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The Mini-SiTian Array: White Paper

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Abstract

This paper outlines the scientific goals and observational strategies of the Mini-SiTian Array. Mounted at Xinglong Observatory, the Mini-SiTian Array consists of three 30 cm telescopes and has been in operation since 2022. The large field of view, combined with the capability for multi-band photometric observations, enables the Mini-SiTian Array to perform rapid follow-up observations to identify optical counterparts of gravitational waves, capture the early light curves of tidal disruption events and supernovae, and monitor stellar flares, Be star outbursts, and cataclysmic variable stars, although its limiting magnitude is not very deep. By collaborating with the Xinglong 2.16 m telescope and leveraging a real-time image processing pipeline, simultaneous photometric and spectroscopic observations could be performed to reveal their underlying physical mechanisms. The observational and research experience provides critical guidance for the implementation of the full-scale SiTian project in the future.

Key words: telescopes – stars: variables: general – stars: flare – (stars:) supernovae: general

1. Introduction

In our universe, there are many types of variable stars including rotating variables, eruptive variables, pulsating variables, which are important tracers to understand the universe. For example, classical Cepheids and Type Ia supernovae could be served as the standard candles (e.g., Leavitt & Pickering 1912; Riess et al. 1998), flaring stars are keys to shed light on stellar dynamo theories (Hawley et al. 2014; Davenport 2016) and multi-messenger observations reveal that the gravitational wave event GW1770817 is a result of neutron star−neutron star merger (Abbott et al. 2017).

Long-term observations and immediate follow-up observations are required to reveal the nature of the variability (Paczyński 2000). As a result, time-domain astronomy, which seeks to map the universe's dynamic changes over timescales ranging from hours to years, is now a rapidly growing field. Thanks to the development of modern techniques, large ground-based and space-borne telescopes gradually came into being, which opens the new era of time-domain astronomy. Up to now many remarkable time-domain sky surveys have been carried out, including the Catalina Real-Time Transient Survey with a field of view (FOV) of 19.4 $\deg^2$ and a limiting magnitude of $V \sim 19.5$ (Drake et al. 2009), the All-Sky Automated Survey for Supernovae (ASAS-SN) with very large sky coverage and a limiting magnitude of $V \sim 17$ (Shappee et al. 2014; Kochanek et al. 2017) and the Zwicky Transient Facility (ZTF) time-domain survey with FOV of 47 $\deg^2$ and a limiting magnitude of $\sim$21.1 (Bellm et al. 2019).

Meanwhile, there are some forthcoming and ongoing time-domain sky surveys including the Wide Field Survey Telescope (WFST. Wang et al. 2023), the Large Synoptic Survey Telescope (LSST; Ivezić et al. 2019). The 1.6 m Multi-channel Photometric Survey Telescope of Yunnan University with FOV of 3.14 square degree (Mephisto; Yuan et al. 2020). After being fully operational, these surveys would provide us with tens of thousands light curves, which are essential for searching for the variables and investigating their nature.

However, these surveys are limited to their relatively long cadence. In this regard, they would miss the early stages of many transient events. Meanwhile, it is difficult for them to trigger immediate follow-up spectroscopic observations. Acknowledging these shortcomings, Liu et al. (2021) are now carrying out an innovative time-domain sky survey project, named SiTian (a Chinese character which means monitoring of the sky) project. The SiTian project will consist of $\sim$20 nodes with each node containing three 1 m telescopes. In other words, the SiTian project will contain 60 1 m telescopes. For each node, the three telescopes are equipped with g, r, or i band filters, respectively, which could enable multi-band observation simultaneously. After being fully operational, the total coverage corresponding to one exposure will be 600 $\deg^2$ for a node with a limiting magnitude of

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21.0 mag at a cadence of 30 minutes, which means a total coverage of 12,000 deg^2 for 20 nodes. Meanwhile, SiTian project will be equipped with at least one 4 m telescope, aiming in carrying out follow-up spectroscopic observations of interesting targets. For more details of the SiTian project, please refer to Liu et al. (2021).

Inspired by the concept of the SiTian project, we designed the pilot project named Mini-SiTian project, whose main purpose is to refine the technical details of the SiTian project and to conduct preliminary observations for the scientific program of the SiTian project (Huang et al 2025). Acting as the pioneer of the SiTian project, the Mini-SiTian Array has already been installed at the Xinglong Observatory. The array consists of three 30 cm telescopes with each capable of functioning in either the g, r, or i band. Each telescope has an FOV of $\sim$3 deg^2. For technique details of Mini-SiTian we refer to the paper of the series by Han et al. (2025). The Mini-SiTian Array has being operated since September of 2022 and the data have been used to test the performance of the telescopes. For more details we refer to the paper of the series by He et al. 2025.

Both the immediate follow-up observations of transients and regular sky survey will be performed by the SiTian project. As the pathfinder of the SiTian project, Mini-SiTian also follows the same observation strategies. Catching the early stages of transients as well as regular sky survey will be performed. Such strategies would be suitable for searching for electromagnetic (EM) counterpart of gravitational wave (GW), catching the early light curves of supernovae and tidal disruption events and identifying variables including flaring stars, Be outbursts and cataclysmic variable stars. Meanwhile, the artificial intelligence could act as a powerful assistant, which could improve the observing strategies of Mini-SiTian. In this paper, we will describe the scientific goals of Mini-SiTian in detail.

2. Scientific Goals

2.1. Electromagnetic Counterpart of Gravitational Wave

The successful detection of gravitational wave GW170817 and its electromagnetic counterpart has opened the new era of multi-messenger astronomy of gravitational wave (Abbott et al. 2017). The electromagnetic counterpart transient of GW170817 is attributed to a kilonova model, which is consistent with r-process of nucleosynthesis (Smartt et al. 2017). Kilonova is the brightest electromagnetic transient of gravitational wave (Kasen et al. 2013). As a result, catching the early stage light curves of kilonova is of great importance while studying the equation of state and mass distribution of neutron stars.

One of the major scientific goals of the SiTian project is to apply immediate follow-up observations if gravitational wave events occur. Due to the limitation of FOV of the Mini-SiTian Array, the observing strategy would be quite different from that of the SiTian project. Once received an alert from the LIGO regarding a gravitational wave event, our scientific group will judge whether such an event is worth observing. If so, the ongoing observation will be interrupted and follow-up observations will be carried out immediately. Finding the electromagnetic counterpart of gravitational wave has the highest priority. For more details of the capability of searching for kilonova events based on the SiTian project, we refer to the paper of the series by Li et al. (2025).

2.2. Flaring Stars

2.2.1. Background

Stellar flares are believed to be due to reconnection of stellar magnetic fields, during which a large amount of energy would be released. This leads to brightening of the star in various bands including radio emission (Güdel 2002), optical flares (e.g., Hawley et al. 2014; Yang et al. 2017), UV flares (e.g., Brasseur et al. 2019) and X-ray flares (e.g., Ghosh et al. 2022). Typically, for optical flares the energy release could reach 10^{29}–10^{32} erg (Yang et al. 2017) or even higher than 10^{34} erg for superflares observed in those most active stars (Maehara et al. 2012).

The solar-stellar connection has long been a hot topic among stellar activity researches. Maehara et al. (2012) studied the flare frequency distribution of superflares detected on solar-like stars in the Kepler field. They argued that on solar-like stars, i.e., slowly rotating G-type stars with effective temperatures of $\sim$5700 K, flares with energy higher than 10^{35} erg could only happen once every 5000 yr. Lingam & Loeb (2017) suggested that extremely powerful superflares could strongly affect habitability of surrounding planets and superflares may occur on the Sun within $\sim$1000 yr.

Statistical study of stellar flares could shed light on stellar structure, stellar dynamo and stellar habitability. One of the key projects of Mini-SiTian is to observe flaring stars in the Kepler and TESS field, especially late-type stars with strong magnetic fields, on which frequent and huge flares could be detected. Fortunately, about 3400 flaring stars have been identified in the Kepler field (Yang & Liu 2019). Meanwhile, during the TESS first and second years' observations, many bright stars with superflares have been discovered (e.g., Tu et al. 2021). These are ideal samples to carry out continuous multi-band follow-up observations.

2.2.2. Observation Design

The Mini-SiTian Array has initiated a long-term monitoring project of the Kepler field since 2023. This project in combination with the Kepler observations could reveal the long-term brightness variations of Kepler targets. Many Kepler targets exhibit frequent superflares and spectroscopic observations are essential for revealing the energy release process and the mass ejection process during stellar flares (e.g., Maehara et al. 2021). Typically, KIC 9201463 is the one of the most active flaring stars in the Kepler field (Yang & Liu 2019),

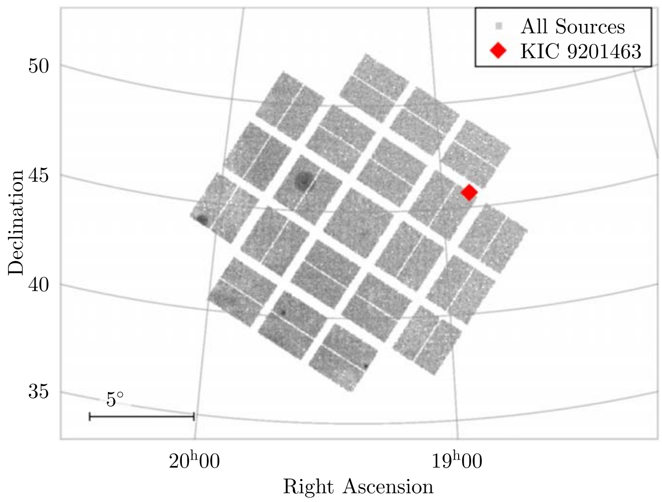

Figure 1. Kepler field. KIC 9201463 is marked with a red diamond, which has been observed by the three Mini-SiTian telescopes simultaneously.

which exhibited stellar flares almost every day and thus increases the probability to capture stellar flares. Meanwhile, the Kepler fields are frequently observed by the LAMOST telescope (Fu et al. 2020). As a result, for the Mini-SiTian telescopes we propose a long-term monitoring of flaring stars in both the Kepler and TESS fields. In Figure 1, we plot the Kepler field. The red diamond represents KIC 9201463, which has been observed by the Mini-SiTian Array since 2023. Such observations could be crucial for investigating different behaviors of stellar flares, which would be useful for constraining stellar dynamo theories.

SiTian brain, the main control system of the SiTian project, which integrated scheduling observations, real-time data analysis and immediate communication of transient alerts, will act as the central facility (Liu et al. 2021). When transients occur, SiTian brain will coordinate the regular scan mode and the immediate follow-up observation mode. As a pioneer of the SiTian project, Mini-SiTian will also be equipped with transients alert system and real-time data processing pipelines. For more technical details we refer to Gu et al. 2025. Such a system could inform observers if transients occur in the field and present the early light curve immediately and trigger multi-band follow-up observations.

Considering the visibility of the Kepler field at the Xinglong Observatory, it is much better to monitor such a field as long as possible during September and October of each year. The longer the duration is, the more flares could be caught. A longer duration will allow the analysis of flare frequency distribution and its impact on stellar habitable zone. Typical timescales of flares range from minutes to hours (Hawley et al. 2014; Yang et al. 2017). Thus the exposure time is set to be 2 minutes. A 2 minutes exposure time would make it possible to reveal more details of flaring phases, which would be useful for investigating topology of magnetic fields. Despite the Kepler field, since the TESS satellite is an all-sky survey, it is possible that Mini-SiTian could carry out a simultaneous observation to the TESS fields. Later in 2024, Mini-SiTian started to monitor the TESS fields in which there are solar-like stars with frequent superflares. The observing strategies would be similar despite that the exposure time needs to be reduced.

2.3. Tidal Disruption Events and Supernova

2.3.1. Tidal Disruption Events

When a star is perturbed occasionally and comes into the tidal sphere of a massive black hole (MBH) hosted in the center of its galaxy, it will be tidally disrupted and partially accreted. This process, referred as a tidal disruption event (TDE), accompanied by the emission of bright flare, which decays on timescales of months to years (Rees 1988). The predicted event rate of TDEs generally falls within the range of 10^{-4}–10^{-5} gal^{-1} yr^{-1}, depending on the properties of the galaxy and the mass of MBH. Recently, Wang et al. (2025), one of the paper in the series, has estimated the detection rates of TDE using the Mini-SiTian telescopes.

TDEs originated in late 1970s as a theoretical concept. The first X-ray TDE was serendipitously identified from archival ROSAT data in 1990s. Subsequently, a couple of more TDEs have been discovered with the launch of XMM-Newton and Chandra satellites. Optical TDEs, however, were not identified until 2010s from the archival SDSS data. Thanks to a variety of wide-field optical surveys, such as the ASAS-SN (Shappee et al. 2014), the Asteroid Terrestrial-impact Last Alert System (Tonry et al. 2018) and the ZTF (van Velzen et al. 2021), an explosively growing number of TDEs have been found in the past decade (Gezari 2021). Consequently, the combination of time-domain surveys and follow-up observations plays a crucial role in the systematic search for TDEs.

TDEs aroused extensive interests because of their scientific values. First of all, TDEs provided us a unique means to probe the supermassive BHs (SMBHs) in quiescent galaxies, which is otherwise particularly difficult in dwarf and distant galaxies. In addition, TDEs can even probe the dormant intermediate-mass BHs (IMBHs) and SMBH binaries (Greene et al. 2020; Huang et al. 2021, 2025). The IMBHs are thought to be the seeds from which SMBHs grow, as they link between stellar-mass BHs and SMBHs. The observed emission of TDEs depends on the parameters such as the black hole mass and spin, hence they offer a unique way to constrain the masses and spin of dormant SMBHs. Moreover, TDEs also act as an ideal laboratory to study the formation of an accretion disk and jet by monitoring the entire life cycle of BH activity. The observations of the infrared and radio echoes in TDEs provide a novel tool to investigate the environment surrounding BHs (Gezari 2021).

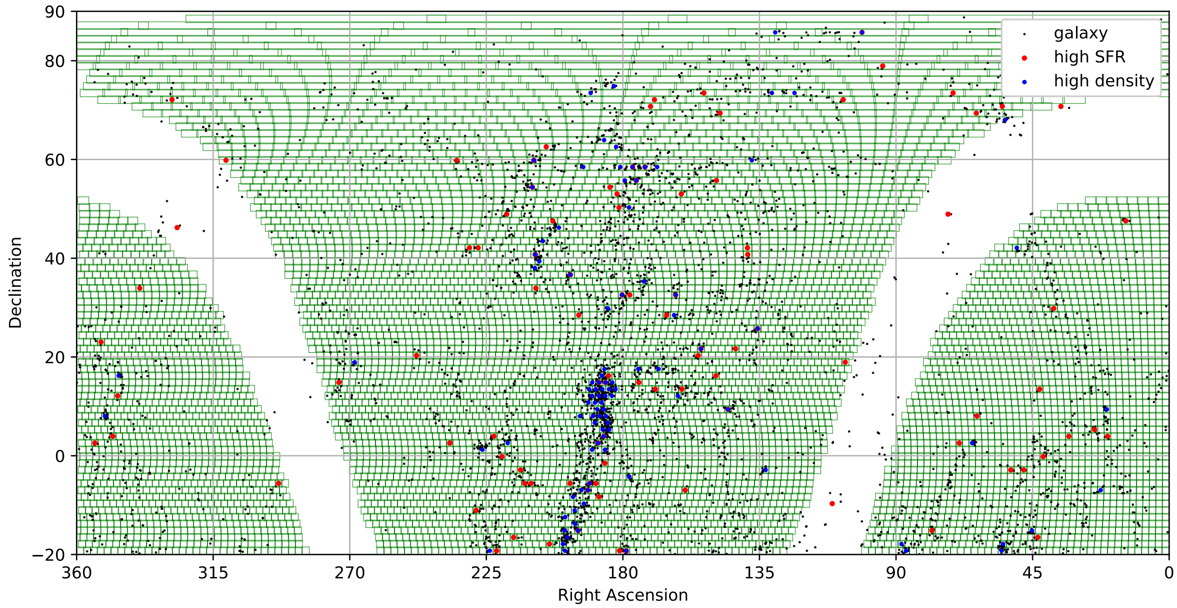

Figure 2. Sky region which would be monitored to search for TDEs and SNe. Areas with high galaxy density are marked with blue dots. Areas with high star formation rate are marked with red dots.

2.3.2. Supernovae

The earliest classifications of supernovae (SNe) were based on their different behaviors in spectroscopic observations, which involves whether their spectra exhibit signatures of Hydrogen. Type II SNe show signature of Hydrogen while Type I SNe do not (Minkowski 1941). Meanwhile, light curves of Type I SNe are homogeneity while Type II SNe have light curves that are heterogeneous, which could provide valuable insights into SNe classification, explosion mechanism, progenitor stars and nucleosynthesis processes.

One of the unsolved problems regarding SNe is the progenitor problem. For Type Ia SNe, Single-Degenerate Models (Whelan & Iben 1973), Double-Degenerate Models (e.g., Iben & Tutukov 1984), Collisional Double-Degenerate Models (e.g., Benz et al. 1989), Double Detonations and Rotating Super-Chandrasekhar-Mass Models (Taam 1980) and some other alternative models for example “core-degenerate” model (Kashi & Soker 2011) have been proposed. Light curves at early stages could shed light on these models and provide strong constraints. As for Type II SNe, the variations of their light curves and spectra could reveal the masses of their progenitors, the mass ejection process and energy source (e.g., Kasen & Woosley 2009). Fortunately, the large FOV of Mini-SiTian Arrays, the real-time data processing pipelines together with the Xinglong 2.16 m telescope could make it possible for us to monitor the early light curves of supernovae and their spectra in the time-domain, making it possible to investigate the physical models of SNe.

2.3.3. Observation Design

For both TDEs and SNe, we adopt the following survey plan and strategies. (1) The sky region with a decl. above $-20°$ is segmented into separate areas and a sky region table is established. Each sky region will maintain a certain overlap with surrounding ones, i.e., $1''$. See Figure 2 for more details. They are suitable for searching for TDEs. Star formation rates are higher among areas marked by red dots and they are designed for searching for SNe. (2) For a continuous sky survey, we follow the same strategy as Mini-SiTian regular sky survey with a cadence of 30 minutes, which has a 5 minutes exposure time, circularly observing 1–2 sky regions. For an independent sky region detection, we select sky regions and exposure time based on scientific objectives. (3) Follow-up spectroscopic observations based on the 2.16 m telescope at the Xinglong Observatory will be immediately applied once a possible TDE or SN is recognized by the STRIP pipeline and our science group.

2.4. Be Stars

2.4.1. Background

Be stars are fast rotating B-type stars that present Hα emission lines, which are believed to originate from the viscous decretion disks (Rivinius et al. 2013). Many studies have tried to reveal the possible mechanisms of the Be outbursts, including interaction of close-in companion and non-radial pulsations (e.g., Kervella et al. 2008; Baade et al. 2018; de Almeida et al. 2020). The mass outflow could feed the decretion disks and thus leads to enhanced Hα emission lines. However, up to now there is no decisive evidence that can distinguish those scenarios. Carrying out multi-band observations of Be stars would be crucial for investigating the nature of decretion disks and mass ejection of Be stars.

In addition, mass distribution of compact objects is an important piece of binary evolution theory. Many studies are dedicated to searching for compact object in binary systems that contain B-type stars (e.g., Liu et al. 2019). To derive precise masses of the compact objects in binary systems, orbital parameters including period, inclination together with mass ratio are essential. Multi-band light curves could help to constrain these parameters. As a result, we plan to carry out multi-band photometric and spectroscopic observations of Be stars.

2.4.2. Observation Design

Based on previous Be star spectra database (e.g., Neiner et al. 2011) and Be stars identified by the LAMOST sky survey (Wang et al. 2022), we will first search for Be spectra that exhibit variations in radial velocities, which may indicate the existence of secondary companions. Then we will monitor them using the Mini-SiTian telescopes. Similar to the monitoring of flaring stars, Be stars will be observed continuously. In addition, based on the STRIP pipeline developed by Gu et al. (2025), if some outbursts appear, immediate spectroscopic observations using the 2.16 m telescope at the Xinglong Observatory will also be applied to monitor the outburst process.

2.5. Cataclysmic Variable Stars

2.5.1. Background

Cataclysmic variable stars (CVs) represent one kind of objects with very rich variability simultaneously in a wide range of timescales and amplitudes. They are short orbital period binary systems (typically from 80 minutes to less than 12 hr, but can be as short as several minutes in AM CVn systems) in which a white dwarf (WD) accretes from a low-mass donor that fills its Roche lobe (Warner 2003). The variability of CVs is primarily determined by the mass accretion rate onto the WD and the strength of its magnetic field. Different subtypes of CVs are further classified, including dwarf novae (generating outbursts quasi-periodically) (Hameury 2020), nova-like stars (stay in stable states but occasionally exhibit state transitions) and magnetic CVs (including polars and intermediate polars). The mechanisms that trigger the state transitions remain unclear (Szkody 2020).

Apart from outbursts, CV light curves can display various features such as orbital modulations (eclipses, ellipsoidal modulations, and reflections), superhumps, stellar flares, stochastic flickerings, quasi-period oscillations, and coherent white dwarf spin modulations. Higher-cadence observations are helpful to characterize these variations. Variability beyond normal dwarf nova outbursts, such as “micronova” (Scaringi et al. 2022), magnetically-gated outbursts (Scaringi et al. 2017), “stunted” outbursts (Honeycutt et al. 1998), and anonymous Z Cam outbursts (IW And-type outbursts) (Kato 2019; Sun et al. 2024), have all been discovered in many CVs (Iłkiewicz et al. 2024). Multi-band observations are essential for distinguishing the underlying complex physical processes. The orbital period, which is the most fundamental parameter to determine the evolution stage of a CV, requires long-baseline observations for accurate determination. Extending these measurements to a larger sample of CVs will facilitate more comprehensive statistical studies to test CV evolution theories.

2.5.2. Observation Design

The wide-field Mini-SiTian Array and the upcoming SiTian project, which provide simultaneous three-band photometry, will improve the discovery of unidentified cataclysmic variables (CVs). We will analyze light curves to identify new CVs among blue, variable stars, thus enhancing the completeness of known CVs within our local volume (Pala et al. 2020). The ongoing Mini-SiTian project has three primary observational goals for studying CVs: (1) Determine the orbital period for more CV candidates, which will utilize the staring mode for CV candidates and poorly known CVs. (2) Capture rapid burst-like events (e.g., micronovae, magnetically gated accretion, stellar flares) with durations of 10 minutes to hr. The staring mode with single exposures under 300 s will facilitate detailed studies of the color evolution. (3) Monitor the state transitions among nova-like stars and magnetic CVs.

The STRIP pipeline enables real-time detection of state transitions (e.g., from high to low states) and can trigger follow-up spectroscopic observations (for example, using the Xinglong 2.16 m telescope). These observations aim to explore changes in the accretion disk during such events and determine binary system parameters during phases of low accretion rates. Furthermore, the Mini-SiTian telescopes can also capture possible nova eruptions. The scanning mode is suitable for the discovery of new novae eruptions while the staring mode could monitor known Galactic recurrent novae (e.g., T CrB Zamanov et al. 2023). The Mini-SiTian telescopes together with other telescopes or satellites, such as Einstein-Probe (X-ray; Yuan et al. 2018) and FAST (radio; Nan et al. 2011), will enable multi-wavelength studies of high-energy phenomena like jets and magnetic accretion in CVs.

3. Mini-SiTian Array, SiTian Prototype and Beyond

The Mini-SiTian Array has been operated since 2022 and both regular sky surveys and follow-up observations have been conducted. According to data processing results given by Xiao et al. 2025, the Mini-SiTian Array is capable of achieving a precision of 5 mmag for stars brighter than 13 mag. Moreover, the STRIP pipeline has been used to successfully detect stellar flares on eclipsing binary systems (Gu et al. 2025). Additionally, the first catalog of variable stars is currently being compiled (L. Y. Mi et al. 2025, in preparation). Further intriguing results are anticipated as the Mini-SiTian Array continues its operations. We believe that many interesting results will come into being during the future operation of the Mini-SiTian Array.

Meanwhile, the SiTian project is advancing steadily. The SiTian prototype, a 1 m telescope, has been installed at the Xinglong Observatory and will be in formal operation earlier 2025. Another SiTian node with three 1 m telescopes at the Lenghu Observatory is currently under construction. With these arrays in place, many new TDEs, SNe, CVs, and stellar flares are expected to be discovered. After the SiTian Project is fully operational, it will produce a large number of light curves, which could help us to characterize the variable universe in all aspects.

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The SiTian project is a next-generation, large-scale time-domain survey designed to build an array of over 60 optical telescopes, primarily located at observatory sites in China. This array will enable single-exposure observations of the entire northern hemisphere night sky with a cadence of only 30 minute, capturing true color (gri) time-series data down to about 21 mag. This project is proposed and led by the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). As the pathfinder for the SiTian project, the Mini-SiTian project utilizes an array of three 30 cm telescopes to simulate a single node of the full SiTian array. The Mini-SiTian has begun its survey since 2022 November. The SiTian and Mini-SiTian have been supported from the Strategic Pioneer Program of the Astronomy Large-Scale Scientific Facility, Chinese Academy of Sciences and the Science and Education Integration Funding of University of Chinese Academy of Sciences.

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