China Catches up in X-ray Astronomy

By XIN Ling (Staff Reporter)

A composite image of the Andromeda Galaxy, our nearest large galactic neighbor. The blue dots are dying stars shining X-rays into space (taken by ESA's XMM-Newton telescope), while the reddish/yellow part shows rings of star formation at infra-red wavelengths (seen by the Herschel spacecraft). *Credit: ESA.*

It is the midnight of June 18, 1962, in the desert of southern New Mexico, that young physicist Riccardo Giacconi and his team watched a sounding rocket pierce through the dark sky. Their mission, funded by the United States Air Force, was to detect reflected X-rays from the Moon and help the US get a head start in the lunar exploration race against the Soviet Union. Before that, people had never observed X-radiation from the outer space other than the Sun.

To everyone's surprise, during its 350-second flight above the atmosphere, the detector did not see the Moon but something very brighter and distant. It was later confirmed as powerful X-ray emissions from a neutron star in the constellation of Scorpius, some 9,000 light years away. Riccardo's group named it Sco X-1.

The discovery of Sco X-1 and the subsequent X-ray sky was revolutionary. On one hand, cosmic X-rays have since been used as a new tool to understand our universe, especially the violent aspect that is otherwise hard to observe, such as the activities of black holes and neutron stars. On the other, because these rays are produced under extreme conditions, they provide a "natural" laboratory to study the behavior of matter and examine the limits of existing physics theories. In 2002, Giacconi shared the Nobel Prize in Physics for his groundbreaking contributions to X-ray astronomy.

X-rays are readily absorbed by the Earth's atmosphere and can only be detected from space. Since 1970, more than 50 telescopes have been launched and dedicated to X-ray astronomy research. Meanwhile, the application of the X-ray focusing imaging technology has greatly enhanced our vision into the deep X-ray universe, especially via milestone missions like NASA's Chandra and ESA's XMM-Newton.

X-ray astronomy started in China in the 1970s. In 1993, scientists from the CAS Institute of High Energy Physics proposed a mission called the Hard X-ray Modulation Telescope (HXMT), which was a pioneering idea at that time to survey the distribution of supermassive black holes in the nearby universe. However, due to funding shortage, HXMT was not launched until two decades later, in June 2017, with renewed science goals and an upgraded design. With HXMT now in operation, China is preparing a second mission known as the Einstein Probe (EP) to look into the remote, dynamic world of soft X-ray transients, hopefully lifting off in 2022. Meanwhile, Chinese researchers are actively promoting collaboration with European colleagues on a next generation X-ray telescope – the enhanced X-ray Timing and Polarimetry (eXTP) mission. If eXTP gets the green light from the Chinese government, China will go for a great leap forward from a later-comer to a world-leader in the field of X-ray astronomy.

Galactic Survey and the Modulation Technology

After more than 20 years of effort, China has finally put its first X-ray astronomy satellite into space. At 11:00 am local time on June 15, 2017, the HXMT was sent from Jiuquan Satellite Launch Center in northwestern China's Gobi Desert into a low earth orbit 550 km above the ground. From there, it will be scanning black holes and neutron stars within the Milky Way Galaxy, and detecting gamma ray bursts from afar with high sensitivity.

HXMT will be a new effort to advance our understanding of the X-ray sky. "Through Galactic survey and pointed observations, our goal is to develop a high precision hard X-ray sky map, look for new sources, and better research the temporal properties of the known sources", said ZHANG Shuangnan from the Institute of High Energy Physics (IHEP) of CAS, who is the principal investigator of the mission.

To achieve that, the 2,500 kg satellite is carrying three sets of instruments onboard: the High Energy X-ray Telescope (HE) detecting at 20-250 keV with a total collecting area of 5,000 cm^2, the Medium Energy X-ray Telescope (5-30 keV, 952 cm^2), and the Low Energy X-ray Telescope (1-15 keV, 384 cm^2). Also, a special design on the HE enables HXMT to catch gamma ray bursts up to 3 MeV's energy.

"Broad-band observations are of key importance for the understanding of the physics of celestial X-ray sources, the emission mechanisms of the radiation at work, and other issues of fundamental physics. HXMT will continue this investigation process given its energy band that extends from 1 keV up to 250 keV," said Italian astrophysicist Filippo Frontera who was at the launch.

However, unlike many recent telescopes which use focusing optics to image X-ray sources, HXMT adopts a unique modulation technology to gather the rays. With a special device called "collimator" which was commonly used in earlier missions, HXMT can filter incoming lights so that only those travelling at a specific angle are allowed through. Then, by assembling different

The Hard X-ray Modulation Telescope (HXMT, or "Insight"), China's first X-ray Telescope, was launched from Jiuquan Satellite Launch Center in northwestern China's Gobi Desert on June 15, 2017. It aims at mapping the hard X-ray sky and looking for new X-ray sources within the Milky Way Galaxy. *Credit: WANG Qiang, CAS.*

collimators into the detector and by swinging the detector in various directions, scientists can reconstruct the image of a specific source, and eventually render a map of the whole X-ray sky.

"The strength of the modulation technique is its simplicity," commented Jonathan Grindlay from Harvard University. "With HXMT's broad energy band coverage for wide-field imaging, it should obtain better spectral energy distribution than what is now being done with similar missions like Swift/BAT or MAXI."

During the first year of observation, HXMT is going to spend one third of its time in Galactic plane scan and monitoring, said ZHANG. The HXMT data will be shared with international collaborators, including Andrea Santangelo and his group from the Institute of Astronomy and Astrophysics, University of Tubingen. "We will work together on the data analysis of HXMT, joining our different expertise and sharing ideas and students," Santangelo told *BCAS*.

"Being a national program but with an international flavor, the HXMT mission will have profound implications in the development of high-energy astrophysics in China," Santangelo added.

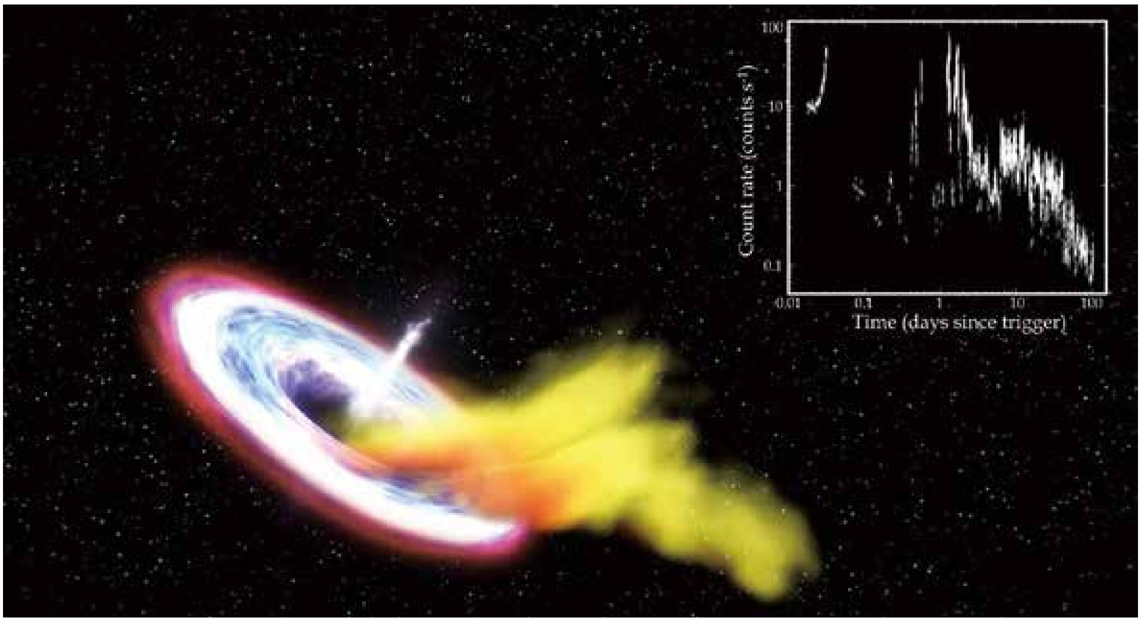
First proposed in the 1990s, HXMT had suffered from funding shortage from the beginning. In 2001, the team received a fraction of money from the Ministry of Science and Technology to cover the mission development phase. The financial gap was not closed until 2011, when the project was officially selected as one of China's first batch of space science missions to be launched during the 12th Five-Year Plan (2011-2015).

Exploring Extragalactic Transients: a "Lobster Eye" in the Making

If HXMT's strength is to study all bright sources in the Galaxy, then the Einstein Probe (EP) – China's next X-ray telescope – will hunt for much fainter, faraway black holes and other transient sources by following their traces in the soft X-ray band.

"Most celestial bodies in our universe appear to be constant, but in fact they are not. Everything is changing," said YUAN Weimin from the National Astronomical Observatories under CAS, who is a space astrophycist and principal investigator of EP. While some changes take a long time, some are rather short-lived. For instance, a typical gamma ray burst induced by the merger of two neutron stars or the core implosion of a massive star only lasts from one second to ten minutes.

To catch such flashes is by no means easy. While



Intense X-ray flares were detected by NASA's Swift telescope on March 28, 2011, which are thought to be caused by a black hole devouring a star. *Credit: NASA/GSFC.*

past telescopes have done a great job mapping the universe with imaging and spectroscopy, their limited field of view reduced their efficiency in spotting sudden and rare events that could happen anytime, anywhere in the vast sky. EP, however, has an exceptionally wide field of view which can cover as much as one eleventh of the entire sky. It will be very powerful in monitoring and discovering transients with a life span anywhere from seconds to years in soft X-rays.

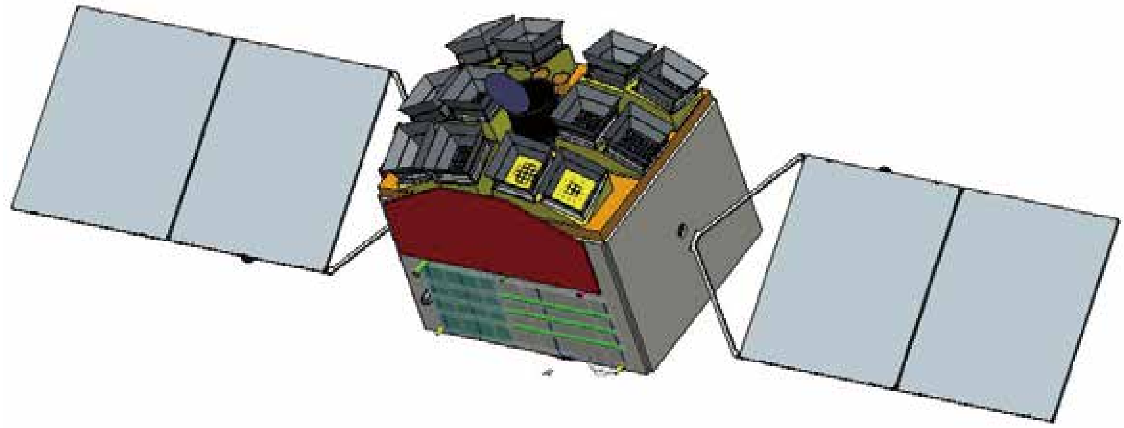
Upon its scheduled completion in 2022, EP will have the opportunity to conduct an all-sky survey of the soft X-ray transients in the energy band 0.5-4 keV, which is the first of its kind. "I'm expecting many unexpected discoveries," YUAN was excited.

One predictable finding, though, is in what he called the tidal disruption events (TDEs). At the center of each galaxy, scientists speculate the existence of a supermassive black hole that is usually dormant and unnoticed. However, if a careless star happens to wander too close, the quiescent black hole will wake up, rip his uninvited guest open, and gobble it up — like a fairy tale monster, "you feed it and it glows." This process usually takes a few months to years, and the energy of its radiation is estimated to be around 1 keV, falling right into EP's detection range.

The study of TDEs is both fascinating and meaningful, because it is almost the only way to monitor those mysterious black holes, which spend most of their lives in a dormant and thus unseeable state. But such events are extremely rare. Statistically, they occur once every 100,000 years in a galaxy. It means a telescope needs to be staring at 100,000 galaxies simultaneously throughout the year just to catch one single event. And there have been only 20-30 confirmed instances of X-ray TDEs so far.

EP is going to change the game. It will not only remarkably increase the sample size by detecting 100 TDEs or so per year, but also serve as an "alert" of such events so that follow-up ground-based observations can be performed from all over the world right after the first detection information is disseminated in time.

To achieve this, EP will adopt a novel technology known as "the micro-pore lobster eye optics" to gain a wide field of view and high detecting sensitivity at the same time. Its main detector, made up of dense blocks of plastic pores with side length of 20 micrometers, resembles the shape of a lobster's eyeball. Spherical and thus "omnidirectional", it is able to look at any corner of the sky with ease, which is fundamentally different from a regular focusing device on an X-ray telescope which has a tube shape and a primary optical axis.



The EP payload has two instruments, a Wide-field X-ray Telescope (WXT) and a follow-up X-ray telescope (FXT). The WXT consists of 12 identical modules of micro-pore lobster eye telescopes, each with a FoV of 300 square degrees, making a total of 3,600 square degree. Each of the WXT modules is equipped with 4 CMOS sensors on the focal sphere. The FXT (center) is a Wolter-I X-ray focusing telescope with a narrow FoV for deep follow-up observations in X-rays. *Credit: YUAN Weimin, NAOC.*

"EP is based on a challenging technology, the lobster eye, which on the other hand promises a two order of magnitude improvement in telescope performances. It is a strategic technology in the field, and in Europe we have also put a lot of efforts on it, recognizing it as one of the strategic technologies for our high energy community in the future," said Luigi Piro, research director at the Institute for Space Astrophysics and Planetology, National Institute for Astrophysics in Italy.

In the meantime, EP will also be equipped with a follow-up observation detector, featuring a smaller field of view but much larger light collecting power and better energy resolution than the main detector.

"EP is a powerful and unique project," commented Paul O'Brien from the University of Leicester, who has been collaborating with the EP team to develop the mission. "It has a payload able to observe large areas of sky in the X-ray band using focusing optics. This makes it much more sensitive than previous X-ray wide-field survey instruments."

Astrophysicist William Brandt from Pennsylvania State University places high hopes on EP, too. As his team recently discovered a new type of transients likely to be related to gamma ray bursts or TDEs, "There is every reason to expect that the Einstein Probe will find more transients of this type, as well as other entirely new source types that we have yet to anticipate," Brandt, who is not officially involved in the mission, told *BCAS*.

As scheduled, the prototype of EP shall be delivered by early 2020. But YUAN considers himself to face a number of challenges. "In China, no one has really developed an X-ray focusing imaging system, not to mention the lobster eye," he said. The lack of professionals and a dedicated organization to support space astronomy also adds to his concerns.

Most of the time, YUAN is thrilled at the prospect of the project. "The idea is that we are entering a time during which we investigate how sky changes over time. I see a golden era for the so-called 'time-domain astrophysics' on its way, and EP will be a part of it," he said.

A Next Generation X-ray Telescope?

It has long been a dream of scientists to use the cosmos as a natural laboratory for experiments not possible on the Earth. X-rays makes a perfect example: they are born under extreme conditions, such as super strong gravitational fields, extra high densities or temperatures, and super intense magnetic fields, and can be used conveniently to study matter behavior and test if contemporary physics laws still hold in such "boundary states". From general relativity theory to quantum electrodynamics, the precise measurement of key parameters of X-rays will be able to confirm or challenge their validity.

A few years ago, scientists in China and Europe came up with similar ideas to achieve this dream. Three missions were proposed – the X-ray Timing and Polarization (XTP) mission in China, the General Relativistic Astrophysics VIa Timing And Spectroscopy

The First Science Meeting on High-throughput X-ray Astronomy and the eXTP mission was convened in Rome, Italy in February 2017. *Credit: The eXTP team.*

(GRAVITAS) mission in Germany, and the Large Observatory For X-ray Timing (LOFT) mission in Italy – which were later merged into a single ambitious proposal, namely the enhanced X-ray Timing and Polarimetry (eXTP) mission, which is now led by ZHANG Shuangnan from IHEP.

“My impression is that eXTP is of very high scientific merit and originality,” commented Michel Blanc, executive director of the International Space Science Institute Beijing, who is independent of the mission. “It will test the theories of fundamental physics in a domain of parameter space which is simply not accessible in Earth laboratories.”

According to the current design, eXTP will use both focusing and collimating technologies to enable the detailed studies of X-ray sources in the energy range 0.5-30 keV, highlighting a total collection area of as big as 4.5 m^2. Of the four different types of detectors on eXTP, China will be developing a spectroscopy focusing array and a polarimetry focusing array, while a large area detector and a set of wide field monitors will be contributed from the European side.

For its high scientific significances and international participation, eXTP won a CAS grant to go through background study between 2011 and 2015, and is now completing its Phase A study. However, it has not been selected for launch around 2020. One reason, said insiders, is its estimated budget, which could stand at as much as 2-3 billion yuan, around two or three times the cost of an average Chinese space mission like HXMT or EP.

The international scientific community remains enthusiastic. Marco Feroci of the Italian National Institute for Astrophysics, who is a main coordinator of the project in Europe, said the telescope is conceived as “the most powerful and general observatory for compact Galactic and bright extragalactic objects ever”. It will offer for the first time the most complete diagnostics of compact sources on a single payload, he said.

Santangelo is confident in China’s ability to lead. “China is building up its own large-science enterprise, and will take good leadership in such a project. I’m very optimistic about the future of eXTP. With great enthusiasm from both sides, we will do great science through collaboration.”

But ZHANG is worried. He heard that the Naval Research Laboratory in the US is proposing a similar mission, and they have just invited his European friends to join. “eXTP was proposed ten years ago as the successor of HXMT. Today, it is still not approved and facing increasingly fierce competition. Will eXTP relive the historical predicament of HXMT? I really hope not,” he warned.