

Time-Domain astro and variable source observation survey

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Abstract. Time domain astronomy is one of the prosperous sub-divisions recent years, which explores the properties and physical origins such as variable and transient sources by observing the spatial and temporal variations of various types of celestial bodies in the universe. Observations of variable and transient sources are an important part of the field of time-domain astronomy, and modern astronomical observations are commonly carried out using advanced large-field telescopes for long-term uninterrupted observations. This paper survey relationship high-energy X-ray, Gamma-ray and bursts with the variable source, refer to the binary star and black hole. Then multi-bands electromagnetic wave is discussed because that is relative to detection of the variable source and instrument sensor of mission in practice. Moreover, the paper surveys the relative ground-based and space-based telescopes and missions recent years. Lastly the new approach and strategy appear the latest mission are discussed.

Keywords: Time domain astronomy; variable source; large-field telescopes; high-energy X-ray; Gamma-ray.

1. Introduction

Time domain astronomy is the study of how celestial bodies change over time and space. In recent years, there has been a great deal of activity in research around time-domain astronomy, especially in the field of high-energy time-domain astronomy, such as gravitational waves, gamma bursts, fast radio bursts, supernovae, and other ephemeral sources. Such research is closely related to cutting-edge topics in astronomy and fundamental physics, such as the nature of dark energy and dark matter, the origin of the universe, the verification of general relativity, and the verification of the quantum gravity model, etc., and has become an important driving force in the development of fundamental physics. The constant change of celestial bodies is a common phenomenon, however celestial outbursts should be one particular extreme case including X-ray, supernovae, Gamma-ray. X-ray is mainly emitted from binary star system or black hole, whose brightness and radiation intensity can change dramatically in a short period of time, which at the same time provides a window to study extreme physical environments. Moreover, supernovae and gamma ray bursts represent the most violent events in the universe. Supernovae are outbursts of massive stars at the end of their lifecycle, releasing large amounts of energy and heavy elements with profound effects on the chemical composition of galaxies. Gamma-ray bursts are the most powerful transient energy release events in the universe that can penetrate the universe and affect distant galaxies. All of those always draw a lot of researcher's attention.

Until gravitational wave [1] were observed in 2016, astronomical object observations mainly are focus on the detection of electromagnetic waves. It plays a key role in scientific research through the observation of electromagnetic waves in different bands so that scientists are able to detect and analyze various phenomena of celestial bodies. Observations of celestial objects in different wavelength bands of electromagnetic waves provide a comprehensive view of the Universe, as the radiation of celestial objects displays its characteristics across the entire electromagnetic spectrum. The electromagnetic spectrum encompasses a wide range from radio waves to gamma rays, with each band revealing different celestial properties and physical processes, as depicted in the Figure 1. Multi-band instruments can reveal information about galactic objects from different perspectives, with infrared wavelengths penetrating dust clouds to reveal star-forming regions, visible-light observations providing information on object morphology, and X-rays and gamma rays detecting extreme

astronomical environments. The widespread use of electromagnetic waves enables a comprehensive understanding of the structure and evolution of the universe. However, the Earth's atmosphere has different absorption and blocking effects on electromagnetic waves of different wavelengths. For short-wavelength and high-energy electromagnetic waves, such as X-rays and gamma rays, the atmosphere exhibits extremely high absorption. Although that protects the Earth and its organisms from the direct harm of high-energy radiation and avoids potential biohazards that constitutes a notable obstacle to astronomical research. Because X-rays cannot penetrate the atmosphere to reach the ground, astronomers do not easily use ground-based telescopes to observe X-ray sources from the universe. As a result, the development of X-ray astronomy started later than the astronomical studies of other wavelengths such as visible light, radio waves and infrared.

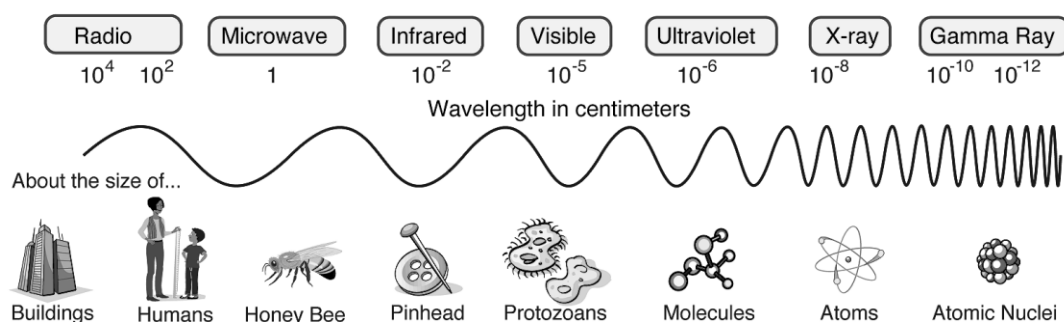


Figure 1. Different appearances of Light at different Frequency and wavelength [2].

The detection about cosmic radiation out of the atmosphere date back to the V2 experiment after World War II in 1958, when NASA launched Explorer 1 and made the first discovery of the Earth's radiation belts, Van Allen radiation belts [3]. These radiation belts are composed of high-energy particles, which is of great significance to the study of space physics and opens the door to the study of high-energy electromagnetic waves. From then on, it entered a stage of prosperous development (Figure 2).

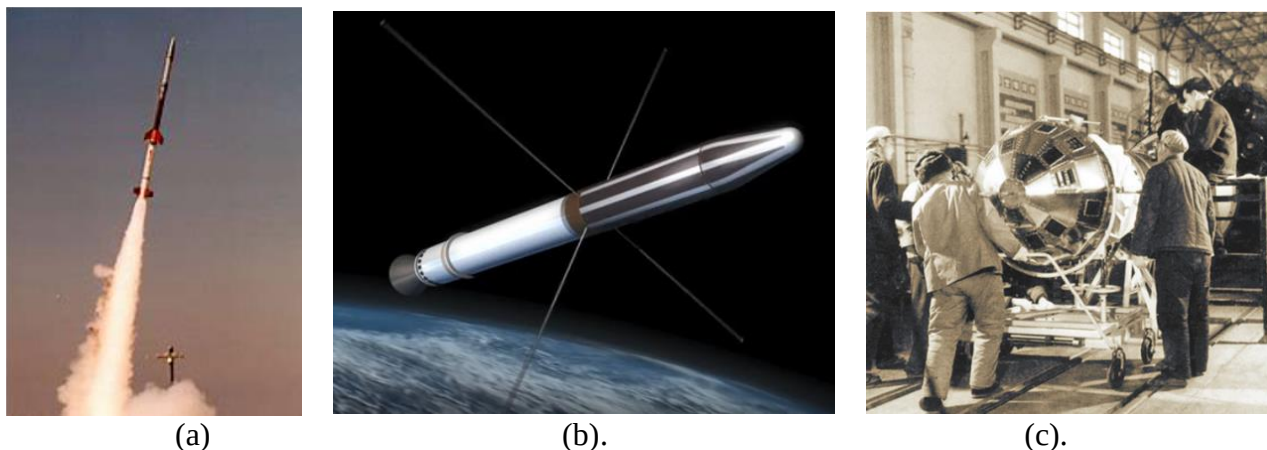


Figure 2. (a)(b) Discovering Earth's radiation belts Explorer1 and Exploer3; (c) DFH-1.

The objects in the extreme environments studied in this paper require X-ray and gamma-ray revealing observations, such as black holes, supernova remnants, and gamma-ray bursts, high-energy events that are not easily detected in other bands.

2. Relationship multi-band high-energy ray with variable source

X-ray is vital to astronomical research, penetrating the vast amounts of gas and dust in the universe to reveal objects and phenomena that cannot be observed with conventional optical telescopes, and also detecting the strong gravitational fields of material in extremely hot environments such as black holes, supernova remnants and neutron stars. Through X-rays, scientists can study the structure,

motion and radiation mechanisms of high-energy objects, thus gaining insight into the formation and evolution of the universe.

Through the study of cosmic X-rays in 1962, scientists discovered X-rays from Cygnus X-1 for the first time with the Constellation X-1 detector, which revealed the high-energy radiation emitted by celestial bodies depicted in the Figure 3. That implies the existence of super-hot objects or phenomena in the universe. Cygnus X-1 is thought to be an X-ray binary star system that includes a massive blue supergiant star and a black hole or neutron star. This discovery gave a major boost to astrophysics and opened an X-ray window into the universe.

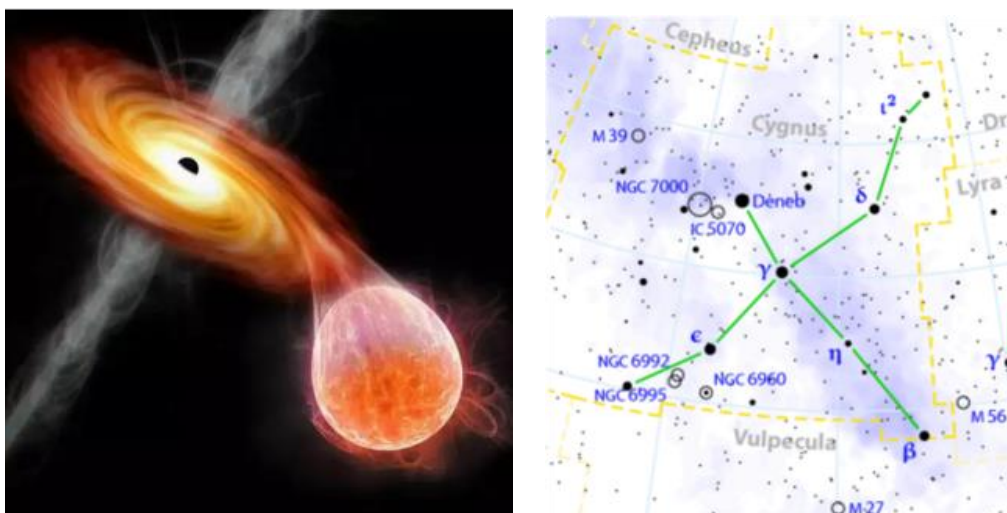


Figure 3. Cygnus.

X-ray observations of celestial objects can reveal objects and phenomena in the universe in some extreme environments that cannot be detected by ordinary optical telescopes. For example, X-ray observations can identify and study high-energy objects such as black holes, neutron stars, supernova remnants and active galactic nuclei. X-ray astronomy has thus become an important tool for the study of cosmic extremes and high-energy physics.

2.1. high-energy emitted from the variable source

Variable sources are generally defined as stars with varying luminosities, whose light variations are complex and varied, and which vary in both the duration and magnitude of the variations. Variable sources are an effective tool in astrophysics and a major scientific driver in many areas of research. Variable sources are essential for establishing distance indicators, identifying dwarf galaxies, understanding the history of galaxy formation, and probing stellar structure and theories of stellar evolution.

In general, variable stars can be divided into two main categories: intrinsic variable stars and extrinsic variable stars. This classification is mainly based on the cause of photometric changes in variable stars, i.e., whether they are determined by physical processes within the star itself, or whether they are triggered by external factors. In the case of extrinsic variable stars, the change in luminosity is usually due to external factors such as the influence of other objects, such as eclipsing binaries, rotating variable stars and pulsars. In contrast, the luminosity variations of intrinsic variable stars arise directly from physical processes within them, such as pulsating stars, explosive variable and cataclysmic variable. Among them are pulsars, which are periodic beams of radiation produced by neutron stars through their magnetic fields, resulting in periodic variations in observed brightness. One of the more typical of binary star systems is Scorpius. It relies on accreting the gas of the companion star, releasing gravitational potential energy, heating the gas to high temperatures, and thus emitting X-rays depicted in the Figure 4. Cygnus is an X-ray binary containing a black hole, where the matter is heated to millions to tens of millions of degrees by releasing gravitational potential energy as it falls into the black hole, thus emitting X-rays.

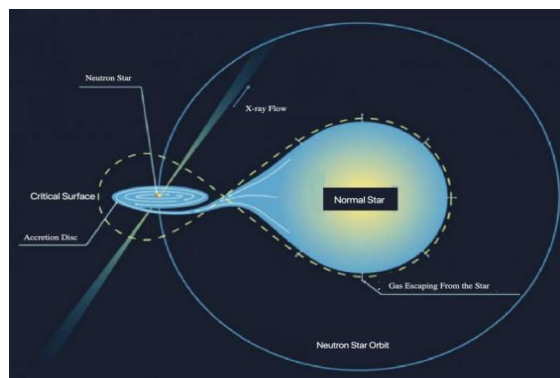


Figure 4. Schematic diagram of X-ray radiation generated by neutron star accreting companion star material [6].

A variable source is a celestial body whose brightness or intensity of radiation changes with time. Such variations can be periodic or irregular and are usually related to the physical properties and dynamical processes of the celestial bodies. Its energy source is the magnetic field. Major coverage in the evolution of celestial bodies: high temperature gases, compact object (White dwarf [compact star, $M =$ the mass of 1 sun but with a radius $R = 5800\text{km}$ smaller than the Earth], neutron stars and pulsars, black holes). For this purpose, X-ray radiating objects are natural laboratories for studying the conditions of extreme objects.

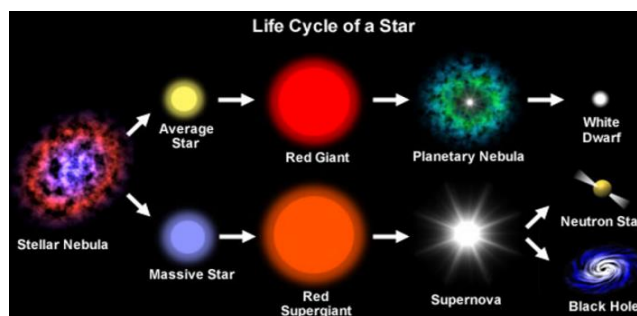


Figure 5. Life Cycle of a star.

Different variable sources have different causes, and this paper examines the causes of several of the more typical variable sources depicted in the Figure 5. In a binary star system, the brightness of a star may vary due to the presence of its companion star. For example, when a companion star passes in front or behind it, it may block the light or produce variations in the light, resulting in periodic changes in brightness; Super black holes in the nuclei of active galaxies can engulf the surrounding gas and dust, producing intense radiation. These processes can lead to significant fluctuations in brightness; pulsars are rapidly rotating neutron stars whose magnetic fields produce beams of radiation that are constantly swept in the direction of observation through their rotational period. This periodic variation in radiation causes the brightness of pulsars to show periodic variations in observations; variations in the brightness of variable stars are due to their internal structure or surface activity. For example, the brightness variations of Mira variables are related to their expansion and contraction cycles. Causes of variable sources cover a wide range of phenomena, from internal stellar processes to interstellar environments, and through the study of these sources astronomers are able to gain important information about stellar structure, evolution and cosmic physical processes.

2.2. Effectiveness of different wavebands in the observation of celestial bodies

When we look at the sun, we can only see the visible wavelengths. The X-EUV imager can monitor the Sun in the X-ray band. It can see the Sun in more detail than the visible wavelengths, forecasting solar activity earlier and predicting catastrophic space weather earlier. Figure 6 shows that the profile of the Sun on different band, such as White Solar Telescope on $360 \pm 2.0\text{nm}$, Solar Disk Image on band $121.6 \pm 4.5\text{nm}$ contributing to Advanced Space-based Solar Observatory (ASO-S) and X-

EUVI on X-ray 0.6~9.0 nm and EUV 19.5±0.1nm . The Advanced Space-based Solar Observatory (ASO-S) was launched with the CZ-2D rocket on Oct 9, 2022, opening the era of comprehensive solar space observation in China.. FY-3E launched on July 5, 2021.

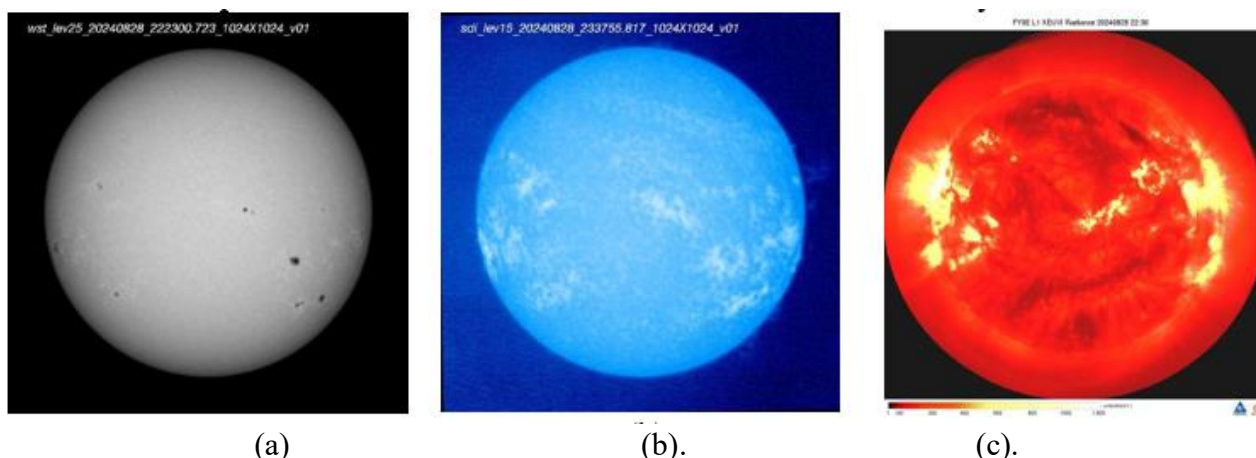


Figure 6. (a) White Solar Telescope on ASO-S
(b) Solar Disk Image on Ultra Vie on ASO-S (c) FY3E XEUUV [4-5].

Also, The Sombrero Galaxy, known for its remarkable shape and bright central halo, is a classic spiral galaxy. That looks like a broad-brimmed Mexican hat, named as M104. The center of M104 is thought to be home to a massive black hole. Observed at different wavelengths, this galaxy shows a wealth of detail and structure depicted in the Figure 7. In visible light, the Sombrero Galaxy reveals a distinctly flat structure, with a bright halo in the centre and outer spiral arms clearly visible. The luminosity and colour variations of the central halo reflect the large number of young and old stars in it. Infrared observations reveal cold dust and molecular clouds in galaxies. These regions are often hidden behind a halo at the centre of galaxies, and observations in the infrared wavelengths can help to understand the process of star formation and the distribution of gas in galaxies. X-ray observations show high-energy phenomena in the Sombrero Galaxy, such as supernova remnants, active black holes or neutron star systems. The X-ray sources are concentrated in the core regions of galaxies and in certain parts of the galactic discs, revealing the distribution of energetic objects and gas. By using multiple bands and combining observations, scientists are able to gain a comprehensive understanding of the structure and evolution of the Sombrero Galaxy, as well as the high-energy phenomena within it.

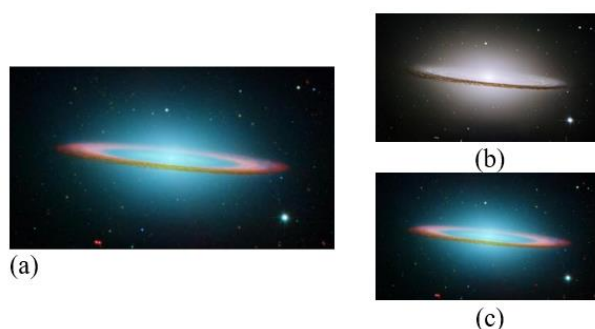


Figure 7. (a) composite image of the Sombrero Galaxy in Visible and Infrared Light,
(b) Sombrero as M104 in visible light contributing to NASA's Hubble Space Telescope
(c) The Sombrero Galaxy in Infrared Light contributing to NASA's Spitzer Space Telescope.

3. Detection methods for variable source

This section will list the detection ways for the variable source, mainly about ground-based telescope and space-based observatory, which as the traditional detection methods. Moreover, we also survey new approach and strategy appear in recent years.

3.1. ground-based and space-based observation missions

Table 1 and Table 2 separately list the ground-based telescope and space-based telescope related to the Time-Domain Astronomical Space borne Exploration (TDSE) mission.

Table 1. Ground-based survey telescope.

Mission	Type	Remark
LONEOS	near-Earth object	58cm Schmidt telescope[7],PSF[8]metering method
LINEAR	near-Earth asteroid	Star table crossover method, image subtraction method
NEAT	Near-Earth object tracking	1.22 metres Samuel OschinJPL
CSS-NEO	Near-Earth asteroids	0.7 metre Schmidt telescope
CRTS	Real-time Ephemeral	Searching for optical transients and transients from the minute to the grade level, with a cumulative total of 16,882 optical transient sources found.
LOSS	supernova survey	75cm aperture, f8.2, 512×512 CCD, FOV 6.7×6.7 arc minutes
DLS	Cosmic	Deep-field survey with gravitational lenses on two 4-m
ESSENCE	Lens All-Sky	telescopes, observing nine high silver-dimensional sky regions
DES	Survey	of 4×4 degrees in the region
NSVS	North Variable Source	Robotic Optical Transient Search Experiment[9] ROTSE-1,Four f200mm focal ratio F1.8 lenses
SDSS	supernova survey	2.5-metre aperture, 3°field of view, multicolour time-field survey
PanSTARRS	Panoramic Sky Survey and Rapid Response System (PSSRS) temporary source search	1.8m Primary + 0.9m Secondary Cassegrain telescope[10]
SkyMapper[11]	The Southern Hemisphere Patrol	1.3-metre aperture, 16k x 16k camera, field of view 5.7 square degrees, pixel resolution 0.5 arc second
LaSilla-QUEST Survey	temporary source search	1-metre aperture, using a Schmidt prime focus, spliced using 112 CCD cameras
DLT40 Survey	Supernova Survey	0.41m panchromatic robotic optical monitoring and polarisation telescope at CTIO[12],
ASASSN[13]	Supernova All-Day Automated Sky Survey	Using a 14cm Nikon telephoto lens to form a field of view of 4.47×4.47 degrees, with an effective observation of up to 5,000 square degrees per night
Evryscope[14]	All weather patrol	Continuous tracking using a set of 27 7-centimetre telescopes and low-cost sensor arrays, covering 8,660 square degrees per 2-minute exposure on a sky tour, with 6 hours of continuous observation per night for 18,400 square degrees
PMO-Tsinghua	Tsinghua Near-Earth Object Survey Supernova Survey	Data from the Purple Mountain Observatory Let's search for supernovae, NEO telescopes have an aperture of 1.05 metres and a field of view of about 9 square degrees
SVOM-GWAC[15]	All-day monitoring -- fast radio bursts	8 small aperture 18-centimetre telescopes, each with a field of view of 12.5×12.5, and a set of 12 all-sky monitors of 3.5-centimetre aperture and 25×25field of view to provide continuous long-term monitoring of a number of celestial regions for the search of ephemeral sources in a filterless manner, as well as tracking and observation of fast radio bursts and other targets[16]
WFST	time domain patrol	Construction of the Purple Mountain Observatory-University of Science and Technology of China Wide Field Survey Telescope at Cold Lake Observatory, Qinghai, with an aperture of 2.5 metres and a field of view of 6.5 square degrees

Table 2. Space-based patrol telescope.

Mission	Type	Remark
CHANDRA[17-18]	X-ray observatory	High-precision X-ray mirrors High-resolution X-ray observations to study high-energy phenomena such as black holes and galaxy clusters.
XMM-Newton[18-19]	X-ray astronomy satellite	RGS-Perform high-resolution X-ray spectroscopy, EPIC-Provides wide field of view X-ray imaging OM-Observation of the ultraviolet to visible wavelengths
FERMI	space telescope	LAT[20]specialising in the detection of high energy gamma rays GBM-responsible for detecting gamma-ray bursts and short-lived events
INTEGRAL	Gamma-ray astronomy satellite	SPI-For high-resolution gamma-ray spectroscopic observations IBIS[21]-Provides high sensitivity gamma-ray imaging
SWIFT[22]	Gamma-ray astronomy satellite	BAT[23]-Rapid detection and localisation of gamma ray bursts XRT[24]-Detailed observation of the X-ray afterglow of gamma-ray bursts UVOT[25]-Capturing the ultraviolet and visible afterglow of gamma-ray bursts
ROSAT[26]	X-ray astronomy satellite	PSPC[27]-Perform X-ray imaging and spectral analysis HRI-Provides higher resolution X-ray images
BeppoSAX[28]	X-ray astronomy satellite	WFCs[29]-For wide-field X-ray imaging during gamma-ray bursts to help locate the source of the bursts MECS-Provides X-ray imaging and spectral data in the medium energy range LECS-Observation and analysis of lower energy X-rays PDS-For the observation of high-energy X-rays, in particular for the detection and analysis of gamma-ray bursts
NuSTAR[30]	X-ray astronomy satellite	Focus Optics[31]-High-energy X-ray optics are used to provide extremely high-resolution imaging Focal Plane Detectors-Includes two detectors responsible for collecting high-energy X-rays and performing precise spectral analyses
RHESSI[32]	High Energy Solar Spectral Imager	GeD-For high-resolution X-ray and gamma-ray spectroscopic observations Collimator-Energetic Radiation for Precise Location and Measurement of Solar Flares
HXMT[33-34]	space astronomy satellite	high energy X-ray telescope(HE)[35]: Observation of X-rays from 30 keV to 250 keV. medium energy X-ray telescope(ME)[36], low energy X-ray telescope(LE)[37]
EP[38]	X-ray astronomy satellite	Wide-field X-ray telescope(WXT):It consists of 12 fully homogeneous modules, each with a field of view of about 300 square degrees, which together form a very large field of view of 3600 square degrees. The detection energy band is 0.5-4.0 keV.Follow-up X-ray Telescope(FXT)[39]:A single FXT has a field of view of about 1 degree, an effective area of about 400 cm ² @1.25 keV, and a detection energy band of 0.5 to 8.0 keV. It has a quasi full-time all-sky field of view (annual average field of view coverage >90 per cent of the day), high sensitivity (2×10 ⁻⁸ erg/cm ² /s) with uniformity in all directions throughout the day , high-precision localisation capability (~1°), a wide-band spectral measurement capability (8keV-2 MeV), and the ability to differentially discriminate between gamma-bursts and space-charged-particle events.
GECAM[40]	astronomical satellite	

SVOM[41-42]	Sino-French Astronomical Satellite	The Astronomical Satellite Mission (ASM), a collaboration between China and France, aims to detect and study high-energy astronomical events. To date, it is the world's most capable satellite to carry out integrated multi-band observations of gamma bursts. Four scientific payloads, namely, a gamma-ray monitor and an optical telescope developed by the Chinese Academy of Sciences, and a hard X-ray camera and a soft X-ray telescope developed by the French side, have been deployed. The payloads are divided into two categories: large field of view and high-precision observation, of which the large field of view detection instrument has an observation field of view of about 10,000 square degrees.
CE-3[43]	scientific experimental satellite	The main task is the detection of the space environment, including measurements of energetic particles and electromagnetic radiation. Energetic particle detection: Monitoring of energetic particles from the solar wind and other sources to study their effects on the space environment. Electromagnetic radiation monitoring: Includes detection of X-rays and gamma rays and indirect knowledge of the effects of these high-energy radiations on the space environment.

3.2. New Approach and strategy

Tight binary star systems [44] are binary star systems consisting of two dense objects (e.g., black holes, neutron stars, etc.). The final evolution of these systems, including the eventual orbiting and merging processes, is an important area of current research in astrophysics. The following is a description of the different types of dense binary systems (black hole-black hole, neutron star-neutron star, black hole-neutron star).

1. Black hole-black hole binary systems [45]

A black hole-black hole binary system consists of two black holes. The mass of the black hole can vary from a few times the mass of the Sun to tens of times the mass of the Sun. These systems emit large amounts of gravitational waves during the merger process, and these fluctuations can be detected by gravitational wave detectors on the ground (e.g., LIGO and Virgo) for eventual rotation and merger. Over time, the pair of black holes gradually lose energy through gravitational wave radiation. The black holes' orbits will gradually spiral inwards, causing their orbital radii to shrink. When their distance is reduced close enough, an eventual merger will occur. This process releases extremely strong gravitational wave signals.

2. Neutron Star-Neutron Star Binary System [46]

A neutron star-neutron star binary system consists of two neutron stars. The mass of each neutron star is usually between 1.1 and 2.2 times the mass of the Sun. The merger of a neutron star-neutron star system also generates gravitational waves and leads to an eventual rotation and merger. Gravitational wave radiation from neutron stars causes them to gradually come closer together. The orbits of binary star systems gradually contract, causing the merger process to become more violent. Eventually the merger may produce a larger neutron star or form a black hole if the mass is too large. The merger process may produce heavy elements (such as gold and platinum) and emit short gamma ray bursts.

3. Black hole-neutron star binary systems [47]

Black hole-neutron star binary systems consist of a black hole and a neutron star. The black hole is usually more massive than the neutron star, perhaps several to several tens of times the mass of the Sun, while the neutron star has a mass between 1.1 and 2.2 times the mass of the Sun. Gravitational wave radiation between black holes and neutron stars similarly brings them closer together. Over time, the orbital radius decreases until the eventual merger. The eventual black hole-neutron star merger may lead to a further increase in the mass of the black hole. If the mass of the resulting black hole is too high, it may accrete neutron star material during the merger and produce high-energy radiation such as X-rays and gamma rays.

The final orbiting and merging processes of dense binaries involve complex gravitational wave radiation and astrophysical mechanisms. The merging of these systems is not only important for understanding gravitational wave sources, but can also provide important information about extreme physical conditions and the production of heavy elements in the Universe. By studying these processes, astronomers are able to better understand dense objects and their interactions in the Universe.

3.3.1. Multi-messenger[48] (Gravitational waves v.s. Electromagnetic waves)

Multi-messenger refers to an approach to the study of celestial and cosmic phenomena by combining observations from different astronomical messengers. Gravitational and electromagnetic waves are the two main messengers, each providing different information and perspectives.

Gravitational waves are fluctuations in spacetime, triggered by gravitational changes produced by massive accelerating objects (black holes, neutron stars, etc.). They propagate through fluctuations in spacetime, almost independent of the medium, and can therefore penetrate extreme environments such as inside black holes or in high-energy cosmic phenomena. The main current gravitational wave detectors include LIGO (Laser Interferometric Gravitational Wave Observatory), Virgo and KAGRA. They are particularly suitable for studying extreme astrophysical events such as black hole mergers and neutron star mergers because they can provide information about the mass, orbit and rotation of the source object. It is also capable of detecting events that cannot be detected by electromagnetic waves, such as processes and signals during black hole mergers.

Electromagnetic waves, which include a wide range of wavelengths from radio waves to gamma rays, are produced by the motion of charged particles. There is a wide variety of equipment for electromagnetic wave observations, including radio telescopes, optical telescopes, X-ray observatories, gamma-ray detectors and others. Electromagnetic waves provide information about the spectra, brightness, composition and motion of celestial objects, which can reveal the structure, evolution and physical processes of celestial objects, and are therefore suitable for a wide range of celestial observations, capable of observing a wide variety of celestial objects and phenomena ranging from interstellar dust to the centres of galaxies.

Gravitational and electromagnetic wave detections provide different perspectives on the same cosmic event. For example, a neutron star merger event detected using gravitational waves can also be followed by electromagnetic wave observations of optical, X-ray or gamma-ray radiation from the same event, helping scientists to understand more fully the physical process and outcome of the event.

On 17 August 2017, the Advanced Laser Interferometer Gravitationalwave Observatory (Advanced LIGO) in the United States and Advanced Virgo in Italy detected the first gravitational wave event from a binary neutron star merger. The first gravitational wave event from a binary neutron star merger, GW170817, has been detected by more than 70 ground-based and space-based electromagnetic detectors around the world, providing a wide range of in-depth multi-band confirmations, including the short gamma-ray burst GRB 170817A, which occurred 1.7 s after the binary neutron star merger contract, the kilonova event detected after about 11 h, and the radiation flux event AT 2017gfo, which was detected after the merger of the two stars. AT 2017gfo, multi-band afterglow emission with peak radiation flux occurring 100-200 d later, and so on. As an extremely successful multi-messenger observation, GW170817 is regarded as a watershed event in the history of astronomy and physics. It not only proves that the binary neutron star merger process is the astrophysical origin of short gamma-ray bursts and kilonova events, but also provides a new way to study dense matter and to test the gravitational theory under extreme conditions.

3.3.2. Space-based and ground-based synergies

Active sky search and follow-up opportunity observations of emergent and variable sources. Specific observation strategies and data processing programmes need to be optimized according to the outburst rate and observation characteristics of the target emergent sources. Time-domain surveys are rapidly developing towards wider fields of view, deeper detection limits and higher sampling frequencies.

Research in this field relies on high temporal resolution observations of celestial variations. The synergy of space-based and ground-based astronomical observing equipment is essential to time-domain astronomy, and each has its own strengths that can be complemented to provide a full range of observing capabilities.

Space-based telescopes are not disturbed by the Earth's atmosphere and are capable of high-precision observations, especially in the X-ray, ultraviolet and high-energy gamma-ray bands. Moreover, space-based equipment can make observations at any time of the day or night on Earth, regardless of day and weather.

Ground-based observing equipment is diverse, ranging from radio telescopes to optical telescopes, capable of covering a wide range of wavelengths. Ground-based telescopes can be very large, with higher optical resolution and sensitivity. Ground-based observation equipment is less expensive than launching and maintaining space-based equipment.

When a transient event is detected by space-based equipment, ground-based observatories can be notified immediately for follow-up observations. In some cases, ground-based telescopes can provide more complete data by rapidly making multi-band observations of an event when alerted by space-based equipment. By combining data from space-based and ground-based observations, it is possible to obtain a comprehensive view of an astronomical event in different bands. For example, the early stages of a supernova outburst can be captured by a space-based X-ray detector with a high-energy signal, and subsequently ground-based optical telescopes can track its optical glow changes.

The 2017 'GW170817' event mentioned above is a classic example of time-domain astronomical synergy. It was the first time that both gravitational and electromagnetic signals were observed at the same time. Specific synergistic process: On 17 August 2017, the LIGO and Virgo detectors detected a gravitational wave signal from a binary neutron star merger. The signal triggered immediate observations from NASA's Swift satellite and the Fermi Gamma Ray Space Telescope, and Swift quickly detected the associated gamma-ray burst. Based on the alerts of gravitational waves and gamma-ray bursts, ground-based optical and infrared telescopes, such as the multiple telescopes in LIGO's Target Logistics Network, followed up closely to capture the optical and infrared signals of supernova outbursts. The combination of space-based and ground-based observations allowed scientists to study the binary neutron star merger event in detail, revealing the nature of the gravitational wave source and confirming that these events produced heavy elements such as gold and uranium. This synergistic work not only verified the existence of gravitational waves, but also deepened the understanding of extreme events in the universe.

The synergy of space-based and ground-based observational equipment in time-domain astronomy has greatly enhanced the understanding of rapidly changing phenomena in the universe. Space-based equipment provides high temporal resolution and all-weather observing capabilities, while ground-based equipment provides high-resolution and multi-band observing capabilities. By working together effectively, scientists are able to obtain more comprehensive astronomical data that allow them to study in depth dynamic phenomena in the universe.

3.3.3. Combined with deep learning

The application of deep learning in time-domain observation is mainly reflected in data analysis and pattern recognition. The combination of deep learning and time-domain observation promotes a leap in data analysis capability and research level in astronomy. In time-domain astronomy, researchers focus on the changes of celestial objects in time, such as outbursts, variable stars and supernovae. These phenomena typically generate large amounts of complex data, and deep learning can significantly improve the efficiency and accuracy of analysing these data.

1. Automatic event detection and classification

Deep learning models, especially Convolutional Neural Networks (CNN), perform well in image recognition tasks. These networks can be used to automatically detect and classify celestial events from astronomical images. For example, CNNs can analyse images from optical telescopes to automatically identify rare events such as supernova outbursts and gamma ray bursts, reducing the reliance on manual classification. This automated process dramatically increases the speed at which

data can be processed, allowing researchers to discover important astronomical phenomena more quickly.

2. Signal extraction and noise reduction

In time-domain astronomy, observational data are often disturbed by noise. Deep learning methods, especially self-encoders and Generative Adversarial Networks (GANs), have powerful capabilities in data denoising and signal extraction. By training deep learning models to remove noise from observational data, scientists are able to extract valuable signals from complex time-domain data. This not only improves the quality of the signal, but also helps reveal subtle changes that are hidden in the noise.

3. Time series analysis and forecasting

Recurrent neural network (RNN [49]) and Long Short-Term Memory (LSTM [50]) are particularly suitable for processing time series data. They are able to learn the light-variation curves of celestial objects and predict their future trends. For example, LSTM networks can model the photometric variations of variable stars and predict their future light-variable behaviour. This capability is crucial for studying periodic celestial phenomena or for early warning of upcoming astronomical events.

4. Anomaly Detection

Deep learning models can effectively identify anomalous events in large amounts of astronomical observations. Using deep learning techniques such as anomaly detection models, observation data that do not conform to normal patterns can be automatically screened out. For example, when certain astronomical events show abnormal photometric changes, deep learning models can detect and alert researchers in a timely manner, helping them to quickly carry out further observations and analyses.

Combining deep learning with time-domain observations allows scientists to extract more valuable information from massive amounts of data. Deep learning models not only improve the efficiency of data analysis, but also uncover patterns and trends that are difficult to identify with traditional methods. The application of this technology allows astronomers to more accurately study and understand dynamic phenomena in the universe, accelerating the pace of scientific discovery.

4. Conclusion

Time-domain astronomy has emerged as a thriving subfield in recent years, revolutionizing our understanding of the variable and transient phenomena in the universe. Through the meticulous observation of spatial and temporal variations of celestial bodies, this field has shed light on the properties and physical origins of these enigmatic sources. The significance of monitoring variable and transient sources cannot be overstated, as they provide invaluable insights into extreme astrophysical processes and phenomena such as binary star interactions and black hole dynamics. The integration of high-energy X-ray, Gamma-ray, and burst observations with studies of variable sources has proven crucial, offering a more comprehensive view of these enigmatic phenomena. Furthermore, the discussion of multi-band electromagnetic wave detections underscores the importance of utilizing a diverse range of sensors and instruments to fully characterize and understand variable sources. Moreover, the advancement in both ground-based and space-based telescopes and missions has significantly enhanced our observational capabilities, enabling long-term, uninterrupted observations of the cosmos. These technological advancements have paved the way for groundbreaking discoveries and have pushed the boundaries of astronomical research. The emergence of new approaches and strategies in time-domain astronomy, particularly in the context of the latest missions, promises to further expand our knowledge of the universe. As the field continues to evolve, it is imperative that we leverage the latest technological advancements and adopt innovative strategies to unravel the mysteries of the cosmos. In summary, time-domain astronomy stands as a testament to the relentless pursuit of scientific knowledge and the endless possibilities of astrophysical exploration.

Reference

- [1] Abbott, B.P., Abbott, R., Abbott, T., Abernathy, M.R., Acernese, F., Ackley, K., Adams, C., Adams, T., Addesso, P., Adhikari, R.X. and Adya, V.B., 2016. Observation of gravitational waves from a binary black hole merger. *Physical review letters*, 116(6), p.061102.
- [2] Whitlock, Laura A., Ms Kara C. Granger, and C. A. Napa. *Imagine the Universe!* No. NASA-EP-1997 (12)-002-GSFC. 1998.
- [3] McDonald, F. and Naugle, J.E., 2008. Discovering Earth's radiation belts: remembering Explorer 1 and 3. *Eos, Transactions American Geophysical Union*, 89(39), pp.361-363.
- [4] Zhang, P., Hu, X., Lu, Q. et al. FY-3E: The First Operational Meteorological Satellite Mission in an Early Morning Orbit. *Adv. Atmos. Sci.* 39, 1–8 (2022).
- [5] Chen, B., Ding, G.X. & He, L.P. Solar X-ray and Extreme Ultraviolet Imager (X-EUVI) loaded onto China's Fengyun-3E Satellite. *Light Sci Appl* 11, 29 (2022).
- [6] Yu Yun Wei. The past and present of neutron star research. *Physics*, 2021, 50(6): 371-377. DOI: 10.7693/wl20210602
- [7] Steinert K .Astrometry With the Tautenburg Schmidt Telescope [J].Symposium - International Astronomical Union, 2016, 141443-448.
- [8] Joana A ,Benoit N ,Manuel S , et al.PSF reconstruction for AO photometry and astrometry[J].Adaptive Optics for Extremely Large Telescopes 4–Conference Proceedings,2015,1(1):
- [9] Wren J ,Akerlof C ,Balsano R , et al.Observations of the Optical Counterpart to XTE J1118+480 during Outburst by the Robotic Optical Transient Search Experiment I Telescope[J].The Astrophysical Journal Letters,2001,557(2):L97-L100.
- [10] Masoomi N ,Zakery A ,Afkhami M .Design of a compact multispectral telescope consisting of a Cassegrain telescope and a concave elliptical grating.[J].Applied optics,2024,63(9):2195-2203.
- [11] Onken A C ,Wolf C ,Bessell S M , et al.SkyMapper Southern Survey: Second data release (DR2)[J].Publications of the Astronomical Society of Australia,2019,36e033-e033.
- [12] Kar A ,Henry J T ,Couperus A A , et al.The Solar Neighborhood LI: A Variability Survey of Nearby M Dwarfs with Planets from Months to Decades with TESS and the CTIO/SMARTS 0.9 m Telescope[J].The Astronomical Journal,2024,167(5):
- [13] V. A P ,J. B S ,T. J H , et al.The Rapid X-Ray and UV Evolution of ASASSN-14ko[J].The Astrophysical Journal,2022,926(2):
- [14] K. J R , M. N L , Octavi F , ET al.Building the Evryscope [J].Publications of the Astronomical Society of the Pacific, 2019, 131(1001):1-23.
- [15] Jianyan W .Progress on SVOM Satellite Development [J].Chin. J. Space Sci., 2020, 40(05):698-699.
- [16] YU Shunjing, GONZALEZ Francois, WEI Jianyan, ZHANG Shuangnan, CORDIER Bertrand. SVOM: a joint GRB detection mission (in Chinese).Chin. J. Space Sci., 2019, 39(6): 800-808.DOI:10.11728/cjss2019.06.800
- [17] Huenemoerder P D ,Pradhan P ,Canizares R C , et al.Chandra HETG X-Ray Spectra and Variability of π Aqr, a γ Cas-type Be Star[J].The Astrophysical Journal Letters,2024,966(2):
- [18] Sarkar A ,Grant E C ,Miller D E , et al.Advancing Precision Particle Background Estimation for Future X-Ray Missions: Correlated Variability between the Alpha Magnetic Spectrometer and Chandra/XMM-Newton[J].The Astrophysical Journal,2024,970(1):
- [19] K.Sriram, Rani G .Optical and X-Ray Studies of Marginal Contact Binary RW Dor Using TESS and XMM-Newton Observatories [J].Research in Astronomy and Astrophysics, 2023, 23(11):185-199.
- [20] A. A K ,I. V K ,V. V G , et al. Localization of the Gamma-Ray Emission Region in the 1 September 2014 Behind-the-Limb Solar Flare According to the Fermi/LAT Data[J].Solar Physics,2024,299(2):
- [21] A. M ,L. B ,R. L , et al. Update of the INTEGRAL/IBIS active galactic nuclei catalogue: Deeper on the Galactic plane and wider beyond[J].Astronomy & Astrophysics,2023,671
- [22] Fouad M A ,Shehata M S ,Pawar D D , et al.X-ray study on the core collapse supernova 2008ax using XMM-Newton and Swift/XRT[J].Physica Scripta,2024,99(7):

- [23] Chirenti C ,Dichiara S ,Lien A , et al.Evidence of a Strong 19.5 Hz Flux Oscillation in Swift BAT and Fermi GBM Gamma-Ray Data from GRB 211211A[J].The Astrophysical Journal,2024,967(1):
- [24] Sanhita K, Nazma I, Biswajit P .Investigating a unique partial eclipse in the high-mass X-ray binary IGR J16393–4643 with Swift-XRT [J].Monthly Notices of the Royal Astronomical Society, 2020, 491(1):1491-1497.
- [25] G. M D ,S. Y ,L. L , et al.The Optical Two- and Three-dimensional Fundamental Plane Correlations for Nearly 180 Gamma-Ray Burst Afterglows with Swift/UVOT, RATIR, and the Subaru Telescope[J].The Astrophysical Journal Supplement Series,2022,261(2):
- [26] Weiwei X ,E. M C R ,Florian P , et al.Catalog of X-ray-selected extended galaxy clusters from the ROSAT All-Sky Survey (RXGCC)***[J].Astronomy & Astrophysics,2022,658
- [27] Ulrich M ,Molendi S .High S/N ROSAT-PPSC Observations of the Quasar PG 1116+215: Power Law Shape of the Soft X-ray Spectrum[J].Symposium - International Astronomical Union,2016,159197-200.
- [28] Frontera F .The key role of BeppoSAX in the GRB history [J].Rendiconti Lincei. Scienze Fisiche e Naturali, 2019, 30(Supl.1):171-184.
- [29] Cocchi M ,Bazzano A ,Capitanio F , et al.BeppoSAX-WFCs monitoring of the high-mass X-ray binary 4U 1700–377[J].Nuclear Physics B (Proceedings Supplements),2004,132(C):592-595.
- [30] Moutard L D ,Ludlam M R ,Sudha M , et al.Investigating the Ultracompact X-Ray Binary Candidate SLX 1735-269 with NICER and NuSTAR[J].The Astrophysical Journal,2024,968(2):
- [31] V. V L .Grazing-Incidence Focusing Optics for X-Ray Telescopes (Review) [J].Instruments and Experimental Techniques, 2022, 65(2):191-217.
- [32] Ping Z ,Wei W ,Yang S , et al. X-Ray Fine Structure of a Limb Solar Flare Revealed by Insight-HXMT, RHESSI and Fermi[J].Research in Astronomy and Astrophysics,2022,22(5):
- [33] Zhang S ,Li P T ,Lu J F , et al. Overview to the Hard X-ray Modulation Telescope (Insight-HXMT) Satellite[J].Science China(Physics, Mechanics & Astronomy),2020,63(04):6-23.
- [34] Q. G D ,L. J Q ,M. L S , et al. Insight-HXMT Detections of Hard X-Ray Tails in Scorpius X-1[J].The Astrophysical Journal,2023,950(1):
- [35] C C, L S X, K C L, ET al. Search for gamma-ray bursts and gravitational wave electromagnetic counterparts with High Energy X-ray Telescope of Insight-HXMT [J].Monthly Notices of the Royal Astronomical Society, 2021, 508(3):3910-3920.
- [36] Cao X ,Jiang W ,Meng B , et al.The Medium Energy X-ray telescope (ME) onboard the Insight-HXMT astronomy satellite[J].Science China Physics, Mechanics & Astronomy,2020,63(4):
- [37] Chen Y, Cui W, Li W, et al. The Low Energy X-ray telescope (LE) onboard the Insight-HXMT astronomy satellite[J].Science China Physics, Mechanics & Astronomy,2020,63(4):
- [38] Xue Y ,Zhixing L ,Chen Z , et al.Visible light transmittance of micro-pore optic plates for the wide-field x-ray telescope on the Einstein probe.[J].Applied optics,2023,62(10):2595-2603.
- [39] Yanji Y, Yusa W, Dawei H, ET al.Design and testing of the Optics for FXT onboard EP satellite [J].Experimental Astronomy, 2023, 55(3):625-637.
- [40] Li, Xinqiao. Design and test of the GECAM satellite payload [J].Radiation Detection Technology and Methods, 2022, (prepublish):1-2.
- [41] D. G ,M. B ,V. B , et al.The scientific performance of the microchannel X-ray telescope on board the SVOM mission[J].Experimental Astronomy,2023,55(2):487-519.
- [42] Shaymaa H ,Florent R ,Martin B , et al. Analysis Methods to Localize and Characterize X-Ray Sources with the Microchannel X-Ray Telescope on Board the SVOM Satellite[J].The Astrophysical Journal,2023,944(2):
- [43] ManHei N ,Xiaoping Z ,Yi X , et al.Major Elements Concentrations in Chang'E-3 Landing Site from Active Particle-Induced X-ray Spectrometer[J].Remote Sensing,2023,15(6):1643-1643.
- [44] Johnstone P C ,Lohinger P E ,Lüftinger T , et al. Stellar activity and planetary atmosphere evolution in tight binary star systems[J].Astronomy & Astrophysics,2019,626a22.
- [45] Jingyi W, Erin K, Matteo L, et al. The NICER “Reverberation Machine”: A Systematic Study of Time Lags in Black Hole X-Ray Binaries[J].The Astrophysical Journal,2022,930(1):

- [46] Meng L, Zhu W, Kramer M, et al. The Relativistic Spin Precession in the Compact Double Neutron Star System PSR J1946+2052[J].The Astrophysical Journal,2024,966(1):
- [47] Liu B, Lai D, Wang Y .Black Hole and Neutron Star Binary Mergers in Triple Systems. II. Merger Eccentricity and Spin–Orbit Misalignment [J].The Astrophysical Journal, 2019, 881(1):41-41.
- [48] Corsi A ,Barsotti L ,Berti E , et al.Multi-messenger astrophysics of black holes and neutron stars as probed by ground-based gravitational wave detectors: from present to future[J].Frontiers in Astronomy and Space Sciences,2024,11
- [49] Priyadarshi S .Prediction of high latitude nightside Geomagnetic Field Disturbances (GGFDs) during the 9-March-2012 geomagnetic storm using Recurrent Neural Network (RNN)[J].Advances in Space Research,2024,74(4):1868-1882.
- [50] Saqib M ,Şentürk E ,Adil A M , et al.Seismo-ionospheric precursory detection using hybrid Bayesian-LSTM network model with uncertainty-boundaries and anomaly-intensity[J].Advances in Space Research,2024,74(4):1828-1842.