simulations of the magnetosphere and its environment, through MHD modelling in China, Europe and the USA are being used to optimize the instrument and mission design; results obtained with different codes will be compared for the same solar wind conditions, in order to establish the margin of error inherent to model predictions. Eventually *SMILE* images and measurements will provide direct scientific input to the studies of space weather by delivering the remote sensing data needed to validate global models of solar wind-magnetosphere interactions.

The cooperation of western nations with China from mission design to launch, flight operations and science exploitation is another first of the *SMILE* mission, and a facet that makes it a brilliant showcase, building on and extending the successful experience of collaboration already proven with Double Star. Moreover, the imaging nature of two of the instruments of the *SMILE* payload offers excellent potential for outreach: the X-ray and UV images and videos that *SMILE* will return will captivate the public to science, to the physics of the Earth's magnetic field which involves many processes that are complex and essentially invisible to the naked eye. *SMILE* will make visible the magnetospheric bubble shielding our Earth from inclement solar wind conditions, and in doing so will make the science of solar-terrestrial interactions more understandable and fascinating.

SMILE will break completely new ground in the way we explore how the Earth environment responds to activity on the Sun and in the solar wind, and will open the way to future systematic and large scale monitoring based on state-of-the-art astronomical X-ray detection and mapping techniques applied to terrestrial space plasma science.

For more information on *SMILE* and its scientific objectives and capabilities, and to express support for the mission, please see http://www.mssl.ucl.ac.uk/*SMILE*/

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About the Authors

Graziella Branduardi-Raymont has been fascinated by astronomy and space research since she was a teenager. After a degree in physics at the University of Milan, Italy, and a PhD in X-ray astronomy at University College London (UCL), she worked at the Harvard-Smithsonian Center for Astrophysics, USA, and then returned to UCL Mullard Space Science Laboratory where she is based and is Professor of Space Astronomy. She has participated in major X-ray observatory missions over many years: *Copernicus*, *Ariel 5* and the *Einstein Observatory* in the 1970s, *EXOSAT* in the 80s, *ROSAT* in the 90s. She is Co-Investigator for the Reflection Grating Spectrometer (RGS) operating on board *XMM-Newton* since 1999, having also been project manager for the MSSL hardware contribution to the RGS. She is now co-leader of the *SMILE* mission with Prof. Chi Wang (CAS/NSSC).

Chi Wang, deputy director of the National Space Science Center, Chinese Academy of Sciences, is also the director of the State Key Laboratory of Space Weather. He graduated from the University of Science and Technology of China, and got his PhD degree from the Massachusetts Institute of Technology, USA. His research interests focus on the large-scale solar wind structures and the interaction of the solar wind with the magnetosphere. He worked on the plasma experiments on *Voyager 2* and developed a multi-fluid solar wind model. Starting from 2002, he led the effort to establish the first state key laboratory of space weather in China. He was the PI of the Chinese Meridian Project, which is the ground-based space environment monitoring chain in China. He currently is the Co-PI of the solar wind–magnetosphere–ionosphere link explorer (*SMILE*), an ESA-China joint space science mission.

News in Brief

Nobel Prize in Physics: Gravitational Waves Finally Captured

(Royal Swedish Academy of Sciences release, 3 October 2017)

On 14 September 2015, the universe's gravitational waves were observed for the very first time. The waves, which were predicted by Albert Einstein a hundred years ago, came from a collision between two black holes. It took 1.3 billion years for the waves to arrive at the LIGO detector in the USA.

The signal was extremely weak when it reached Earth, but is already promising a revolution in astrophysics. Gravitational waves are an entirely new way of observing the most violent events in space and testing the limits of our knowledge.

LIGO, the Laser Interferometer Gravitational-Wave Observatory, is a collaborative project with over one thousand researchers from more than twenty countries. Together, they have realised a vision that is almost fifty years old. The 2017 Nobel Laureates have, with their enthusiasm and determination, each been invaluable to the success of LIGO. Pioneers Rainer Weiss and Kip S. Thorne, together with Barry C. Barish, the scientist and leader who brought the project to completion, ensured that four decades of effort led to gravitational waves finally being observed.

In the mid-1970s, Rainer Weiss had already analysed possible sources of background noise that would disturb measurements, and had also designed a detector, a laser-based interferometer, which would overcome this noise. Early on, both Kip Thorne and Rainer Weiss were firmly convinced that gravitational waves could be detected and bring about a revolution in our knowledge of the universe.

Gravitational waves spread at the speed of light, filling the universe, as Albert Einstein described in his general theory of relativity. They are always created when a mass accelerates, like