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Space Astronomy

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Abstract This chapter reports the recent progress on the space astronomy missions of China, including the following missions: currently operating in orbit, *e.g.*, DAMPE, Insight-HXMT, GECAM, PolarLight, GRID and Lobster-eye X-ray Satellite; approved and under development for launch in the next a couple of years, *e.g.*, SVOM and EP; planned experiments to be onboard China's Space Station in the next several years, *e.g.*, CSST, HERD, POLAR-2, DIXE and LyRIC; candidate missions that have passed the first round of review of Strategy Priority Program on space science (III) of the Chinese Academy of Sciences, *e.g.*, eXTP, DAMPE-2, Earth 2.0, DSL and CHES.

Key words Space science, Space astronomy, Satellite, Space station

Classified index P17

1 Introduction

This chapter reports the recent progress on the space astronomy missions of China. It covers the space astronomy projects in the following four categories: (i) missions currently operating in orbit; (ii) approved and under development for launch in the next a couple of years; (ii) planned experiments to be onboard China's Space Station in the next several years; (iv) candidate missions that have passed the first round of review of Strategy Priority Program on space science (III) of the Chinese Academy of Sciences. The brief introduction to each mission/project is summarized in Table 1.

2 DAMPE: Dark Matter Particle Explorer

Launch time: it was launched on 17 December 2015.

2.1 Scientific Goals

DAMPE is a high energy cosmic-ray and gamma-ray observatory aiming to study cosmic-ray physics, to probe the nature of dark matter, and to detect high energy gamma-ray emissions from astronomic sources.

2.2 DAMPE Detector

Fig.1[1] shows a schematic DAMPE detector, consisting of a Plastic Scintillator strip Detector (PSD), a Silicon-Tungsten tracKer-converter (STK), a BGO imaging calorimeter and a NeUtron Detector (NUD). The PSD provides charged-particle background rejection for gamma rays and measures the charge of incident cosmic rays; the STK measures the charges and the trajectories of charged particles, and allows to reconstruct the directions of incident gamma-rays that have been converted into electron/positron pairs mainly in the tungsten layers; the hodoscopic BGO calorimeter, with a total depth of about 32 radiation lengths, allows to measure the energy of incident particles with high resolution and to provide efficient electron/hadron identification; finally, the NUD provides a further improvement of the electron/hadron discrimination.

2.3 Main Scientific Results

(1) DAMPE has measured the Cosmic Ray Electron (CRE) plus positron spectrum in the energy range 25 GeV to 4.6 TeV with unprecedentedly high energy resolution and low background. The major part of the spectrum can be well fitted by a smoothly broken power-

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Table 1 Summary of space astronomy missions/projects of China. Phase A-feasibility; Phase B-preliminary definition/design; Phase C-detailed definition/design; Phase D-qualification and flight model

Name of project	Launch time	Status	Category
DAMPE	17 Dec. 2015	In orbit	1
Insight-HXMT	15 Jun. 2017	In orbit	1
GECAM	9 Dec. 2020	In orbit	1
PolarLight	29 Oct. 2018	In orbit	1
GRID	29 Oct. 2018 (GRID-01) 6 Nov. 2020 (GRID-02) 27 Feb. 2022 (GRID-03 b and GRID-04)	In orbit	1
Lobster-eye X-ray Satellite	2020 Jul. 25	In orbit	1
SVOM	2023	Phase D	2
EP	2023	Phase D	2
CSST	2023/2024	Phase C	2
HERD	2027	Phase B	3
POLAR-2	2024 (European payload) 2025 (Chinese payload)	Early Phase D (European payload) Phase B (Chinese payload)	3
DIXE	–	Phase A	3
LyRIC	2025+	Phase A	3
eXTP	2027	Phase B	4
DAMPE-2	2025–2026 (Suggested)	–	4
Earth2.0	TBD	–	4
DSL	2026	Phase A	4
CHES	TBD	–	4

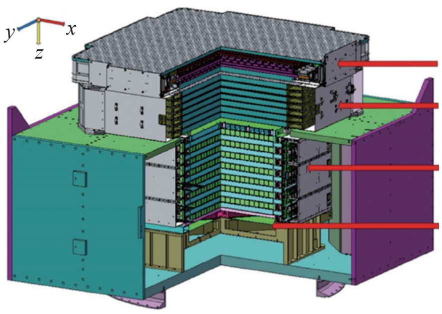

Fig. 1 Schematic drawing of the DAMPE detector

law model rather than a single power-law model. There is a sharp spectral break at about 0.9 TeV, which clarifies the behavior of the CRE spectrum at energies above 1 TeV and sheds light on the physical origin of the sub-TeV CREs[2].

(2) DAMPE has directly measured the cosmic ray proton fluxes with kinetic energies from 40 GeV to 100 TeV. In addition to confirming the spectral hardening at about 300 GeV found by previous experiments, DAMPE reveals a softening at about 13.6 TeV, with the spectral index changing from 2.60 to 2.85, establishing the presence of a new spectral feature of cosmic rays at energies lower than the so-called knee[3].

(3) With the 4.5 years of data recorded by DAMPE, the energy spectrum of cosmic ray helium nuclei from 70 GeV to 80 TeV has been obtained. A hardening of the spectrum is observed at about 1.3 TeV, similar to previous observations in space. In addition, a spectral softening at about 34 TeV is identified for the first time by big statistics with well controlled systematic uncertainties, with an overall significance of 4.3σ. Together with the proton spectral features revealed by DAMPE, we find a particle charge dependent softening energy, although with current uncertainties a dependence on the number of nucleons cannot be ruled out[4].

(4) Thanks to its unprecedented high energy resolution, DAMPE is well suitable for searching for monochromatic and sharp gamma-ray structures in the GeV–TeV range. With five years of DAMPE data, we do not

find line signals or candidates between 10 and 300 GeV in the Galaxy. Compared to the previous Fermi-LAT results, though DAMPE has an acceptance smaller by a factor of about 10 and an exposure time shorter by a factor of about 2, similar constraints on the dark matter parameters are achieved and below 100 GeV the lower limits of the decay lifetime are even stronger by a factor of about 2[5].

For further details, please refer to Ref. [1–5].

3 Insight-HXMT: Hard X-ray Modulation Telescope

Launch time: it was launched on 15 June 2017.

3.1 Scientific Goals

(i) To scan the Galactic Plane to find new transient sources and monitor the known variable sources; (ii) to observe X-ray binaries to study the dynamics and emission mechanism in the strong gravitational or magnetic fields; (iii) to monitor and study the Gamma-Ray Bursts and Gravitational Wave Electromagnetic counterparts.

3.2 Payloads

Insight-HXMT is China's first X-ray astronomical satellite and is currently in service in an orbit of 550 km altitude and 43° inclination. Insight-HXMT carries three slat-collimated instruments: High Energy X-ray Telescope (HE), Medium Energy X-ray Telescope (ME), and Low Energy X-ray Telescope (LE). HE consists of 18 NaI/CsI phoswich modules (main detectors) with a total geometrical area of about 5000 cm^2 in 20–50 keV. ME takes 1728 Si-PIN pixels which cover an energy range of 5–30 keV and ends up with a total geometrical area of 952 cm^2. LE adopts the Swept Charge Device (SCD) its detectors, which is sensitive in 1–15 keV with a total geometrical area of 384 cm^2. For the details about the payloads see Table 2 and Fig.2, and refer to Ref. [6].

3.3 Main Scientific Results

3.3.1 Discovery of Quasi-periodic Oscillation with the Highest Energy

Low-Frequency Quasiperiodic Oscillations (LFQPOs) are commonly found in black hole X-ray binaries, and their origin is still under debate. The properties of LFQPOs at high energies (above 30 keV) are closely related to the nature of the accretion flow in the innermost regions, and thus play a crucial role in critically testing various theoretical models. Insight-HXMT is capable of detecting emissions above 30 keV, and is therefore an ideal instrument to do so. Insight-HXMT discovered LFQPOs above 200 keV in the new black hole MAXI J1820+070 in the X-ray hard state. The phase lag of the LFQPO is constant around zero below 30 keV, and becomes a soft lag above 30 keV. The soft lag gradually increases with energy and reaches about 0.9 s in the 150–200 keV band. The detection at energies above 200 keV, the large soft lag and the energy-related behaviors of the LFQPO pose a great challenge for most existing models, but suggest that the LFQPO probably originates from the precession of a small-scale jet[7].

3.3.2 Discovery of Accelerating Jet During Outburst of a Black Hole X-Ray Binary System

A black hole X-ray binary produces hard X-ray radiation from its corona and disk when the accreting matter heats up. During an outburst, the disk and corona co-evolves with each other. However, such an evolution is still unclear in both its geometry and dynamics. Insight-HXMT detected an unusual decrease of the reflection fraction in MAXI J1820+070, which is the ratio of the coronal intensity illuminating the disk to the coronal intensity reaching the observer, as the corona is observed to contrast during the decay phase. With this discovery, a jet-like corona model is postulated, in which the corona can be understood as a standing shock where the material flowing through. In this dynamical scenario, the decrease of the reflection fraction is a signature of the corona's bulk velocity. These findings suggest that as the corona is observed to get closer to the black hole, the coronal material might be outflowing faster[8].

3.3.3 Identification of Magnetar Counterpart of the Fast Radio Burst

Fast Radio Bursts (FRBs) are short pulses observed in the radio band from cosmological distances and remain a puzzle due to no identification of the counterpart in multi-wavelength.

Insight-HXMT detection of a non-thermal X-ray burst in the 1–250 keV energy band allows for the first identification of FRB 200428 from SGR J1935+2154[9]. The X-ray burst showed two hard peaks with a separation of 34 milliseconds, broadly consistent with that of the two bursts in FRB 200428. The delay time between

Table 2 Major characteristics of the Insight-HXMT

Detectors	LE: SCD, 384 cm^2 ME: Si-PIN, 952 cm^2 HE: NaI/CsI, 5000 cm^2
Energy range	LE: 1–15 keV ME: 5–30 keV HE: 20–250 keV
Time resolution	HE: 25 μs ME: 280 μs LE: 1 ms
Energy resolution	LE: 2.5% @ 6 keV ME: 14% @ 20 keV HE: 19% @ 60 keV
Field of view of one module	LE: 6°×1.6°; 6°×4°, 60°×3°, blind ME: 4°×1°, 4°×4°, blind HE: 5.7°×1.1°, 5.7°×5.7°, blind
Angular resolution (20σ source)	<5'
Source location (20σ source)	<1'
Sensitivity (3σ, in 105 s)	0.5 mCrab (only statistical uncertainties included)
Orbit	Altitude: 550 km
Attitude	Inclination: 43° Three-axis stabilized Control precision: 0.1° Measurement accuracy: 0.01°
Data rate	LE: 3 Mbit·s^{-1} ME: 3 Mbit·s HE: 300 kbit·s
Payload mass	1000 kg
Nominal mission lifetime	4 years
Working mode	Scan, pointing, GRB

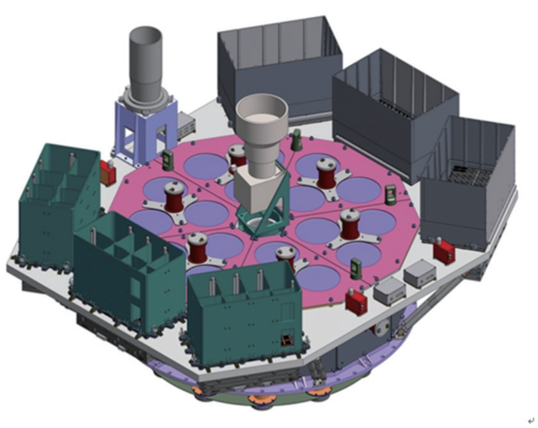

Fig. 2 Main payloads onboard Insight-HXMT. The 18 cylindrical NaI/CsI detectors located around the center are HE, the boxes on the lower left are LE and upper right ME

the double radio peak and the X-ray peaks is about 8.62 s, fully consistent with the dispersion delay of FRB 200428. The Insight-HXMT results suggest that the non-thermal X-ray burst and FRB 200428 share the same physical origin in an explosive event from SGR J1935+2154, and thus provide the first identification of an FRB in multi-wavelength.

3.3.4 Discovery of the Cyclotron Resonant Scattering Feature with the Highest Energy

Insight-HXMT observed the outburst of high mass X-ray binary system GRO J1008-57 and detected a Cyclotron Resonant Scattering Feature (CRSF) line at around 90 keV with a significance of more than 70 σ[10]. Such results provide for the first time the first firm detection of so far the highest centroid energy of CRSF and hence the strongest magnetic field ever measured directly from the NS system. Previous observations by a series of international X-ray telescopes reported only at most roughly 4 σ due to their shortages in bandwidth and detector area for covering the hard X-rays.

For further details, please refer to Ref. [6–10].

4 GECAM: Gravitational Wave High-energy Electromagnetic Counterpart All-sky Monitor

Launch time: 9 December 2020.

4.1 Scientific Goals

GECAM is a dedicated all-sky monitor with a very large instantaneous field-of-view in the X-ray and soft gamma-ray band. The primary scientific objectives are: (i) monitor and characterize the high energy counterparts of Gravitational Waves (GWs), to reveal the underlying physics of neutron stars, black holes and merger process of them; (ii) monitor and characterize the high energy counterparts of Fast Radio Burst (FRBs), to reveal their origin and emission mechanism; (iii) discover various types of Gamma-Ray Bursts (GRBs) and Soft Gamma-Ray Repeaters (SGRs), to deepen our understanding of their burst physics.

4.2 GECAM Detectors

GECAM is composed of two microsatellites in the same Low Earth Orbit with opposite orbital phase (Fig.3), each of which is equipped with 25 Gamma-Ray Detectors (GRD) and 8 charged Particle Detectors (CPD) pointing to different directions to cover a very large field of view. All these detectors are based on SiPM technology which ensures the detector and satellite very compact and light-weighted but with good performance in detection. The specifications of GECAM are listed in Table 3.

Due to the unexpected anomalies in the power supply system of both satellites, currently only GECAM-B* can observe about 10 hours per day while GECAM-A has not been able to observe yet.

4.3 Main Scientific Results

GECAM-B has detected hundreds of transients in hard x-ray and soft gamma-ray, including Gamma-Ray Bursts (GRBs), Soft Gamma-Ray Repeaters (SGRs), bursts from X-Ray Binaries (XRB), Solar Flares and Terrestrial Gamma-ray Flashes (TGFs). GECAM-B also has been monitoring the potential gamma-ray counterparts of many Fast Radio Burst (FRBs). GECAM-B will seek for gamma-ray counterparts of Gravitational Waves (GWs) during the forthcoming O4 observation of LIGO/Virgo/KAGRA.

With the novel application of Beidou navigation System (BDS), GECAM-B has been able to downlink the trigger data nearly real-time (latency is about 60 s), and then guide other space-borne or ground-based telescopes to do follow-up observations of various bursts (See Fig.4). GECAM-B is the first Chinese space mission with the capability of sending prompt astronomical alert to the world-wide community.

For further details, please refer to Ref. [11].

5 PolarLight

Launch time: it was launched on 29 October 2018.

5.1 Scientific Goals

PolarLight is a collimated X-ray polarimeter observing the brightest X-ray sources in the sky in order to diagnose their magnetic field or accretion geometry.

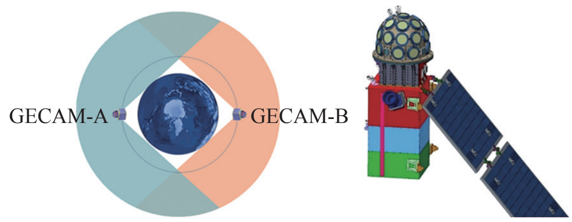

Fig. 3 Design of GECAM mission which is composed of two microsatellites (GECAM-A and GECAM-B) (left). Currently, only GECAM-B is working. Layout of the GECAM spacecraft and scientific payloads, which include 25 gamma-ray detectors and 8 charges (right)

Table 3 Specifications of GECAM

Parameters	Values	Notes
Orbit	600 km, 29°	–
Life time	3 years	Goal: 5 years
GRD energy range	15 keV–5 MeV	–
Field of view	60% all-sky	For GECAM-B only
Burst sensitivity	$<2\times10^{-8}$ $\mathrm{erg\cdot cm^{-2}\cdot s^{-1}}$	20 s, 10–1000 keV
Burst localization accuracy	<1° (1σ stat.)	Flux: 1×10^{-6} $\mathrm{erg\cdot cm^{-2}\cdot s^{-1}}$, 10 s
Absolute timing accuracy	<3 μs	–
Relative timing accuracy	0.1 μs	Between detectors
Time latency of trigger data	60 s	For the first BDS message

Note 1 erg=10^{-7} J

*Since June 1st 2022, GECAM-B has resumed full operation, as its power supply system has self-recovered

5.2 Payload

The payload has a size of 1 U (about 10 cm × 10 cm × 10 cm), containing three Printed Circuit Boards (PCBs) in an aluminum case. From top to bottom, the three PCBs respectively host the Gas Pixel Detector (GPD), the high voltage power supply, and the data acquisition system. A collimator is mounted on top of the GPD to avoid source confusion and reduce the diffuse background. The GPD is a 2D gas proportional counter using the Gas Electron Multiplier (GEM) with an ASIC pixel readout, filled with Dimethyl Ether (DME) at a pressure of 0.8 atm as the working gas. It enables us to measure the tracks of photoelectrons following the absorption of X-rays, and infer the polarization degree and angle from the emission angles of photoelectrons on the 2D plane (See Fig.5 and Table 4).

5.3 Main Scientific Results

Prior to PolarLight, the Crab nebula was the only astrophysical source with a significant polarimetric measurement in the keV band, performed in the 1970 s with the Bragg polarimeter onboard OSO-8 in narrow bands around 2.6 keV and 5.2 keV. The main scientific results with PolarLight are as follows.

In 2019, PolarLight revealed a possible variation in polarization (a sudden decrease in PF) coincident in time with the glitch of the Crab pulsar on July 23[12]. The variation was found to have a significance of 3σ using different methods. This may suggest that the pulsar magnetosphere altered after the glitch. Then, the polarization recovered roughly 100 days after the glitch[13]. With more data being accumulated, the PA measured with PolarLight from the total nebular emission was found to

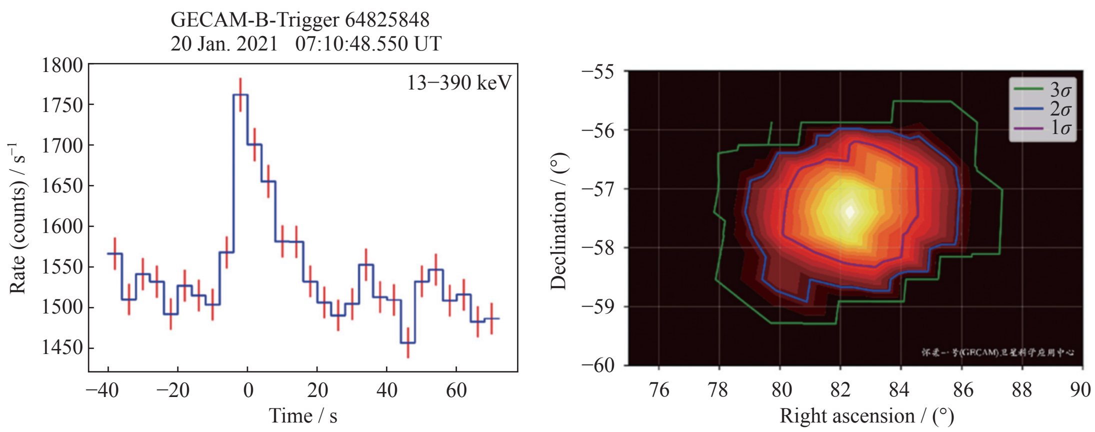

Fig. 4 GECAM real-time light curve of gamma-ray burst downlinked through the Beidou navigation system (left). The low-latency GECAM localization map of a gamma-ray burst (GRB 211105 A, right)

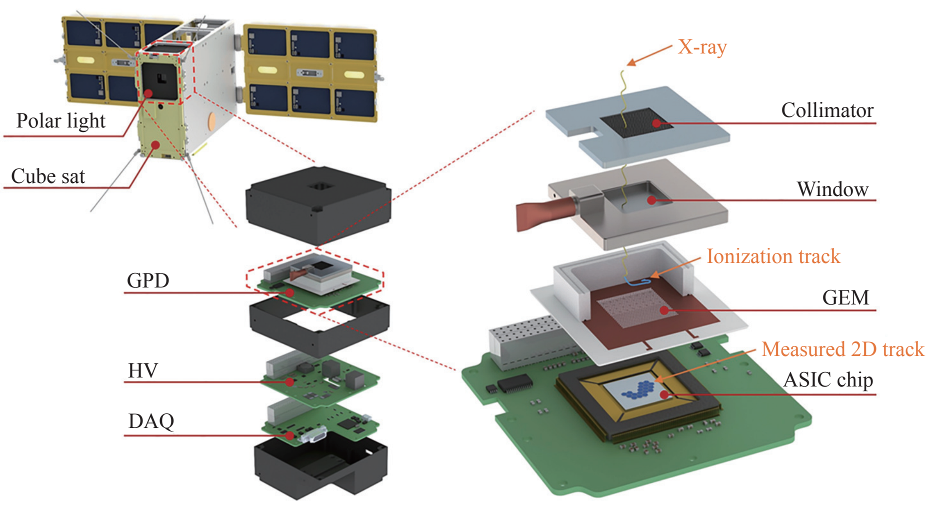

Fig. 5 Schematic drawing of PolarLight

have a difference of 18.0°±4.6° from that measured 42 years ago with OSO-8, indicating a secular evolution of polarization associated with either the Crab nebula or pulsar[13]. The long-term variation in PA could be a result of multiple glitches in the history, magnetic reconnection in the synchrotron emitting regions in the nebula, or secular evolution of the pulsar magnetic geometry.

Sco X-1 is the brightest persistent extrasolar object in the keV sky, powered by accretion from a low-mass companion star onto a low-magnetic neutron star. OSO-8 observed the source and produced a non-detection in X-ray polarization around 2.6 keV, but obtained a 3σ detection around 5.2 keV. PolarLight yielded consistent results: a null-detection below 4 keV but a significant detection in 4–8 keV; the significance in the hard band is up to 5σ when the source shows the highest intensity[14]. The PA measured with PolarLight is consistent with that obtained with OSO-8 within errors, and in line with the orientation of the radio jet of Sco X-1 on the plane of the sky. The jet is supposed to be launched along the symmetry axis of the system. The results favor the scenario that an optically-thin corona is located in the transition layer of Sco X-1 under the highest accretion rates, and disfavor the accretion disk corona model.

For further details, please refer to Ref. [12–14].

6 GRID

Launch times: 29 October 2018 (GRID-01), 6 November 2020 (GRID-02), 27 February 2022 (GRID-03 b and GRID-04).

Table 4 Specifications of PolarLight

Energy range	2–8 keV
Energy resolution	19% @ 6 keV
Field of view	2.3° FWHM or 5.7° FWZR
Gas mixture	pure DME at 0.8 atm, 1 cm thick
Window	100 μm beryllium
GEM	100 μm pitch and 100 μm thick
ASIC	50 μm pitch
Modulation factor	0.42 @ 3.74 keV
Weight	580 g
Power	2.2 W
Size	1 U (about 10 cm × 10 cm × 10 cm)

6.1 Scientific Goals

GRID is a project led by students, with multiple detectors deployed on low Earth orbits, to monitor the transient gamma-ray sky, with particular interests in identifying gamma-ray bursts associated with gravitational wave events and soft gamma-ray repeaters associated with fast radio bursts.

6.2 Payloads

GRID is a network of gamma-ray detectors on low Earth orbits. Each detector contains four GAGG crystals read out with Silicon Photomultipliers (SiPMs). Each crystal has a geometry of 3.8 cm × 3.8 cm × 1 cm, sensitive in the energy range from several tens of keV to about 2 MeV. The field of view is roughly half of the sky. The payload has a size of 0.5 U (about 10 cm × 10 cm × 5 cm) with three print circuit boards, respectively for the SiPMs, preamplifiers, and data acquisition, from top to bottom. The GRID project is lead and operated by students. So far, four GRID payloads have been launched, all led by students from Tsinghua University. In the future, students from other universities will join the GRID collaboration and launch their own payloads (see Fig.6 and Table 5).

6.3 Main Scientific Results

GRID-01 was used for technical demonstration[15].

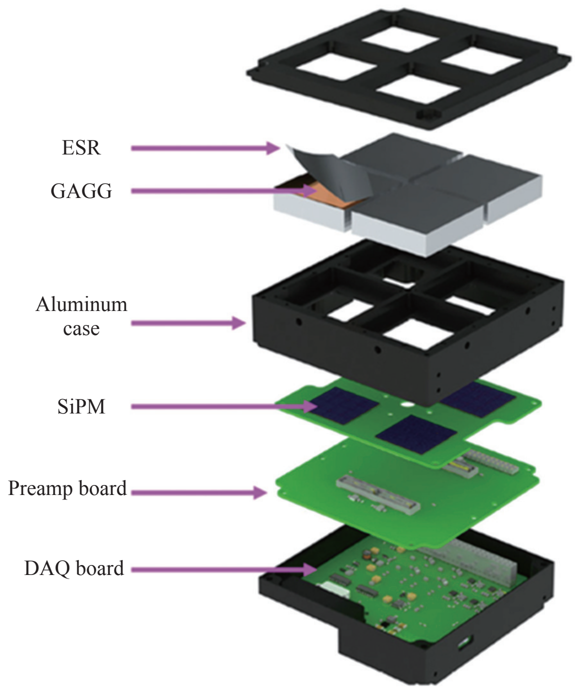

Fig. 6 Schematic drawing of the GRID payload

GRID-02 started to produce scientific results[16]. The first gamma-ray burst reported with GRID-02 is GRB 210121 A[17], which was jointly observed with Fermi GBM, HXMT, and GECAM. The burst is characterized by a hard low-energy spectral index, likely due to thermal origin, possibly a typical fireball burst from a host galaxy at z = 0.319. GRID-03 b and GRID-04 were just launched as of this writing.

For further details, please refer to Refs. [15–17].

7 Lobster-eye X-ray Satellite

Launch time: it was launched on 25 July 2020.

7.1 Scientific Goal

To perform wide-field X-ray imaging of rich galaxy clusters, to detect early X-ray emissions from gamma-ray bursts, and to probe solar wind charge exchange X-ray emission from comets.

7.2 Mission

The "Lobster-eye X-ray Satellite" was developed by Nanjing University in a joint effort with the University of Hong Kong and the Beijing Institute of Space Mechanics and Electricity (BISME). Successfully launched on 25 July 2020 and operating to this date, the "Lobster-eye X-ray Satellite" is the first astronomical satellite equipped with the lobster-eye focused X-ray imaging technology, which was invented more than four decades ago[18]. The key parameters and layout of the satellite are shown in Table 6 and Fig.7, respectively.

8 SVOM: Space-based Multiband Astronomical Variable Objects Monitor

Launch time: in 2023.

8.1 Scientific Goal

SVOM (Space-based multiband astronomical Variable Objects Monitor) is a mission dedicated to studying Gamma-Ray Bursts (GRBs)[19].

8.2 Mission

The mission has been approved jointly by both Chinese and French space agencies. The satellite will have an orbit with an altitude of 600–650 km and an inclination of 29°. The system Critical Definition Review (CDR) was carried out by CNSA and CNES in July 2020. It had been planned to be in orbit in 2023.

GRBs are extremely luminous transient sources appearing when a newborn stellar mass black hole or magnetar emits an ultra-relativistic jet towards the Earth. Consequently, the study of GRBs not only has the potential to expand or revolutionize our understanding of key astrophysical issues on the mechanisms driving stellar explosions and the radiation processes of relativistic jets. In the next years, GRBs will also undoubtedly shed new light on the evolution of the young universe, particularly on the history of star formation, the metal enrichment of galaxies, and the reionization of the intergalactic medium[20]. GRB 170817 A, a normal short GRB detected by Fermi-GBM, was the first confirmed counterpart of gravitational-wave transients, which made GRBs even hotter topic[21].

The scientific objectives of SVOM put a special emphasis on two categories of GRBs: very distant GRBs at z>5 which constitute exceptional cosmological probes, and faint/soft nearby GRBs which allow probing the nature of the progenitors and the physics at work in the explosion. These goals have a major impact on the design of the mission: the on-board hard X-ray imager is sensitive down to 4 keV and computes online image and rate

Table 5 Specifications of GRID

Energy range	20 keV–2 MeV
Energy resolution	20% FWHM @ 662 keV
Field of view	2π
Scintillator	Ce-doped $Gd_3(Al,Ga)_5O_{12}$ (GAGG)
SiPM	J-60035 manufactured by SensL
Payload size	0.5 U (about 10 cm × 10 cm × 5 cm)

Table 6 Key parameters of "Lobster-eye X-ray Satellite"

Dimension	750 mm×500 mm×320 mm (2840 mm with solar panel)
Power	30 W
Orbit	LEO
Optics	2×2 MPO (f = 375 mm, A = 4 cm×4 cm)
Detector	CCD 1024 pixel×1024 pixel
Field-of-view	2°(with detector)
Angular resolution	<0.2°
Energy range	1–6 keV (in-orbit)
Energy resolution	<200 eV

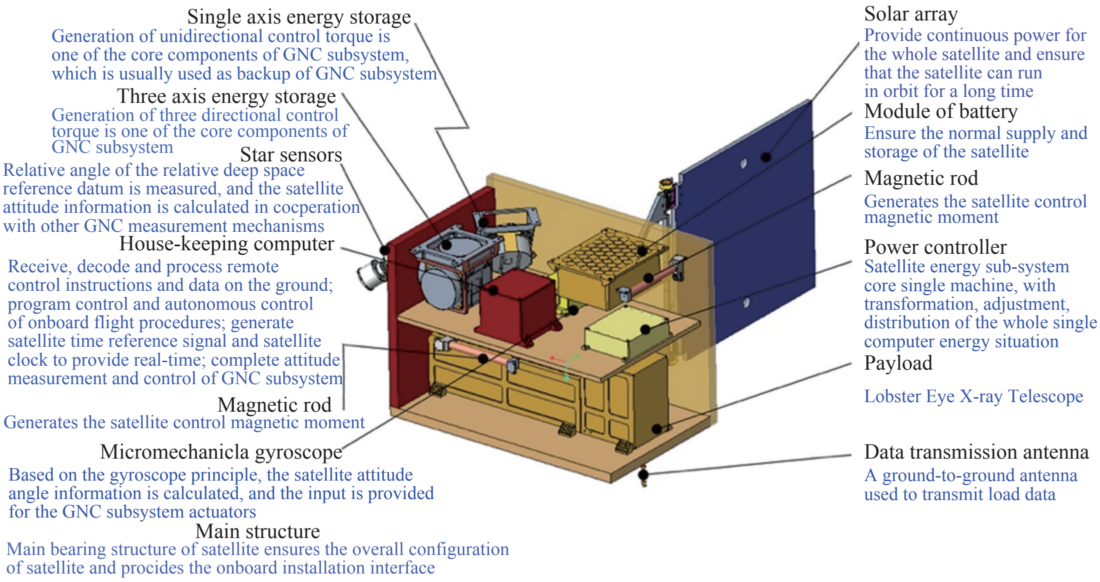

Fig. 7 Layout of the “Lobster-eye X-ray Satellite”

triggers, and the follow-up telescopes on the ground are sensitive in the NIR.

In order to take advantage of the astrophysical potential of GRBs, SVOM is designed to: (i) permit the detection of all known types of GRBs; (ii) provide fast, reliable GRB positions; (iii) measure the spectral shape of the GRB prompt emission from visible to MeV; (iv) measure the temporal properties of the GRB prompt emission from visible to MeV; (v) identify quickly the afterglows of detected GRBs at both X-ray and visible bands, including the ones that are highly redshifted ($z > 5$); (vi) measure the spectral shape of the early and late GRB afterglow from visible to X-rays; (vii) measure the temporal evolution of the early and late GRB afterglow from visible to X-rays.

SVOM mission by design consists of a set of scientific instruments to implement the synergy bet-ween space and ground observations. The space-based instruments include: (i) ECLAIRs, a wide field-of-view hard X-ray imager and spectrometer; (ii) GRM, a wide field-of-view soft gamma-ray spectrometer; (iii) MXT, a narrow field-of-view low-energy X-ray telescope; (iv) VT, a narrow field-of-view visible/near infrared (NIR) telescope. An artist view of the SVOM satellite is shown in Fig.8. And the ground-based instruments include: (i) GFTs, two follow-up telescopes (one of which featuring efficient NIR capabilities); (ii) GWAC, an array of wide field-of-view cameras in visible band. A network of about 45 VHF receiving stations, and a Beidou short-message system as a supplement, are designed for real-time downlink communication.

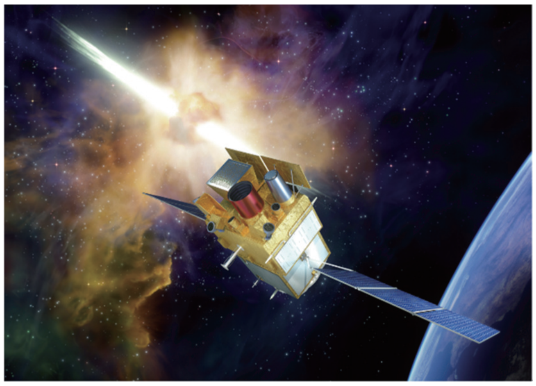

Fig. 8 Artistic view of the SVOM satellite

SVOM is a unique multi-wavelength observatory with rapid slew capability and quick command up-link capability. Therefore, SVOM will also be a powerful target-of-opportunity observatory for the whole astronomy community beyond the specific objectives linked to GRBs. For example, the SVOM mission has been conceived to promptly point to the celestial fields where sources have been detected by the wide field of view astronomical devices such as the upgraded generation of gravitational wave detectors (LIGO, VIRGO, GEO and KAGRA) and high-energy neutrino detectors (IceCube, KM3 NeT).

For further details, please refer to Refs. [19–21].

9 Einstein Probe Mission

9.1 Expected Launch Time and Current Phase

The EP project is currently in Phase D (flight model phase) and the satellite is planned for launch by the end of 2023.

9.2 Scientific Goals

The Einstein Probe will carry out systematic sky monitoring surveys with a large instantaneous field-of-view in the soft X-ray band with the sensitivity and grasp one order of magnitude better than those currently in orbit. The primary science objectives are: (i) discover and characterize cosmic X-ray transients, to reveal their properties and gain insight into their nature and underlying physics; (ii) discover and characterize X-ray outbursts from otherwise quiescent black holes, for a better understanding of the demography of black holes and their origin and evolution, as well as accretion physics; (iii) search for X-ray sources associated with gravitational-wave events and precisely locate them.

9.3 EP

EP carries two scientific instruments: an X-ray monitoring instrument Wide-field X-ray Telescope (WXT) with a large instantaneous FoV, and a narrow-field Follow-up X-ray Telescope (FXT). Some of the specifications of WXT and FXT are listed in Table 7.

To achieve both wide FoV and X-ray focusing, the novel micro-pore optics in the lobster-eye configuration is adopted for WXT. WXT consists of 12 identical modules with a 375 mm focal length. One WXT module includes the MPO mirror assembly, 4 scientific CMOS sensors and electronics units, optical baffle, structure and thermal control. The nominal detection bandpass of WXT is 0.5–4.0 keV. EP WXT has a large grasp (effective area times FoV) of the order of 10^4 cm^2·(°)^2, which is the largest among all focusing telescopes in X-rays ever built. WXT has a nominal theoretical sensitivity of 10^{-11} erg·s^{-1}·cm^{-2} for 1000 second exposure in the 0.5–4 keV band.

The FXT is composed of a pair of Wolter-I focusing mirror assemblies. For each of the telescope a CCD detector is mounted on the focal plane. FXT covers an energy passband of 0.3–10 keV and has an effective area of about 300 cm^2 each at around 1 keV. EP is also capable of fast transient alerts triggering and downlinking, aiming at multi-wavelength follow-up observations by the world-wide community.

Fig.9 showed Layout of the Einstein Probe spacecraft and scientific payloads, which include 12 modules of WXT aligned with different directions and 2 coaligned modules of FXT.

For further details, please refer to Ref. [22].

10 CSST: Chinese Survey Space Telescope/Chinese Space Station Telescope/Xuntian Space Telescope

Project name: Chinese Survey Space Telescope (CSST, also known as the Chinese Space Station Telescope or Xuntian Space Telescope). Launch time: 2023/2024. Development phase: Phase C. An artist view of the CSST is showed in Fig.10.

Table 7 Specifications of WXT and FXT

Parameters	WXT	FXT
Number of modules	12	2
Telescope optic	Lobster-eye MPO	Wolter-I
Detector	CMOS	CCD
Field of view	⩾3600 square degrees	⩾38′(diameter)
Focal length/mm)	375	1600
Effective area @1.2 keV·cm^{-2}	2.7	300 (each module)
Spatial resolution (1 keV)	5′(FWHM)	30″ (HPD)
Bandpass/keV	0.5–4	0.3–10
E-resolution @1.25 keV (eV)	170	120
Sensitivity/(erg·s^{-1}·cm^{-2})	1×10^{-11} @ 1 ks	1×10^{-14} @10 ks

Note 1 erg=10^{-7} J

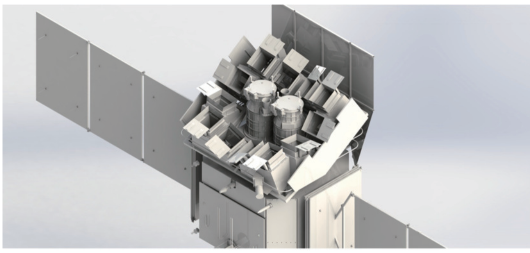

Fig. 9 Layout of the Einstein Probe spacecraft and scientific payloads, which include 12 modules of WXT aligned with different directions and 2 coaligned modules of FXT

Fig. 10 An artistic rendition of CSST in orbit (provided by Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences)

10.1 Science Goal

The CSST aims to explore the nature of dark energy and dark matter through precision measurements of gravitational lensing signal and galaxy clustering properties over its planned 17500 square degrees of high-resolution multiband imaging and slitless spectroscopy survey covering a wavelength range of 255 nm to 1000 nm. The same survey and observations of its versatile instruments will provide extremely rich data for a wide range of studies from the solar system to distant galaxies and beyond.

The CSST[23] is a major science project of China Manned Space (CMS). It has a nominal mission lifetime of 10 years, which could be extended in principle. During normal observations, the CSST will fly independently in the same orbit as China's Tiangong space station while maintaining a large distance apart. It can dock with the space station for refueling and servicing as scheduled or as needed. With a Cook-type three-mirror anastigmatic design, the CSST can achieve superior image quality within a large Field of View (FoV), which gives it an advantage for survey observations. Being an off-axis telescope without obstruction, its Point Spread Function (PSF) does not have diffraction spikes from mirror support structures and is thus helpful for precision photometry, position, and shape measurements when properly sampled. The radius encircling 80% energy of the PSF within the CSST's central 1.1 square degrees of FoV is specified to be no more than 0.15″, including all wavefront errors in the optics and instruments and dynamical effects such as the telescope's attitude control and vibration.

10.2 CSST

The CSST will be launched with 5 first-generation instruments including a Survey Camera, a Terahertz Receiver, a Multichannel Imager, an Integral Field Spectrograph, and a Cool Planet Imaging Coronagraph. The Survey Camera is equipped with 30 9000×9000 detectors for science observations, each with a filter or two grating elements mounted above, a defocused 9000×9000 detector for flux calibration in r band, eight 640×512 near-infrared detectors, two Fine Guide Sensors, and four Wavefront Sensors. It will take the Survey Camera roughly 7 years of operation accumulated over 10 years of orbital time to image roughly 17500 square degrees of the median-to-high galactic latitude and median-to-high ecliptic latitude sky in NUV, u, g, r, i, z, and y bands and take slitless spectroscopy of the same sky in 3 bands. The point-source 5σ limiting magnitudes in g and r bands can reach 26th magnitude (AB mag) or higher. The spectral resolution ($R=\lambda/\Delta\lambda$) of the slitless spectrograph is specified to be on average no less than 200, and the wide-band-equivalent limiting magnitudes in GV (400–620 nm) and GI (620–1000 nm) bands will reach the 23rd magnitude or higher. In addition, a number of deep fields will be selected for more observations to reach at least one magnitude deeper than the wide-area survey. The Multichannel Imager plans to observe five ultra-deep fields of 300 square minutes in total to 30th magnitude in the visible.

Unlike the Survey Camera, the other four instruments all have a small FoV. They enable unique capabilities for detailed studies of individual objects or small fields. The Terahertz Receiver will be used to carry out spectral line surveys or mapping of star-forming regions of the Milky Way, nearby galaxies, late-type stars, and solar system objects. The Multichannel Imager can observe the same field in three bands simultaneously, capable of obtaining instantaneous color of fast varying objects such as fast transients, comets, and spinning asteroids. The Integral Field Spectrograph splits its 6"×6" FoV into 32×32 units and obtains 1024 spectra of these units. It can provide both two-dimensional spatial information and spectral information of the target, particularly helpful for investigations of the co-evolution of supermassive black holes and galaxies and star formation in the nearby universe. The Cool-Planet Imaging Coronagraph aims to realize 10^{-8} high-contrast direct imaging of exoplanets in the visible. It plans to follow up exoplanets discovered by radial velocity observations, study planet formation and evolution, and probe protoplanet disks.

For further details, please refer to Ref. [23].

11 HERD: High Energy Cosmic Radiation Detection Facility

Expected launch time: in 2027. Current status: Phase B.

11.1 Scientific Goals

The primary scientific objectives of HERD are: dark matter search with unprecedented sensitivity in the energy spectra and anisotropy of high energy electrons from 10 GeV and in the gamma-ray spectrum from hundreds of MeV, precise cosmic ray spectrum and composition measurements up to PeV in order to determine the mechanism of the cosmic rays “knee” structure, as well as gamma-ray monitoring with a wide FOV and full sky survey with high sensitivity[24].

11.2 Payload Description

HERD is an astronomy and particle astrophysics experiment onboard China’s Space Station. HERD is a China-led mission with a large European collaboration led by Italy. HERD is composed of five scientific instruments (see Fig.11). The primary instrument in the innermost is a deep 3D imaging Calorimeter (CALO) with an innovative design that insures better e/p separation for particles and one order of magnitude larger geometrical factor than all previous experiments, by accepting particles impinging on its top face but also on the four lateral faces. Each sensitive face of CALO is instrumented from inside out with a FIber Tracker (FIT), a Plastic Scintillation Detector (PSD) and a Silicon Charge Detector (SCD) to precisely measure the charges of cosmic rays. A Transition Radiation Detector (TRD) is located on one lateral side for the energy calibration of TeV nuclei. The total mass of HERD payload is about 4 tons[25].

Table 8 shows HERD main specifications. For further details, please refer to Refs. [24, 25].

12 POLAR-2: Gamma-Ray Burst Polarimetry on the China Space Station

Launch time: 2024 and 2025. There are two payloads of POLAR-2, which are European payload and Chinese payload, respectively. The two payloads are relatively independent and have their own scientific importance, although their joint observation in orbit will produce the best scientific observations for the whole project. Thus, the two payloads do not have to be launched at the same time. The European payload was proposed in 2018 and has been officially accepted in 2019 for execution with an anticipated launch date of 2024. While for the Chinese payload, which was proposed in 2021, the launch is aimed at 2025.

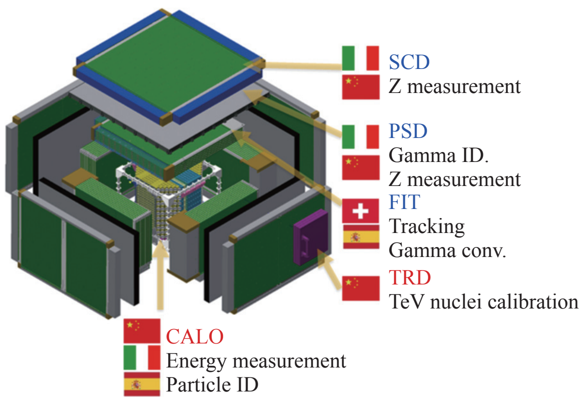

Fig. 11 HERD payload

Table 8 HERD main specifications

Energy range (e/γ)	10 GeV–100 TeV (e) 0.5 GeV–100 TeV (γ)
Energy range (CR)	30 GeV–PeV
Angular resolution	0.1° @10 GeV
Charge resolution	0.1–0.3 c.u
Energy resolution (e)	1%@200 GeV
Energy resolution (p)	20%@100 GeV–PeV
e/p separation	10^6
G.F. (e)	>3 m^2·sr@200 GeV
G.F. (p)	>2 m^2·sr@100 TeV

12.1 Current Phase of the Project

For the European payload, it is at the end of Phase C and early Phase D. For the Chinese payload, it is in Phase B.

12.2 Scientific Goals

Following the important results of the POLAR experiment as the first major step toward understanding the details of the Gamma-Ray Burst (GRB) nature and the open questions raised according to POLAR's new findings[26], the POLAR-2 experiment mainly aims to measure the linear polarization of GRBs prompt emissions and early X-ray flare with high precision, thus trying to answer the fundamental questions regarding the powering mechanism, jet characteristics, radiation physics and so on for GRBs and electromagnetic counterparts associated with the gravitational wave sources. The secondary scientific objective of POLAR-2 is to precisely measure the linear polarization of magnetar high-energy bursts, exploring the physical mechanism of their association with the fast radio bursts, which will make the key contribution to answering the questions of their origin.

12.3 POLAR-2 Payloads

The European payload of POLAR-2 will contain 100 High-energy Polarimeter Detector (HPD) modules by a factor of 4 compared to its predecessor POLAR. Each HPD module is composed of 64 Plastic Scintillator (PS) bars with optimized dimensions for Compton polarimetry purposes, which is the most effective way for polarization measurement in the 30 to 800 keV energy range of hard X-rays to soft Gamma-rays. Different from POLAR which used the multi-anode photomultiplier tube device for reading out the fluorescence signals from the PS bars, a Silicon Photo Multiplier (SiPM) array will be used for each HPD module in order to increase the Photo-Detection Efficiency by about a factor of 2 and reduce the lower energy limit of the detector down to several keV, as well as to eliminate the cross-talk signals existed mostly among the neighboring PS bars in POLAR to a negligible level. More details of the HPD design are described in Ref. [27]. Although it is possible to localize GRBs and deduce their spectra roughly by making use of the HPD detector arrays, a better GRB localization and spectrum measurement precision is required in order to perform the polarization measurements with higher precision. Thus, a dozen of Broadband Spectrometer Detector (BSD) modules are proposed to enhance these two aspects. Each BSD module consists of the $LaBr_3$(Ce) crystal with a compact dimension as well as a SiPM array for the signal readout. A dual-channel design with different gains for each BSD module enables its detectable energy range from about 10 keV to several MeV. Besides, diverse pointing configurations for the BSD modules further increase the localization precision for GRBs. As it is vital to understand the radiation mechanism, geometry and magnetic field structure of the jet by observing comprehensively the polarization parameters during both the prompt and early afterglow emissions phases of GRB, a Low-energy Polarimeter Detector (LPD) was also proposed which consists of about eighteen independent modules. Each LPD module is filled with DME or Xenon mixture as the working gas to enable the soft X-ray polarization measurement from several keV to about 10 keV based on the photoelectric polarimetry. The signals will be collected by a gas multiplication microchannel panel and read out by customized ASIC electronics.

Currently the design optimization for the two payloads is still ongoing, the CAD models are shown in Fig.12. A summary of the main anticipated features of the two payloads is listed in Table 9.

For further details, please refer to Refs. [26, 27].

13 DIXE: DIffuse X-ray Explorer

Status of project: Phase A.

13.1 Scientific Goals

Bying conducting an all-sky survey with a high-resolution X-ray spectrometer, DIXE is expected to complement eROSITA with data of much improved spectral resolution. The primary scientific issues that DIXE hopes to address include the origin of the soft diffuse X-ray background, the nature of the "eROSITA Bubble", and the physical state of the hot halo around the Milky Way. The issues are intimately related to some of the unsolved problems in understanding the ecosystem of galaxies.

13.2 Payload

The DIXE payload is to be installed on the Chinese Space Station. It employs a 10×10 array of microcalorimeters at the heart of its detector system. The microcalorimeters are based on superconducting Transition-Edge Sensor (TES) technology, promising to pro-

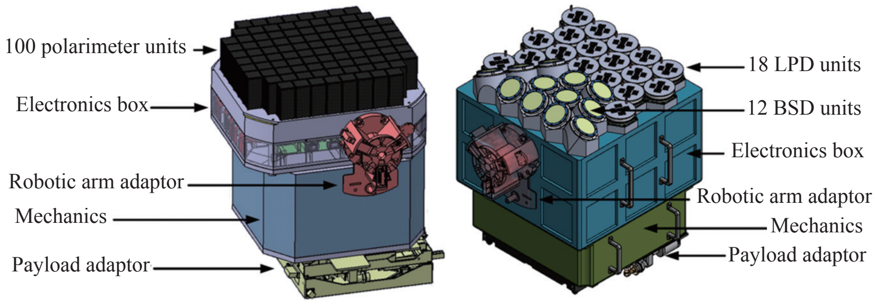

Fig. 12 Design of the POLAR-2 two payloads. On the left, the European payload CAD model is shown, while the Chinese payload CAD model is shown on the right

Table 9 Main anticipated technical performances of POLAR-2

Characteristics	Instrument		
	HPD	LPD	BSD
Detector sensitive material	Plastic scintillator bars array	DME or Xenon mixture	$LaBr_3$ crystal
Energy range	30–800 keV	2–10 keV (potentially can be extended to 30 keV depending on the gas)	10–2000 keV
Detection area	2000 cm^2	⩾290 cm^2	For each module⩾40 cm^2
Field of view	50% sky	90°×90°	50% sky
Energy resolution	–	⩽25%@5.9 keV	⩽18%@59.5 keV
Dimensions	590×664×700 mm^3	600×600×710 mm^3	

vide an energy resolution better than 6 eV, and are optimized for performance over the energy band of 0.1 – 5 keV (allowing an examination of the claimed 3.5 keV emission line, which is speculated to be associated with dark matter). The detector is mechanically collimated to a field-of-view of about 100 square degrees. Table 10 shows the key parameters of the preliminary payload design.

To achieve the required energy resolution, the microcalorimeter array needs to be cooled to an operating temperature of about 50 mK. In the preliminary design, the cooling system consists of a two-stage cryocooler and a two-stage Adiabatic Demagnetization Refrigerator (ADR), with the cryocooler reaching down to 4.2 K and the ADR down to 50 mK. The microcalorimeter array is read out by multiplexing electronics.

From a technical point of view, DIXE serves as a pathfinder mission for the HUBS project[28], hoping to advance the TRLs of key technologies including TES microcalorimeter, multiplexing readout electronics, cryocooler, and ADR.

For further details, please refer to Ref. [28].

14 LyRIC: Lyman Ultraviolet Radiation from Interstellar Medium and Circum-galactic Medium

Launch times: TBD. Current status: Phase A.

14.1 Scientific Goals

Accretion and feedback are of the frontiers in Astrophysics, as well as one of the important goals for the future space astronomical observatories. Circum-galactic Medium (CGM) is the best and hot target in this field. We propose an external scientific payload operating on Chinese Space Station: “LyRIC: Lyman ultraviolet Radiation from ISM and CGM”, to measure the LUV radiation of our Galaxy and nearby galaxies. LyRIC will fill in the unique LUV windows for the high-quality spectroscopic radiation measurements from CGM of nearby galaxies with a big angular size, HVCs in our Galaxy and M31, and the diffuse sources in our Galaxy and SMC/LMC for the first time. Such a scientific payload will also help us to verify our LUV technologies in space.

14.2 Payload

LyRIC is designed to take advantage of the mature technology, Long-Slit Spectrograph (LSS) operating on Chinese Space Station. Limited by the size and weight of the independent external payload operating on CSS, the new optimizations of LyRIC (the optical design, inside view and outlook, major specifications) are summarized in Fig.13. LyRIC will have a mirror with an aperture less than 30 cm, spectral resolution $R \approx 3000$, and spatial resolution about 30 arcsec, working in the wavelength range of 91.2–115 nm for a lifetime longer than 5 years.

For further details, please refer to Ref. [29].

15 eXTP: The enhanced X-ray Timing and Polarimetry Mission

Expected launch time and current phase: Expected to be launched in 2027, currently in Phase B.

15.1 Scientific Goals

The three core objectives of eXTP aim at answering key open questions of fundamental physics: (i) the physical nature of cold ultra-dense matter; (ii) the behaviour of matter and light in the space-time shaped by strong-field gravity; (iii) the astrophysics and physics of the strongest magnetic fields in nature. The matter inside neutron stars (NSs), the space-time in the vicinity of the Black Hole (BH) horizon, and the extremely magnetized vacuum close to magnetars and accreting pulsars are uncharted territories of fundamental physics. NSs and BHs provide a unique arena for their exploration. The eXTP mission will revolutionize these fundamental areas of today's research by high precision X-ray observations of NSs across the magnetic field scale and BHs across the mass scale.

Table 10 Key parameters of the preliminary payload design

Parameter	Value	Notes
Lower energy/keV	0.1	Goal
Upper energy/keV	5	Point of optimization
Energy resolution/eV	<6	Goal: 2 eV at 1 keV
Field of view/(°)^2	100	With mechanical collimator
Effective area/cm^2	>0.5	Goal: 1 cm^2
Grasp/[cm^2·(°)^2]	>50	Goal: 100 cm^2·(°)^2
Power/W	800	Peak: 1000 W
Mass/kg	300	Goal: < 200 kg

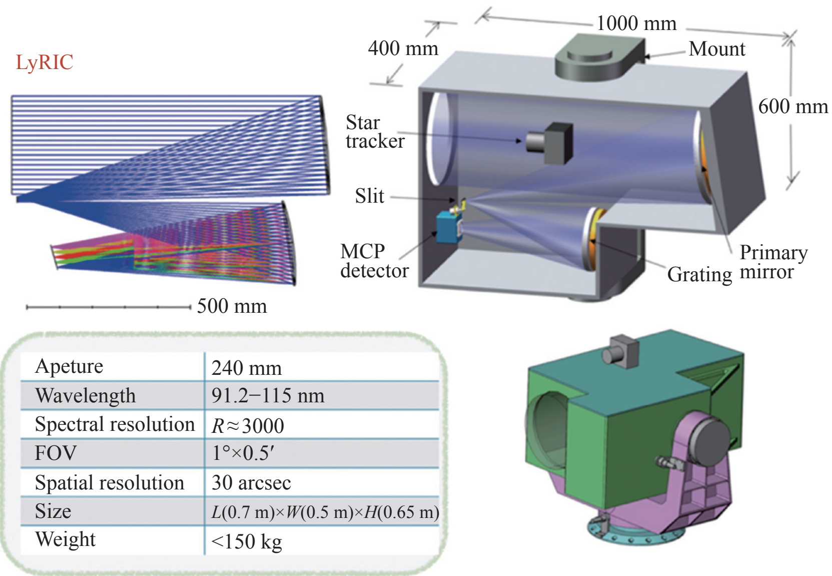

Fig. 13 Current optimizations of LyRIC: the optical design (upper left), the inside view (upper right); major specifications (lower left); the outlook (lower right). Taken from Ref. [29]

In addition to investigating questions of fundamental physics, eXTP will enable excellent observatory science opportunities, providing observations of unprecedented quality on a variety of galactic and extragalactic objects. eXTP's wide field monitoring capabilities will also be crucial in the context of multi-messenger astronomy by detecting and monitoring the electromagnetic counterparts of gravitational waves and neutrino cosmic sources. eXTP will operate at the time of operation of major facilities in multi-messenger astronomy, such as the second generation of the GW interferometer network (*e.g.*, aLIGO, aVIRGO, KAGRA, LIGO-India), the neutrino observatories IceCube-Gen2 and KM3 NeT, and other multiwavelength facilities including SKA, LOFAR and FAST (radio), HERD (GeV to TeV), CTA and LHAASO (from TeV to PeV), and ALMA (mm). eXTP observations will be of crucial interest to a very wide international community, well beyond the X-ray astronomy community. It is a goal of the Consortium to make data available to this community through a robust guest-observer programme and multi-messenger programmes coordinated through agreements with international facilities.

15.2 eXTP

What makes eXTP unique in comparison to other existing X-ray missions, including those currently in development, is its unprecedented combination of broad-band large collecting area, polarimetric capability, and spectral resolution. Owing to this combination, eXTP is expected to open an entirely new window in X-ray observations: simultaneous spectral-timing-polarimetry, which requires innovative analysis tools that are already being developed. eXTP will thus be complementary to ATHENA in terms of science and payload. An artist view of eXTP is shown in Fig.14.

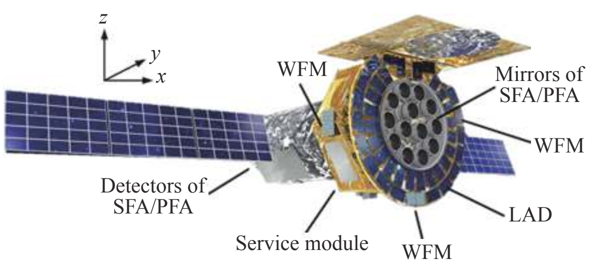

Fig. 14 Artistic view of the eXTP satellite. The science payload consists of four instruments: the focused SFA and PFA telescopes arrays, the large area instrument LAD, and the WFM to monitor a large fraction of the sky

The current baseline of the scientific payload includes four science instruments: the Spectroscopy Focusing Array (SFA, China), the Large Area Detector (LAD, Europe), the Polarimetry Focusing Array (PFA, China), and the Wide Field Monitor (WFM, Europe). The instrument configuration and key specifications are summarized in Table 11.

For further details, please refer to Ref. [30].

16 DAMPE-2: DArk Matter Particle Explorer-2

Launch time: 2025–2026 (suggested).

Scientific Goals

Like DAMPE, the data sets of DAMPE-2 could be used to reveal the astrophysical origins of the gamma-ray emitters, to study the acceleration, propagation and radiation of high energy cosmic-rays, and to probe the nature of dark matter. The wide field-of-view gamma-ray flash monitors are appended to detect the sub-MeV outbursts. Moreover, the newly designed operation orbit and survey mode enable a quick coverage of the full sky in two orbits and a timely pointed observation. Therefore, DAMPE-2 provides the opportunity to monitor the violent sub-MeV and GeV-TeV transients for various purposes. It also serves as the pioneer of the proposing Very Large Area gamma-ray Space Telescope (VLAST) that is characterized by an acceptance of about 10 m^2·sr.

DAMPE-2 is a general-purpose high-energy gamma-ray and cosmic ray observatory. As a low-cost and rapid space mission benefited from the R&D and run experiences of DAMPE, the capabilities are enhanced with the “minimum” modification of the hardware. In comparison to DAMPE, DAMPE-2 is optimized in some sub-detectors, the trigger system, and the survey mode to considerably improve its performance in the detection of low-energy gamma-rays (see Fig.15) as well as very high energy cosmic rays.

17 DSL: Discovering the Sky at the Longest Wavelength/The Hongmeng Project

Expected launch time and current phase: the Hongmeng project has completed the Intensive Study of Future

Table 11 Instrument configuration and key specifications

Instrument	SFA	LAD	PFA	WFM
Configuration	9 telescopes	40 modules	4 telescopes	6 cameras
Optics or Collimator	Wolter-I, Nickel $F = 5.25$ m	capillary-plate collimators	Wolter-I, Nickel $F = 5.25$ m	Coded mask
Detector	19-pixel Silicon Drift Det. (SDD)	SDD	Gas Pixel Detector (GPD)	SDD
Energy range	0.5–10 keV	2–30 keV	2–8 keV	2–50 keV
Effective area or FoV	⩾0.6 m^2@1–2 keV 0.4 m^2 @ 6 keV	3.0 m^2 at 8 keV	500 cm^2 @ 2 keV 300 cm^2 @ 3 keV	FoV ⩾ 3.1 sr
Energy resolution (FWHM)	180 eV @ 6 keV	260 eV @ 6 keV	25% @ 6 keV	⩽500 eV@6 keV
Time resolution	10 μs	10 μs	10 μs	10 μs
Remarks	Unprecedented effective area in the soft X-ray energy range	High throughput; effective area is a factor of 5–10 larger than any previous mission	About 5 times the area of IXPE, X-ray polar. Pathfinder by NASA; Min. Detectable Polarization about 3% in 2–8 keV range	Peak sensitivity: 1 Crab in 1 s and 5 mCrab in 50 ks (5σ source).Point source localization ⩽ 1′

Space Science Missions in the CAS Strategic Pioneer Program on Space Science, which is roughly equivalent to a phase A study. If selected as a flight mission, it can be developed in about 3 and half years and be launched in 2026.

17.1 Scientific Goals

The Hongmeng project has three main scientific goals.

(1) To reveal the dark ages and cosmic dawn with high-precision measurement of the low-frequency global spectrum. A measurement of the global spectrum on the lunar orbit can avoid systematics arising from the ionosphere, RFI and ground reflection, and achieve the ultimate high accuracy. The precisely measured spectrum will enable extraction of the 21 cm global signal from the cosmic dawn, which can provide us a unique probe of the early history of the Universe and reveal the nature of the first stars and galaxies.

(2) To open up the last unexplored electromagnetic window at 0.1–30 MHz. With the high-resolution sky map obtained at the ultra-long wavelength, we will discover for the first time what are the primary sources in this band, which may include stars and exoplanets, supernovae remnants, radio galaxies, and possibly even unknown and unexpected objects. These observations at the new wavelength may fundamentally change our understanding of many astrophysical processes. The absorption of the radio wave can also be exploited to reconstruct the three-dimensional structure of the interstellar medium, especially the local environment of the Solar system, and help resolving the problem of the origin and propagation of cosmic rays.

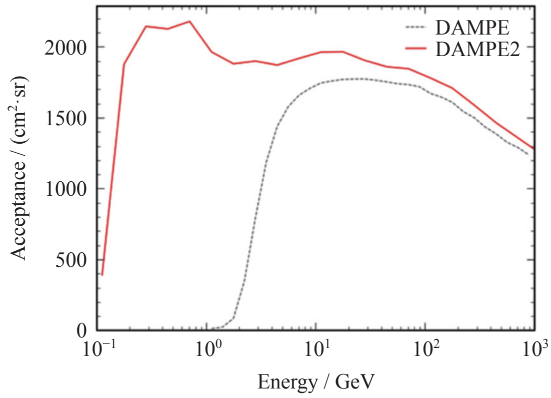

Fig. 15 Expected acceptance of DAMPE-2 on gamma-ray observation

(3) To observe the Sun and planets to uncover the dynamics of the interplanetary space. Solar activity can cause severe disturbances in the solar-terrestrial space, and the radiation below 30 MHz comes mainly from the interplanetary space beyond 3–5 R_s. By making quasi-imaging observations of solar radio bursts at low frequencies, we will be able to study the physical mechanism of the solar radio bursts, and the propagation, acceleration and evolution of the ejected plasma, and gain insights on the planetary magnetosphere.

17.2 DSL

The Hongmeng mission consists of one mother satellite and nine daughter satellites, which will be launched as an assembly by a single rocket, and released into a linear array along the same orbit[31], as shown in Fig.16. The array will make astronomical observations when in the part of orbit that is shielded from the Earth, and communicate with the Earth when it is in view. The larger mother satellite at the front or end of the array is equipped with a high gain antenna for ground communication. It will collect the digital signals from each daughter satellite, process them and store the results, and transmit the data back to the Earth. Among the daughter satellites, one has a cone shaped antenna dedicated to make global spectrum measurement in the 30–120 MHz band. The other 8 daughter satellites have deployable tripole antennas on both sides. They form an array to make interferometric imaging observation as well as global spectrum measurement in the band 0.1–30 MHz, with baseline length up to 100 km. The satellites will move in the same circular orbit, at a height of about 300 km and an inclination angle of 30°. The precession of the orbital plane will generate a three-dimensional distribution of baselines, allowing the whole sky to be mapped without ambiguity.

For further details, please refer to Ref. [31].

18 CHES: Closeby Habitable Exoplanet Survey

18.1 CHES's Major Scientific Goals

To discover and explore habitable planets beyond our solar system, will provide essential answers to "Are we alone in the universe?", "Is the Earth unique?", "How do planets become the cradle of life?" or "Is our solar system special?". The in-depth understanding of the formation and evolution of planetary systems relies on the detection of the diverse exoplanets (especially habitable planets), which is of great significance to enriching human beings' exploration of the unknown worlds, understanding the origin and evolution of life, and recognizing our status in the universe.

The CHES mission is proposed to discover Earth-like planets around the nearby solar-type stars *via* ultra-high-precision relative astrometry. The key scientific goals are: (i) to search for the terrestrial planets in habitable zones orbiting 100 FGK stars within 10 pc (the nearby stars), (ii) further to conduct a comprehensive survey and census on the nearby planetary systems.

CHES will offer the first direct measurements of true masses and inclinations of Earth Twins and super-Earths orbiting our neighbor stars based on micro-arcsecond astrometry from space. This will definitely enhance our understanding of the formation of diverse nearby planetary systems and the emergence of other worlds for nearby solar-type stars, and finally reflect the evolution of our own Solar system.

18.2 Scientific Instruments

The payload is a high-quality, low-distortion, high-stability telescope with the optical subsystem, camera subsystem and on-board calibration subsystem. The optical subsystem is a coaxial Three-Mirror Anastigmat (TMA) with a 1.2 m-aperture, 0.44°×0.44° field of view and 500–900 nm working waveband. The camera focal plane is composed of 81 MOSAIC scientific CMOS detectors each with 4000×4000 pixels. The on-board calibration subsystem consists of a metrology assembly. A heterodyne laser interferometric calibration technology is employed to ensure micro-arcsecond level (1 μas) relative astrometry precision that is required to detect the habitable Earth Twins orbiting our nearby stars.

The mission orbit of the CHES satellite travels about the Lagrange L2 point of the Sun and the Earth. The satellite is designed to have a lifespan of 5 years, during which the entire target stars will be extensively observed.

18.3 Scientific Additional Benefits

CHES will produce fruitful achievements not only in the Earth-like planets but also for cosmology, dark matter and black holes using this extreme relative astrometry precision, which helps us better understand the philosophy, life and planet.

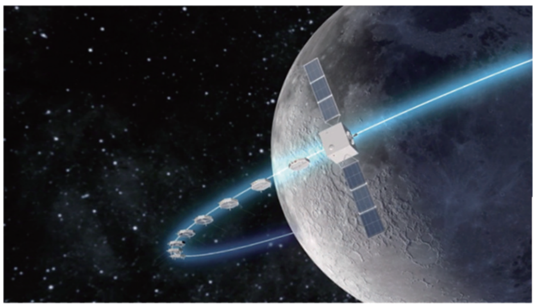

Fig. 16 Artistic concept of the DSL array

Table 12 Summary of CHES

Science case	Habitable exoplanets orbiting nearby stars
Science objectives	To discover habitable Earths about nearby solar-type stars To conduct a comprehensive survey and census on the nearby planetary systems Extended: cosmology, dark matter and black holes
Overview	Spacecraft at L2 for 5 years Optical telescope (500–900 nm); Micro-arcsecond astrometry (1 μas) Point and stare strategy to enable relative astrometry
What makes CHES unique	Ultra-high-precision relative astrometry simply reachable from space: 0.3 μas (habitable Earths about the stars at 10 pc) To obtain true masses and orbital architecture (inclinations, *etc.*) of habitable-zone terrestrial planets and to conduct the census and characterization of nearby planetary systems Extended: Measurements of orbits and distances to reveal the interiors of neutron, *etc*
Primary observational targets	closeby F, G, K stellar systems (100 stars with 10 pc) Extended: ultra-faint dwarf galaxies, neutron stars in X-ray binaries, *etc*.
Scientific Payload	Coaxial three-reflection TMA system Primary mirror: D = 1.2 m diameter Long focal length: f = 36 m FoV: 0.44°×0.44°, with 6 to 8 reference stars; focal plane with 81 scientific CMOS detectors (4000×4000, ⩾50 frame·s^{-1}) Nyquist sampling of the PSF Metrology calibration of the Focal Plane Array (FPA): relative positions of pixels at the micro-pixel level for each detector, geometrical parameters of FPA
Spacecraft	Spacecraft dry mass with margin: 1,558 kg. Launch Mass: 2930 kg, fuel mass (990 kg + 382 kg) Attitude Control System: pointing accuracy of 0.07 arcsec, pointing stability of 0.0036 arcsec/0.02 sec Propulsion system: orbital maneuver engines: 490 N+12×10 N, attitude control thrusters: 12×(1–50 μN) + 12×20 mN Thermal Control System: working temperature: 20±5° and temperature stability of 45 mK for payload; working temperature: –15 to +45℃ for other instruments Telecommand: X-band, communication rate: 20 Mbit·s^{-1}
Launcher and operations	CZ-3 C: GTO (200 km× 35958 km). Orbital maneuver to Halo orbit at L2. Launch in 2025 Nominal mission: 5 years. Launch site: Xichang

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