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SOTHE: SOlar-terrestrial habitability explorer

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Abstract

Among more than 5000 exoplanets discovered up to now, around 60 are believed to be potentially habitable. The Sun-Earth system provides a unique example based on which detailed insights into the properties, formation, evolution, and thus habitability of exoplanets could be gained. However, simultaneous observation of the Sun as a star and the Earth as an exoplanet has been rare. In this paper, we introduce the SOlar-Terrestrial Habitability Explorer (SOTHE) to be deployed to the Sun-Earth L1 point. SOTHE will carry a science payload comprising four instruments to obtain the integrated spectra of the whole solar disk and the whole sunlit Earth at the same time, together with images of the Earth at 11 unique passbands from UV to NIR and the local plasma and magnetic field parameters at the L1 point. The core scientific goal of SOTHE is to understand key characteristics related to the habitability of the Sun-Earth system and provide a unique baseline for exploring habitable exoplanets, especially Earth-like planets around Sun-like stars.
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Keywords: Space mission design; Sun-Earth relation; Habitability

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1. Introduction

The first exoplanet orbiting a solar-type star was inferred from measuring the star's radial velocity in 1995, which was then named "Jupiter-mass companion" and later "51 Pegasi b" (Mayor and Queloz, 1995). The discovery of "51 Pegasi b" opened a new chapter in humanity's exploration of extraterrestrial civilizations and extraterrestrial life. Since then, more than 5700 candidates of exoplanets have been found until September 2023 according to the Exoplanet Catalog[1]. Fig. 1 depicts the distances to the solar system and the temperatures of the host stars of 2324 confirmed exoplanets out of the 5747 candidates. It is seen that most of these exoplanets orbit stars with temperatures similar to the Sun (5000–6000 K).

There are several methods for observing or detecting exoplanets, including transiting, radial velocity, gravitational microlensing, direct imaging, and astrometry, among which the transit method is employed in discovering more than 70% of all known exoplanets. The transit method is based on the observational fact that the brightness of a target star would drop when its planet is located at the star-Earth line. This method has been used in many ground-based telescopes as well as space missions in exoplanet surveys, including but not limited to the TRAnsiting Planets and PlanetesImals Small Telescope (TRAPPIST, Jehin et al., 2011), the Hungarian-made Automated Telescope Network (HATNet, Hartman et al., 2004), Convection, Rotation and planetary Transits (CoRoT, launched in 2006, Baglin et al., 2008), Kepler space telescope (launched in 2009, e.g., Borucki et al., 2011), Transiting Exoplanet Survey Satellite (TESS, launched in 2017, Ricker et al., 2015), and CHaracterising ExOPlanets Satellite (CHEOPS, launched in 2019, Benz et al., 2021). PLAnetary Transits and Oscillations of stars (PLATO), a space telescope under development and planned to be launched in 2026 by the European Space Agency (ESA), also utilizes the same method for searching and identifying exoplanets (Rauer et al., 2014).

A habitable planet refers to a planet capable of fostering life, which requires many strict conditions (Schwieterman et al., 2018), with the presence of liquid water being considered the primary requirement. This corresponds to a belt-like region around a star, and only when a planet is within this belt-like region can its surface temperature maintain the existence of liquid water. This belt-like region is commonly referred to as the Circumstellar Habitable Zone (CHZ, e.g., Kasting et al., 1993) of a star. For solar-type stars, the habitable zone is located near 1 astronomical unit (AU). Earth is located approximately in the center of the Sun's habitable zone, while Venus is too close to the Sun, and Mars is on the outer edge. Another criterion for habitable planets is the planet's mass. If a planet's mass is greater than 10 times that of Earth, it is likely to be a gas giant planet like Neptune or Jupiter (e.g., Piso and Youdin, 2014). On the other hand, if a planet's mass is less than 10% of Earth's mass, it is unlikely to maintain an atmosphere for life's emergence and evolution (e.g., Arnscheidt et al., 2019).

Overall, the criteria for determining habitable planets are relatively simple at present, primarily based on whether a planet is located within the CHZ and the planet's mass and orbital period. However, the CHZ is essentially a temperature restriction and a planet's surface temperature is influenced not only by the star's luminosity (radiation intensity) and distance from the main star but also by factors such as planetary albedo and greenhouse effects in the planet's atmosphere. For example, on Earth, oxygen (O_2) is a gas produced by photosynthesis, essential for animal respiration; ozone (O_3) is a byproduct of oxygen and is needed to shield against UV radiation; methane (CH_4) is produced through the decay (oxidation) of plants; and nitrous oxide (N_2O) is also generated through life processes. These gases can be considered indicators of the existence of life, among other possible biosignatures, including surface and temporal ones (Schwieterman et al., 2018). If we can detect these gases in the atmospheres of solid planets in CHZs, it can be roughly assumed that the planet may host extraterrestrial life.

In addition, stellar radiation and activities (such as flares and coronal mass ejections) profoundly impact the formation and variability of the space environment surrounding their planets (Bothmer and Daglis, 2007). For example, the (E) UV radiation and plasma outflows (stellar wind) from stars can affect the interplanetary environment and the ionosphere of planets, altering their chemical composition and further affecting their habitability. The detection and study of the physical and dynamic processes of stellar and planetary (magnetized) atmospheres, as well as the vast interplanetary space between them, play a crucial role in refining models of planetary origin and evolution. Another important factor for habitability which is missing in the standard CHZ model is the magnetic forcing and the potential stripping of the planetary atmosphere due to extreme eruptive transients in the host stars (e.g. Samara et al., 2021). Using data from the MAVEN (Mars Atmosphere and Volatile EvolutioN) mission, Jakosky et al. (2015) found that ions and the embedded magnetic field in the solar wind induce currents in the Martian ionosphere and strip gas away into space. Via reconstructing the magnetic field of a solar-type star younger than the Sun, Kay et al. (2019) studied the impact frequency of coronal mass ejections (CMEs) on early Venus, Earth, and Mars. The simultaneous spacecraft observations from Tianwen-1 and MAVEN reveal the depletion of the topside Martian ionosphere on the nightside, indicating ion escape from Mars to space due to the interaction between the CMEs and the largely unmagnetized atmosphere of Mars (Yu et al., 2023). In general, recent research progress on star-planet relations suggests that assessing the impacts of host stars on the habitability of terrestrial planets will greatly

[1] http://exoplanets.org/

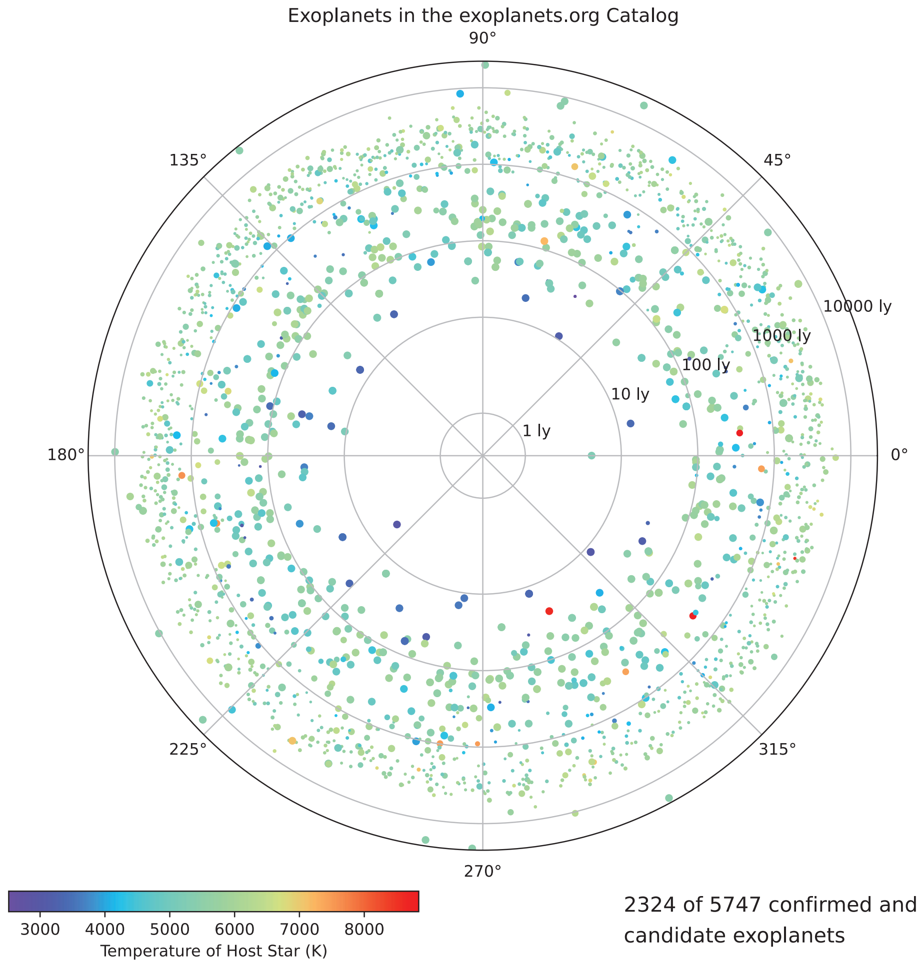

Fig. 1. **Distribution of exoplanets in the plane of the sky.** Only 2324 with measurement of distances to the solar system of 5747 exoplanet candidates are included. Colors denote the temperatures of their host stars in units of Kelvin. Sizes of dots are scaled according to the radii of exoplanets. The radial and azimuthal axes represent the distance from the solar system in units of light-year (ly) and the right ascension in degrees.

expand our definition of the CHZ to the biogenic zone and provide new observational strategies for searching for signatures of life (Airapetian et al., 2020).

Among the more than 5700 exoplanets detected so far, about 60 are potentially habitable (see the Habitable Exoplanets Catalog[2]). Due to red dwarfs making up 70–80% of the total number of stars and their low mass and luminosity, planets orbiting red dwarfs are easier to detect. Therefore, most (70–80%) of the potentially habitable planets have been found around red dwarfs. However, the habitability of planets near red dwarf stars has been a subject of debate. This mainly involves two issues: 1) Red dwarf stars frequently exhibit flaring activity that produces intense high-energy particle eruptions (stellar winds) and ultraviolet radiation (Cohen et al., 2014), with the former having strong erosive effects on the planet's atmosphere and the latter highly detrimental to organic life. 2) Planets near red dwarf stars are usually tidally locked due to their close distances to the stars, causing uneven heating between the day and night sides (Joshi, 2003). Although it was observed that intense high-energy radiation primarily originates from young stars, as red dwarf stars age, their magnetic activities gradually weaken, leading to the stable emission of visible light radiation. This stable phase can endure for billions of years. Nevertheless, it remains a formidable challenge for most planets orbiting red dwarf stars to support life (France et al., 2020). On the other hand, Sun-like stars still make up a significant number and remain key targets in studying habitable planets. Petigura et al. (2013) found through Kepler observations that about 22% of Sun-like stars (effective temperature T_{eff} = 4100–6100 K and gravity $logg$ = 4.0–4.9) could harbor Earth-size planets orbiting in their habitable zones. According to the Exoplanet Catalog[3], about 20%-30% of the stars that host planets are G-type stars (T_{eff} = 5300–6000 K with a radius between 0.9 to 1.1 solar radii). Among these G-type stars, more than 100 ones are found to have Earth-like planets (with a radius between 1 to 2 Earth radii). With more

[2] https://phl.upr.edu/projects/habitable-exoplanets-catalog

[3] http://exoplanets.org/

high-resolution planet-searching telescopes, this number is expected to increase rapidly.

Therefore, studying the spectra of (Sun-like) stars and their planets is vital in discovering habitable exoplanets. As the only known star-planet system with life, the Sun and Earth provide us with a unique natural laboratory for studying the habitability of extraterrestrial bodies. For instance, as mentioned previously and to be detailed in the next section, strong solar flares (X-class and above) and fast coronal mass ejections could introduce severe impacts to the terrestrial interplanetary space and upper atmosphere, changing its physical and chemical properties (e.g. Dang et al., 2022). Long-term variation of the solar activity level greatly modulates the global temperature, rainfall, and overall habitability of Earth (e.g. Brehm et al., 2021). Although many missions have been dedicated to this field of solar-terrestrial relations, which have resulted in numerous research findings, many questions have yet to be answered. Research on the habitable characteristics of Earth and their solar-interplanetary factors will help to boost the understanding of the planet's habitability, facilitate the development of more comprehensive theoretical frameworks, and establish a standard model for habitable planets and their hosting stars, playing an essential and inevitable role for humanity in the quest for Earth-like habitable exoplanets. This will not only promote research on the formation and internal interaction of star-planet systems, and the habitability of extraterrestrial environments but also boost our understanding of the solar system and the evolution of the habitable Earth.

2. Scientific rationale and objectives

2.1. Earth as a planet

In the 1990s, using simultaneous spectral and imaging observations by the Galileo spacecraft, the global spectrum of Earth was obtained and analyzed for the first time. This analysis revealed high concentrations of oxygen, enhanced red-edge features of vegetation (i.e., rapid increase in the reflectance of vegetation around 700 nm), thermodynamically unstable methane, and electromagnetic communication signals, all of which are indicators of the existence of life on Earth if observed from interstellar scales (Sagan et al., 1993; Geissler et al., 1995). Using the Deep Impact spacecraft in 2008, global imaging observations of the entire Earth's surface were conducted over two separate days, and the corresponding light curves showed the effects of surface land-sea distribution and atmospheric cloud movement. From this, a one-dimensional map of the surface land-sea distribution of Earth was derived (Cowan et al., 2009; Cowan et al., 2011; Cowan and Strait, 2013). Subsequently, with the launch of the Deep Space Climate Observatory (DSCOVR) at the Sun-Earth L1 point in 2015, related research made further progress.

DSCOVR is the first space mission to provide long-term fixed-point observations of the entire sunlit side of Earth. Its payload includes the Earth Polychromatic Imaging Camera (EPIC, Marshak et al., 2018), the National Institute of Standards and Technology Advanced Radiometer (NISTAR), the Plasma Magnetometer (PlasMag) experiment suite, and the Pulse Height Analyzer (PHA). EPIC covers 10 spectral bands from UV to visible, to measure essential parameters such as ozone content, aerosol amount, cloud height and phase, vegetation distribution, and surface UV radiation. NISTAR covers four spectral bands: UV to far-infrared (0.2–100 μm), solar light (0.2–4 μm), near-infrared (0.7–4 μm), and a passband for calibration (0.3–1.1 μm).

Using data from DSCOVR/EPIC, the first two-dimensional land-sea distribution inferred from light curves without spatial resolution has been derived (Jiang et al., 2018; Fan et al., 2019; Gu et al., 2021; Gu et al., 2022), and related inversion methods have been further improved (Aizawa et al. 2020, Kawahara 2020). Subsequent research has also conducted comparative analyses of the complexity of light curves for multiple solar system planets, and Earth has shown the highest complexity due to its habitable environment with global partially covering oceans and clouds (Bartlett et al., 2022).

However, the capability of DSCOVR to resolve Earth as a planet is limited. DSCOVR/EPIC only images Earth in 10 narrow bands ranging from 310 nm to 780 nm. Meanwhile, DSCOVR/NISTAR only measures Earth's total irradiance in four wide bands without any spectral resolution. The limited spectral sampling points make it difficult to use spatially integrated observations to detect surface vegetation and its changes over time. Additionally, the absence of the infrared spectral band in EPIC prevents the analysis of important trace components of life, such as water and carbon dioxide in Earth's atmosphere, which are crucial in understanding Earth's habitability.

In terms of ground-based observations, through the Earthshine Project, a collaboration between the Big Bear Solar Observatory (BBSO) and the California Institute of Technology that began in 1998, Goode et al. (2001) obtained Earth's albedo by simultaneously observing the bright and dark parts of the Moon (Goode et al., 2021). On September 4, 1999, based on the data from the Palomar Observatory, Rodriguez et al. (2004) used the same method and calculated Earth's reflected spectrum. In subsequent studies, Pallé et al. (2009) briefly obtained Earth's transmitted spectrum during lunar eclipses using lunar reflections from the William Herschel Telescope and the Nordic Optical Telescopes. Recently, a new EarthShine project has been proposed (Boyd et al., 2022), which describes a scenario of deploying a detector to the Moon to observe the global spectra of Earth at 400–1750 nm from the Moon. Due to the different observed Earth phases over time, EarthShine cannot continuously observe the spectrum of the sunlit side of Earth from a fixed point. Meanwhile, slit-jaw images by EarthShine are limited by their relatively low spatial and temporal resolutions.

2.2. Sun as a star and its impacts on Earth's habitability

The resolution of solar observations has experienced dramatic improvements in the past half-century, yielding great advances in understanding the Sun's intricate atmospheric structures and dynamic evolution. However, with the rapid development of planetary science in the 21^{st} century, research has increasingly focused on the Sun and stars' overall activity patterns, in terms of which solar and stellar small-scale fine structures are less important compared to their integrated radiation characteristics (for example, signatures of flares and CMEs in the integrated spectral of the Sun are common, e.g., Del Zanna and Woods (2013); Cheng et al. (2019); Yang et al. (2022), but signatures of small-scales fine structures, such as jets, are rare), partly due to the current technical limits on stellar observations.

The solar system, as the only stellar-planetary system we can study in detail, offers invaluable opportunities to observe the global responses of planets to stellar activities, such as stellar wind and flares. The Sun has been found to experience various periods with the most prominent one of 11 years, known as the solar activity cycle, which greatly modulates the behaviors of a variety of solar phenomena, including but not limited to sunspot numbers, full-disk EUV irradiance, active regions, solar flares, CMEs, and even small-scale localized eruptions (Maunder, 1904; Solanki and Krivova, 2011; Song et al., 2016; Bhowmik and Nandy, 2018; Liu et al., 2023; Korsós et al., 2023). These 11-year variations, together with other potential longer-term cycles of the Sun (Hathaway et al., 1999), could have vital impacts on the Earth's habitability. For example, the decadal and Milankovitch cycles are deterministic and cause Earth's surface temperature variability with decadal and Milankovitch period (23,000- and 41,000-year) cycles (Huybers and Curry, 2006). Via analyzing the ^{14}C concentration in tree rings from five countries across Asia, Europe, and North America, Brehm et al. (2021) found critical evidence on the previous occurrence of solar eruptive events and their influences on Earth's lives of the solar 11-yr Schwabe cycle throughout the past thousands of years. Although it has been widely proven by models that Earth might not experience severe atmospheric erosion (e.g., Ngwira et al., 2014; Patsourakos and Georgoulis, 2017) like many Earth-like exoplanets around M dwarfs and active K stars would do (Airapetian et al., 2017) during extreme stellar eruptive events with energies comparable to or higher than the well-known Carrington Event in September 1859, it is worth further study of how the Earth would react during these extreme space weather events, in terms of its geophysical, geochemical, astrophysical, biological and technological conditions (e.g., (Avakyan, 2005; Avakyan and Voronin, 2006; Haigh, 1996); Brehm et al., 2021; Lozitsky and Efimenko, 2021; Dang et al., 2022). The influence of host stars on the climate and habitability of terrestrial planets will broaden our current understanding of habitability (Airapetian et al., 2020).

It is widely accepted that the thermal structure and composition of Earth's atmosphere are fundamentally determined by solar irradiance (Haigh et al., 2010), whose (E) UV component dissociates atmospheric molecules and plays important roles in modulating ozone, and the visible/infrared component warms Earth's surface and its lower atmosphere. It is also worth noting that, during solar cycles, the (E) UV emission of the Sun experiences dramatic changes (with a factor of 10 causing similar variations in the ionization of the Earth's ionosphere). In contrast, the visible and infrared emission stays almost invariable (Floyd et al., 2002; Lean et al., 2020; Schmutz, 2021). Solar eruptive events, especially flares, also have their most prominent footprints in (E) UV and X-ray bands. Thus, the observations of the solar (E) UV irradiance have gained great interest considering their importance in understanding the short-/long-term variations of the Sun and their impacts on Earth and its climate (Airapetian et al., 2020).

Launched in 2010, the Extreme Ultraviolet Variability Experiment (EVE, Woods et al., 2013) suit onboard the Solar Dynamics Observatory (SDO, Pesnell et al., 2012), was the most advanced instrument that could measure the full-disk integrated EUV spectra of the Sun, with a spectral resolution of $\sim$0.1 nm and coverage from 5 nm to 100 nm. Using data from SDO/EVE, the EUV late phase after some solar flares was discovered (Woods et al., 2011). EVE observations also connect coronal dimming from coronal mass ejections to the depression of EUV spectral line irradiance, indicating whether flares have associated CMEs (Mason and Woods, 2016). Remarkably, EVE data reveals long-term coronal abundance shifts (Brooks et al., 2017) and plasma flows at varying flare temperatures (Cheng et al., 2019), as well as heating and cooling during flares (Wang et al., 2016). Recent work shows that EVE spectra can be used to determine CME line-of-sight velocities and vector velocities aided by imaging data (Xu et al., 2022; Lu et al., 2023). Models confirm that a EUV spectrograph with a spectral resolution of above $\sim$500 is required to accurately resolve CME velocities (Yang et al., 2022). These show that the full-disk integrated EUV spectra excellently monitor solar activities and provide key atmospheric and space sciences inputs. However, MEGS-A of EVE, covering a spectral range of 5 nm to 35 nm and containing many strong spectral lines emitted from different layers in the solar atmosphere, stopped working in 2014. And no similar instruments have been available since then.

2.3. Scientific objectives

From the above brief recap of the current progress on studying Earth as a planet and the Sun as a star, one can infer that the global spectra from Earth contain vital information about its land-sea distribution, atmospheric composition, vegetation distribution, and life activities, thus providing a unique baseline for exploring habitable exoplanets. Moreover, studying the global spectra of Earth could also help us understand its energy budget, climate change, and the impacts of life activities on its habitability. On the other hand, as Earth's primary energy source, solar activities and their interplanetary consequences play vital roles in affecting Earth's climate and radiation. Thus, a space mission that could simultaneously obtain the integrated spectra of Earth and Sun is urgently needed and will boost research in solar physics, earth sciences, climate change, and space sciences. Most importantly, such a mission will also incubate breakthroughs in searching for exoplanets and extraterrestrial lives by providing unprecedented data on the only known star-planet system that hosts lives (Seager and Bains, 2015; Fan et al., 2019).

Based on these scientific rationales and lack of corresponding observations, we propose the SOlar-Terrestrial Habitability Explorer (SOTHE) deployed to the Sun-Earth L1 point. SOTHE will perform the first-ever simultaneous observations of the solar and Earth's global spectra, carry out imaging observations of the Earth at 11 unique passbands, and measure the in situ plasma and magnetic field parameters at the Sun-Earth L1 point. Using these observations, SOTHE will help us to explore key characteristics related to the habitability of the Sun-Earth system and provide a unique baseline for habitable exoplanets exploration.

Fig. 2 is a cartoon that illustrates the concept of the SOTHE mission. It highlights some of the key aspects of this mission that it will simultaneously observe the Sun and Earth, and monitor the interplanetary space at the L1 point. The core scientific goal consists of the following two major scientific objectives.

The first objective is to unveil the global time-dependent spectra of Earth from UV to near-infrared (NIR). SOTHE will unprecedentedly carry out simultaneous detection of the integrated UV, visible, and NIR spectra with imaging at a variety of passbands of the sunlit Earth, to construct UV to NIR characteristic models of habitable planets (especially those Earth-like ones) using the Earth as a blueprint, establish models for the Earth's atmospheric radiation transfer across a wide wavelength range, reveal the energy balance processes of the climate system, provide reference samples for the search for extra-solar habitable planets, and thus foster major discoveries in the above areas. This scientific objective focuses on the characteristics of Earth's habitability to build a unique baseline to understand the spectral characteristics of exoplanets, by answering the following two scientific questions: 1) What observations are needed to explore life-related information on Earth-like planets? 2) How is the energy of Earth and Earth-like planets balanced?

The second objective is to uncover the spectral responses of Earth to solar activities. SOTHE will perform the in situ detection of solar wind plasma and magnetic fields at the L1 point, combined with the detection of Earth's global

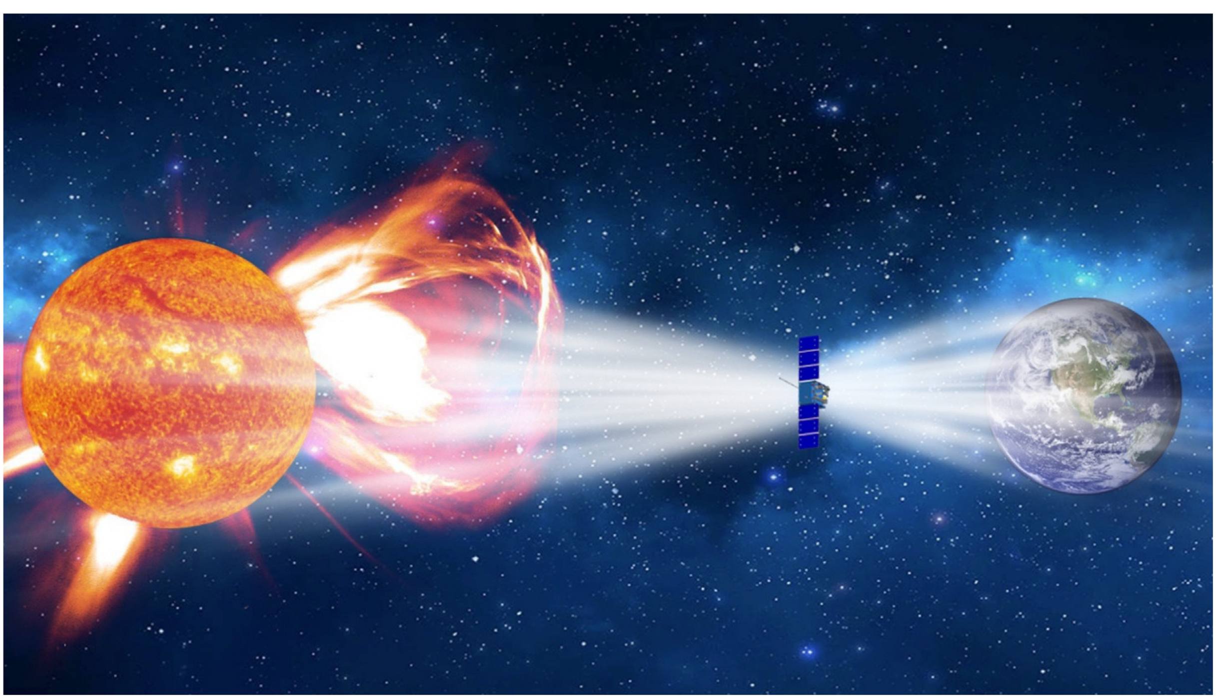

Fig. 2. **A cartoon for the SOlar-Terrestrial Habitability Explorer (SOTHE).** Image of the Sun consists of observations from SDO (Pesnell et al., 2012) and SOHO/LASCO (Domingo et al., 1995; Brueckner et al., 1995). Image of Earth is an observation by DSCOVR (Marshak et al., 2018). The blue inset shows the actual designed structure and appearance of the spacecraft with the solar panels unfolded. Objects in this cartoon are not in scale. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

images and spectra from UV to NIR, to reveal the impacts of solar wind on the Earth's global radiation at various passbands. By combining the detection of full-disk integrated solar EUV emission with solar and interplanetary imaging observations from other missions, SOTHE will reveal the global EUV spectral responses of solar activities and their impact on the global radiation of Earth, providing important references for establishing the relation between stellar activities and exoplanets' global spectra. This scientific objective targets building a unique baseline for the interactions between exoplanets and their host stars by answering the following two scientific questions: 1) How is the Earth spectrum affected by solar wind variations? 2) How do solar eruptive events impact the global radiation of Earth?

3. Instruments and mission profile

In the previous section, the two scientific objectives and their corresponding key scientific questions to be answered have been formulated. To answer these scientific questions and ensure the scientific objectives can be accomplished, instruments onboard SOTHE need to meet certain detection requirements. Table 1 lists a summary flow from the scientific objectives and questions to the detection requirements. It could be summarized from the detection requirements that the following observations with sufficient temporal, spectral, spatial, and energy resolution are needed: 1) imaging and spectral observations of Earth, 2) in situ detection of solar wind plasma and magnetic fields at the L1 point, and 3) full-disk integrated EUV spectral observations of the Sun. After many in-depth exchanges of thoughts and discussions between scientific and technical experts in two years from 2022, four instruments have been proposed based on the detection requirements. These instruments are: Earth Multiband Imager (EMI), Earth Integral UV to Near-Infrared Spectrometer (EIUNIS), Solar Wind ANalyzer (SWAN), and SOLar EUV Irradiance Spectrometer (SOLEIS).

3.1. Detection requirements and instruments

In this subsection, we demonstrate in detail the detection requirements for achieving the above-mentioned scientific objectives of the SOTHE mission. Recent advances and what is still missing in available observations are also briefly identified for each detection requirement, from which each instrument's technical specifications are then derived.

Imaging and spectral observations of Earth. DSCOVR is currently the only one of its kind that can observe the whole sunlit side at once of Earth from a fixed point. However, its EPIC instrument only performs imaging in 10 narrow bands located at 310 nm to 780 nm, lacking some critical near-infrared bands that could trace the habitability of Earth. Meanwhile, the NISTAR instrument only measures the total irradiance of Earth from 4 broad bands, and cannot provide any spectral information. Based on the above-mentioned scientific goals and the lack of relevant observations, SOTHE plans to carry an Earth Integral UV to Near-Infrared Spectrometer (EIUNIS) that will, for the first time, observe the spectra of the whole sunlit side of Earth with a wavelength range from 300 nm to 1700 nm. To resolve the spectral features of target atmosphere components, the spectral resolution is required to be better than 3 nm. At the same time, to coordinate with the integral spectrometer to resolve the dynamic processes and specific causes of changes in Earth's radiation, SOTHE will carry an Earth Multiband Imager (EMI). To complete the scientific goals, EMI must have high spatial and temporal resolution at some important passbands that trace information about the Earth's habitability and life. These bands include 317.5 nm and 340 nm for ozone measurement, 470 nm for clouds and aerosols detection, 550 nm for aero-

Table 1
Scientific requirements derived from the mission objectives and scientific questions to be answered.

Scientific Objectives	Scientific Questions	Detection Requirements	Instrument
Unveiling the global time-dependent spectra of Earth from UV to NIR	What observations are needed to explore life-related information on Earth-like planets?	• Typical passbands containing indicators about the Earth's habitability and life should be covered	Earth Multiband Imager (EMI)
	How is the energy of Earth and Earth-like planets balanced?	• Spectral, spatial, and temporal resolutions should be enough to monitor corresponding changes in various observables	Earth Integral UV to Near-Infrared Spectrometer (EIUNIS)
Uncovering the spectral responses of Earth to solar activities	How is the Earth spectrum affected by solar wind variations?	• Solar wind plasma with a wide range of energy should be detected • Magnetic field structures of both quiet and eruptive solar wind features can be measured	Solar Wind ANalyzer (SWAN)
	How do solar eruptive events impact the global radiation of Earth?	• Passbands sensitive to solar eruptions should be covered • Spectral and temporal resolutions should be enough to measure rapidly changing solar wind structures	SOLar EUV Irradiance Spectrometer (SOLEIS)

sol optical depth analysis, 589.3 nm for measuring atmospheric sodium atom density, 650 nm for measuring the vegetation red edge effects, 760.5 nm for the oxygen molecular absorption, 860 nm for the normalized vegetation index (NDVI), 940 nm for tracing water vapor, 1240 nm for vegetation water content analysis, and 1640 nm sensitive to cloud microphysics parameters and cloud amount, etc. Among the above 11 passbands, simultaneous observation of the whole sunlit Earth has never been done before at 470 nm, 589.3 nm, 650 nm, 760.5 nm, 860 nm, 940 nm, 1240 nm, and 1640 nm.

In-situ detection of solar wind plasma and magnetic fields at the L1 point. Solar activities have significant impacts on the interplanetary space around Earth. The electrons, protons, and ions, as well as the magnetic fields carried in the solar wind, continuously affect the Earth's thermosphere, magnetosphere, ionosphere, and upper atmosphere, which may, in turn, have important impacts on Earth's climate system and human production and living activities. Thus, acquiring solar wind plasma and magnetic field parameters at the L1 point upstream of Earth is essential for us to understand the propagation and consequences of solar eruptive events. In-situ detection of solar wind plasma and magnetic fields at the L1 point, combined with simultaneous spectral observations of the Sun and Earth, will also help us to explore the impacts on Earth radiation of interstellar material exchange represented by the solar wind (Turner et al., 2019; Friedberg et al., 2011), and to further construct models of the impact of interplanetary material exchange on the global radiation of planets. Based on this, to achieve the corresponding scientific objectives, SOTHE needs to carry a Solar Wind ANalyzer (SWAN). SWAN should be able to detect solar wind particles with typical energy range from hundreds of eV to tens of keV. To measure the magnetic fields of quiet solar wind and violent eruptive structures, the magnetic field measurement range should be at least ± 2000 nT. To resolve the rapidly changing structures in the solar wind, the time resolution should be better than 1 min.

Full-disk integrated EUV spectral observation of the Sun. Among the wide range of passbands from EUV to infrared, the EUV emission of the Sun is the most sensitive one to its activities and eruptions. The integral spectrum of the solar disk is a key input for studying the Earth's and planetary atmospheres and is also essential information for understanding the impact of solar eruptions on Earth's total radiation. Since the MEGS-A spectrometer on SDO/EVE stopped working in 2014, there have been no more observations of the sun-as-a-star EUV spectra. Such observation is in urgent need, especially considering that the current solar cycle is already reaching its maximum with more than 10 X-class flares in the first half of the year 2024. Therefore, SOTHE plans to perform real-time high-resolution spectral observations of the full-disk integrated solar EUV emission in the 17–31 nm range by carrying a SOLar EUV Irradiance Spectrometer (SOLEIS). This wavelength range contains many characteristic spectral lines in the chromosphere, transition region, and corona that have significant responses to solar activities, especially flares and CMEs. These lines include He II 30.4 nm (0.05 MK), Fe IX 17.11 nm (0.64 MK), Fe XI 18.04 nm (1.17 MK), Fe XV 28.42 nm (2 MK), etc.

Overall, SOTHE is designed to carry 4 instruments: the Earth Multiband Imager (EMI). the Earth Integral UV to Near-Infrared Spectrometer (EIUNIS), the Solar Wind ANalyzer (SWAN), and the SOLar EUV Irradiance Spectrometer (SOLEIS). EMI will carry out uninterrupted observations of the whole sunlit side of Earth from the L1 point at 11 passbands from UV to NIR, of which 8 passbands are not included in DSCOVR/EPIC. EIUNIS will, for the first time, conduct continuous measurements of the spectra of the sunlit Earth from 300 nm to 1700 nm. SWAN will measure the solar wind plasma and magnetic field at the L1 point with high temporal resolutions. SOLEIS will be the only spectrometer that measures the spectra of the whole solar disk from 17 nm to 31 nm with a spectral resolution of 0.04 nm, which is >2 times better than that of SDO/EVE. The key specifications of EMI, EIUNIS, SWAN, and SOLEIS are summarized in Table 2.

3.2. Technical profiles

The total mass of all instruments will be below 100 kg, minimizing the size and financial cost of the mission. The spacecraft consists of 9 subsystems, including payload (100 kg), structure and mechanism (90 kg), thermal control (16 kg), platform compartment control (15 kg), payload compartment magnetic levitation and two-compartment cooperative control (28 kg), propulsion (22 kg), integrated electronics (18 kg), telemetry, tracking and command (18 kg), and power supply and distribution (58 kg). The total weight of the spacecraft is estimated to be below 450 kg, of which the payload compartment is $\sim$155 kg and the platform compartment is $\sim$295 kg. The overall data rate and power consumption of SOTHE are estimated to be $\sim$5.61 Mbps and $\leqslant$500 W, respectively. The current estimation shows that the whole mission will cost less than 0.5 billion Chinese Yuan. The spacecraft is planned to be launched in early 2026, taking the opportunity to study the maximum and declining phases of the current solar cycle (Solar Cycle 25). It should be noted that 2026 is the optimal option, while a launch time after 2026 would not affect the achievement of the main objects of the mission.

Fig. 3 depicts the orbits of the spacecraft during its launch (purple), transfer (red), and operation (green) phases. The spacecraft will be launched by a CZ-4C rocket with 16×5 N thrusters and fly for about 3 months at the transfer orbit before it reaches a halo orbit around the L1 point, which occupies a volume of $220 \times 700 \times 125$ Mm^3.

Table 2
Parameters and technical specifications of SOTHE's four payloads.

Payload	Weight (kg)	Power Consumption (W)	Data Rate (Mbps)	Technical Specifications
EMI	52	251	5.26	Field of View: 42′ Focal Length: 1000 mm Aperture: 150 mm Passbands: 317.5±2 nm 340±2 nm 470±20 nm 550±2 nm 589.3±2 nm 650±2 nm 760.5±2 nm 860±2 nm 940±50 nm 1240±2 nm 1640±50 nm Cadence: ~10 min Spatial Resolution: ⩽10 km (UV to Visible) ⩽20 km (NIR)
EIUMIS		101	0.0056	Field of View: 42′ Focal Length: 70 mm Spectral Range: 300–1700 nm Spectral Resolution: ⩽3 nm Signal-to-Noise Ratio: > 200:1 Cadence: ~10 min
SWAN	10	25	0.0015	Magnetic Field Range: −2000–2000 nT Magnetic Field Resolution: < 0.01 nT Solar Wind Plasma Energy Range: 100 eV-30 keV Energy Resolution ΔE/E: < 0.15 Mass Range: 1–70 amu Mass Resolution Δm/m: < 0.20 Cadence: ⩽1 min
SOLEIS	29	40	0.28	Field of View: 42' Spectral Range: 17–31 nm Spectral Resolution: ⩽0.04 nm at 20 nm Signal-to-Noise Ratio: > 10:1 Cadence: ⩽1 min

This orbit is designed so that the minimum angle between the spaeccraft-Sun line and the Sun-Earth line is above 5° to ensure that the spacecraft will be free of eclipse throughout the entire mission. Some of the key technical specifications of the mission are summarized in Table 3.

4. Summary and prospectives

In summary, the SOlar-Terrestrial Habitability Explorer (SOTHE) is a carefully designed mission to be launched at the Sun-Earth L1 point. It will be the first mission that simultaneously observes the Sun's and Earth's integrated spectral radiation. SOTHE will also be the first mission that continuously monitors the UV to NIR spectra and images at 11 passbands, of which 8 (470 nm, 589.3 nm, 650 nm, 760.5 nm, 860 nm, 940 nm, 1240 nm, and 1640 nm) were previously never covered, of the whole sunlit Earth. These 11 passbands range from UV (300 nm) to NIR (1700 nm) and are sensitive to many life-related features, including clouds, vegetation, oxygen, and water. Once launched, SOTHE will be the only space-based mission that measures the full-disk solar EUV spectrum with an unprecedented spectral resolution of ~0.04 nm, providing crucial inputs for studying solar activities and their impacts on Earth's habitability.

The core scientific goal of SOTHE is to understand key characteristics related to the habitability of the Sun-Earth system and provide a unique baseline for exploring habitable exoplanets, especially Earth-like planets around Sun-like stars. Two objectives and four scientific questions have been formulated to achieve this goal. By answering the four proposed scientific questions and achieving the scientific objectives, SOTHE is expected to contribute to understanding the habitability characteristics of the Sun-Earth system and help foster future breakthroughs in habitable exoplanet exploration.

With the proposed unique combination of instruments, SOTHE will enable many cutting-edge and interdisciplinary studies in multiple areas, including but not limited to solar physics, earth sciences, space sciences, astronomy, planetary sciences, and astrobiology. Here, we list some of these studies that could be fostered by data from SOTHE:

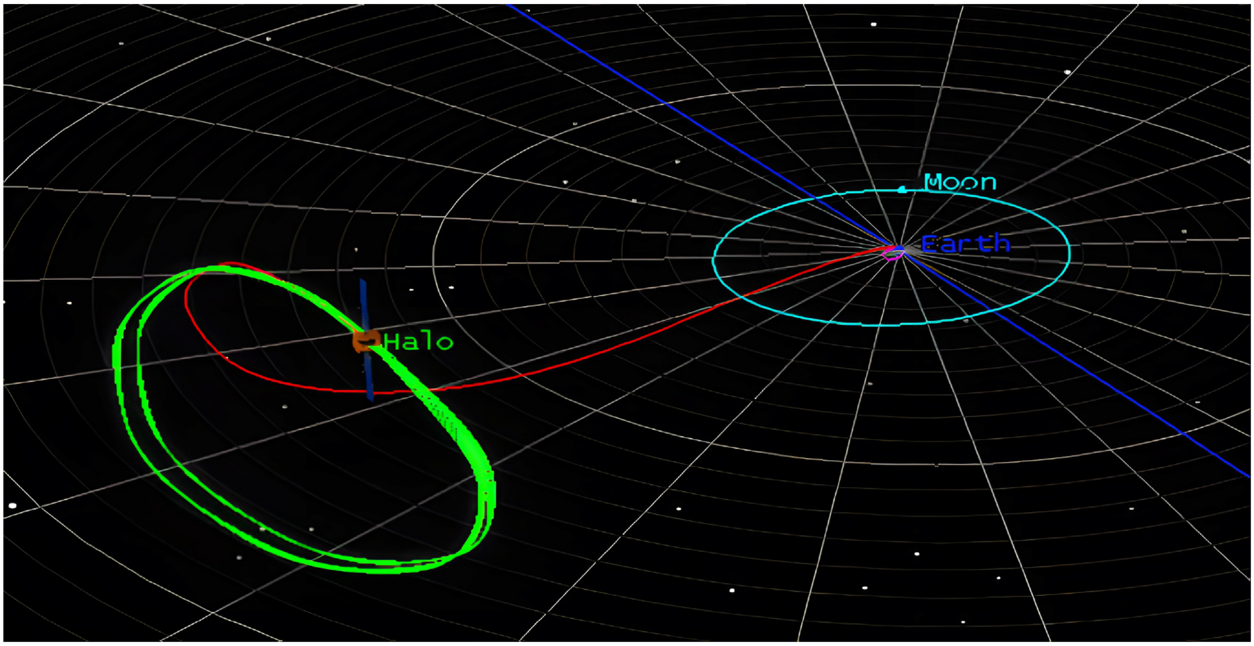

Fig. 3. **Orbit of SOTHE.** Blue and cyan dots are the Earth and the Moon, respectively. The cycle ellipse denotes the Moon's orbit. The purple and red curves are the path of SOTHE during its launch and orbit transfer phases. The green curve is the orbit of SOTHE during its operation phase. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Key specifications of the mission.

Parameters		Technical Specifications
Spacecraft	Mass	⩽450 kg
	Orbit	Halo orbit around the L1 point 220,000×700,000×125,000 km3
	Lifetime	⩾5 years
	Power consumption	⩽1000 W
	Envelope size	⩽ ϕ2120 mm×1420 mm
Payloads	Mass	⩽100 kg
	Power consumption	⩽500 W
Control	Control mode	Zero momentum three-axis stabilized
	Pointing accuracy	⩽0.02° (3σ)
	Stability	⩽0.001 $^{\circ}s$ (3σ)
Propulsion	Configuration	16×5 N chemical thrusters
	Propellant	Anhydrous Hydrazine (85 kg)
	Tank capacity	120 L
Power Supply	Solar array	6 solar panels in total for two fixed wings Total substrate area of 6 m
	Bus voltage	30±1 V
	Battery	Lithium-ion battery (30 Ah)

1. **Developing an Earth radiation transfer model that can be used in inferring biomarker information of exoplanets.** Earth can be treated as a hypothetical exoplanet, but with high-resolution imaging observations at various passbands. By analyzing the 300–1700 nm spectral observations of the whole sunlit Earth and its time variation provided by SOTHE, one can derive the temporal and spectral resolution required for detecting Earth-like exoplanets' rotation and orbital parameters. Combining with the imaging data at 11 passbands, the contribution of life-related features (e.g., clouds, land-sea distribution, atmospheric composition, and plants) to the global spectra of Earth could be obtained. Based on the above studies, an Earth radiation transfer model could be developed and employed to analyze the observational requirements for obtaining biomarker information of Earth-like exoplanets. The model will be based on the Earth Spectrum Simulator (e.g., Gu et al., 2022), which combines surface reflectors and clouds derived using DSCOVR/EPIC observations (Gu et al., 2021) and a two-stream-exact-single-scattering (2E-ESS) line-by-line scheme to compute radiative transfer of the Earth's

atmosphere (Spurr and Natraj, 2011). The spectral range will be extended to 1700 nm to meet the scope of SOTHE. Through the above research, the time-dependent spectral characteristics of Earth as a habitable planet will be systematically studied, and thus, a reference sample for exploring habitable planets using the Earth as a blueprint could be established.

2. **Exploring the energy balance process of Earth's climate system to provide an important basis for estimating the energy budget of (earth-like) exoplanets.** The continuous and direct observation by SOTHE of the shortwave radiation reflected by Earth is expected to greatly improve the estimation accuracy of Earth's Energy Balance (EEB). Variations in ozone, cloud, vegetation, sodium layer, water vapor, and other factors observed through Earth imaging at 11 passbands will improve our understanding of the key factors affecting the energy balance of Earth's climate system and provide an important reference for understanding the energy budget of habitable planets.
3. **Establishing the relation between solar wind disturbances and Earth's global radiation.** The solar wind and its disturbances have a decisive influence on Earth's space environment. By detecting the evolution of key parameters (e.g., velocity, density, magnetic field, and temperature) of the solar wind near the L1 point, combined with the spectral and imaging observations of the sunlit Earth, the impact of interplanetary disturbances such as coronal mass ejections on Earth's global radiation could be explored. Located at the L1 point, SOTHE will provide magnetic and plasma observations around Earth. However, by combining data from SOTHE and many other facilities that measure the near-Earth space environment and Earth's upper atmosphere, the magnetic forcing of the Sun on Earth could also be studied. These relations would then be taken as a representation to study the impact of interplanetary material exchange on Earth-like planets.
4. **Finding the impacts of solar EUV emissions on Earth's global radiation**. There are currently many observatories deployed or to be deployed along and away from the Sun-Earth line, providing tremendous high-resolution imaging data of the Sun and interplanetary space from different viewpoints. These missions include but are not limited to the Parker Solar Probe (PSP, Fox et al., 2016), the Solar Orbiter (SOLO, Howard et al., 2020; Marirrodriga et al., 2021), and the Solar Ring (Wang et al., 2023). Combining the unique full-disk integrated spectral data obtained by SOTHE/SOLEIS at 17 nm to 31 nm with imaging and in situ data from these missions, the 3-dimensional EUV manifestation of solar flares could be explored. Taking advantage of high-resolution spectral observations formed at different temperatures during flares, mechanisms of plasma heating and energy release during flares will be studied. By obtaining Doppler velocities, plasma dynamics at different temperatures during flares and the line-of-sight velocities of CMEs could both be inferred. Using data from SOLEIS, EMI, and EUMIS, the impact of solar eruptions on the global radiation of the sunlit Earth could be explored, which will further provide an important reference for studying the impact of stellar flare activities on planets (Bothmer and Daglis, 2007).

The SOTHE mission is now under intensive development, and any international collaborations are welcome.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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