Chapter

Optical Remote Sensing of Planetary Space Environment

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Abstract

Planetary science is the scientific investigations of the basic characteristics and the formation and evolution processes of the planets, moons, comets, asteroids and other minor bodies of the solar system, the exoplanets, and the planetary systems. Planetary scientific research mainly depends on deep space exploration, and it is highly interdisplinary and is built from Earth science, space science, astronomy and other relevant disciplines. Planetary space, a critical region of mass and energy exchange between the planet and the interplanetary space, is an integral part of the planetary multi-layer coupling system. Atmospheres of different compositions and plasmas of different densities and energies exist in planetary space, where mass transportation at different temporal and spatial scales and various energy deposition and dissipation processes occur. Optical remote sensing overcomes the difficulties of capturing global views and distinguishing spatiotemporal variations in in-situ particle and field detections. This chapter introduces the principles and applications of optical remote sensing in planetary science. The first ground-based planetary observatory in China, the Lenghu Observation Center for Planetary Sciences, will be introduced in detail. Future development of optical remote sensing platforms in Chinese planetary exploration program will also be introduced.

Keywords: Planets, Space Environment, Optical Remote Sensing, Atmosphere, Space Plasma, Radiation Mechanisms

1. Introduction

How a planet is formed? What initial conditions and combinations of subsequent geological, chemical, and biological processes lead to at least one planet that is the home of innumerable life forms? What determines the fate of lives on a planet? These scientific questions can be summarized to three fundamental questions that human beings are always thinking about: where we come from, how we develop to current state, and where we will go? These questions are closely related to science, religion, philosophy, humanity, and other fields.

Thousands of years ago, or in the much more distant past, the human beings have already started looking at the stary sky to try to understand how everything works and which corner our planet is at in the Universe. However, limitations of the eyes also confined the thoughts of human beings, until the 1910s, G. Galilei developed the first astronomical telescope and use it to observe the Universe. With the help of optical telescope, our field of vision is greatly extended to the deep Universe. Discoveries by G. Galilei, such as the four Galilean moons circling Jupiter, the variation of Venus phase, and the sunspot, opened a new era of planetary science and astronomy. Observation and exploration of planets transformed human's philosophical thinking to scientific activations, deeply changed the human's path to the answer.

In 1668, I. Newton developed the first reflective optical telescope, also called Newton telescope, and a window was opened for large aperture telescopes, based on which, we could see the Universe further and clearer. In 1789, the British scientist F. W. Herschel developed the first reflective optical telescope with aperture larger than one meter. Using this large telescope, he discovered Uranus and its two moons. As the increase of our requirements on observing further and weaker targets, the aperture and optical performance of the telescope become the main limitations of the applications of optical remote sensing in planetary science. Until the middle of the 20th century, benefited from the breakthroughs in optical techniques, such as the fabrication of high-accuracy large aperture mirrors, the maturity of optical aberration correction technology, the development of opto-electronic detectors, and the applications of active optics and adaptive optics, the ground-based large aperture optical telescopes have greatly advanced, and many new results were obtained. For example, the discovery of Na and K in Mercury atmosphere, the discovery of large amount of CO_2 in the Venusian atmosphere, the discoveries of CO_2, H_2O, and CH_4 in Martian atmosphere, the discovery of neutral nebula and Io plasma torus around Jupiter.

Nowadays, even the aperture of the ground-based optical telescope has achieved tens of meters (e.g., the Extremely Large Telescope currently under construction by European Southern Observatory), our vision is still limited by the atmospheric envelope. First, due to the absorption and attenuation of the atmospheric gases, observations at many wavelengths are unavailable, such as wavelengths shorter than ultraviolet (UV) and specific absorption bands in infrared (such as H_2O, O_3, CO_2, CH_4). Second, atmospheric turbulence greatly limited the resolution of the telescopes and diffraction-limited imaging is difficult to be achieved even with adaptive optics. Third, the atmospheric background emissions limited the observable time and the detectable weakest emission. The best way to escape from the constraints of the atmosphere is to go above the atmosphere, e.g., in the stratosphere or in the space.

In the 1960s, the stratospheric balloons have been used to observe planetary atmospheres. When a balloon floats above 35 km from the surface, it rises above 99.5% of the atmosphere, all of the telluric water vapor, and almost all of the CO_2 and CH_4, the radiations at the wavelengths from near-UV (200–400 nm) to far infrared (tens of micrometers) become detectable, and the conditions are like space in some regards. Moreover, influence of atmospheric turbulence becomes negligible, diffraction-limited imaging can be utilized for telescopes of several meter aperture, allowing for a marked improvement in the observation resolution. Although the daytime sky brightness is much brighter in the stratosphere but may still allow daytime observations, particularly at long wavelengths and at angles away from the Sun. In 1964, Bottema et al. determined the amount of water vapor presented above the reflective cloud layer on the Venus using an automatic daytime telescope of 30-cm aperture carried by balloon to 26.5 km. Currently, more and more attentions have been paid to balloon-borne planetary explorations, for example, the Scientific Experimental system in Near SpacE (SENSE) program in China, the European Stratospheric Balloon Observatory (ESBO) program in Europe, the Fujin program in Japan, the Balloon Rapid Response for ISON (BRRISON) mission in the United States.

The development of space technologies since the 1950s completely set the optical remote sensing free in space and the scientists and engineers have taken the remote sensing play the most incisive. Theoretically, all the wavelengths can be detected, and high-resolution diffraction-limited imaging can be realized. Compared with traditional in-situ particle and field detections, optical remote sensing is sensitive in characterizing matter compositions and overcomes the difficulties of capturing global views and distinguishing spatiotemporal variations. Therefore, optical payloads including photometer, spectrometer, spectrograph, and imager have been widely carried on almost all the planetary spacecraft. These different types of instruments greatly helped us uncover the secrets of planets that are shaded by the terrestrial atmosphere.

Benefited from the first upsurge of the international deep space exploration in the 1960s–1970s, a new and interdisciplinary discipline, the planetary science, is established developed in western countries. Planetary science is the scientific investigations of the basic characteristics and the formation and evolution processes of the planets, moons, comets, asteroids and other minor bodies of the solar system, the exoplanets, and the planetary systems [1]. A planet is a multilayer coupling system that contains (not completely and not limited) interior, surface, atmosphere and space. The Earth is the planet with the most complete spheric layers and is the only planet with life in the solar system. The interior and geological processes generate the atmosphere above the planetary surface and extends to space.

In this chapter, logical understanding of principles and applications of optical remote sensing in planetary science is delivered. The planetary space environment will be briefly introduced in Section 2. Then, the principles of optical remote sensing and the planetary optical radiations will be introduced in detail in Section 3, followed by current and future optical remote sensing plans in China in Section 4. Finally, a summary and outlook will be present in Section 5.

2. What is planetary space environment?

The space surrounding the Earth and other planets, the space between planets, and the space between stars and planets are far different from the environment we regularly experience on Earth. It is not empty and far from calm. It's a complex electromagnetic system in which variational magnetic fields generate electric currents and vice versa, while neutral or charged particles of different energy experience complex dynamics in the electromagnetic field. Particle and electromagnetic radiations continuously blowing from the sun (or a star), cosmic rays outside the solar system (or an extrasolar planetary system), and the planets themselves (e.g., planetary magnetic fields and even planetary weather) can cause changes in the system. Understanding the forces that drive the changes in space environment of our planet Earth and other planets not only help us protect technology and astronauts from radiation hazards, but also help us understand what makes a planet habitable. Incubation of lives on a planet takes more than just the right distance from a star. The star's interaction with the planet's atmosphere and electromagnetic system can make all the difference between a planet that's too dry, too hot, or too radiation-filled versus one where life could take root.

Generally, the space above the surface of a planet can be regarded as planetary space environment. The broad topic of physics of planetary space environment, designated planetary space physics, a subdiscipline in planetary science, focuses on the particles and fields within the space regions of the solar system and its immediate vicinity. For planets and moons, the space regions specifically refer to the neutral upper atmosphere, the ionosphere, the magnetosphere and the interplanetary space. Usually, planetary space research does not extend downward into the thick lower atmosphere of planets and moons, which is traditionally relegated to the realm of meteorology. Nevertheless, the planet is an integrated system, in which its multi-spheres are coupled, from the space to the inner core. Therefore, in the perspective of planets' evolution, we should treat the planets and their space environment as a whole system. Optical remote sensing can be applied to every aspect of this system, e.g., planetary geological activities, atmospheric activities and space plasma activities.

In the solar system, the planets can be divided into different categories according to variety criteria, for example, the terrestrial planets (Mercury, Venus, Earth and Mars) which are also called rocky planets, and Jovian planets (Jupiter, Saturn, Uranus, Neptune) which are also called gas giants. The planets can also be divided into two categories, one for magnetized planets with intrinsic dipolar magnetic field (Mercury, Earth, Jupiter, Saturn, Uranus, Neptune, and the largest moon of Jupiter, the Ganymede), the other for unmagnetized planets without intrinsic dipolar magnetic field (Venus and Mars). The space environments of magnetized planets, unmagnetized planets, asteroids and comets exhibit significant differences [2].

For the space environment of magnetized planets, the Earth has representativeness most. A schematic illustration of the terrestrial magnetosphere is shown in **Figure 1**. The magnetospheres of other planets with intrinsic magnetic field are similar but with different spatial scales decided by the magnetic field strength (**Table 1**, summarized from reference [2]). The magnetosphere, the region dominated by the planet's magnetic field, is a part of dynamic, interconnected system that responds to solar, planetary, and interstellar conditions. On the sun-facing side, or dayside, constant bombardment by the solar wind compresses the magnetic field and forms a magnetopause at a distance of about six to 10 times the radius of the Earth, depending on the activity of solar wind. On the nightside, the magnetosphere stretches out into an immense magnetotail, which can measure hundreds of Earth radii.

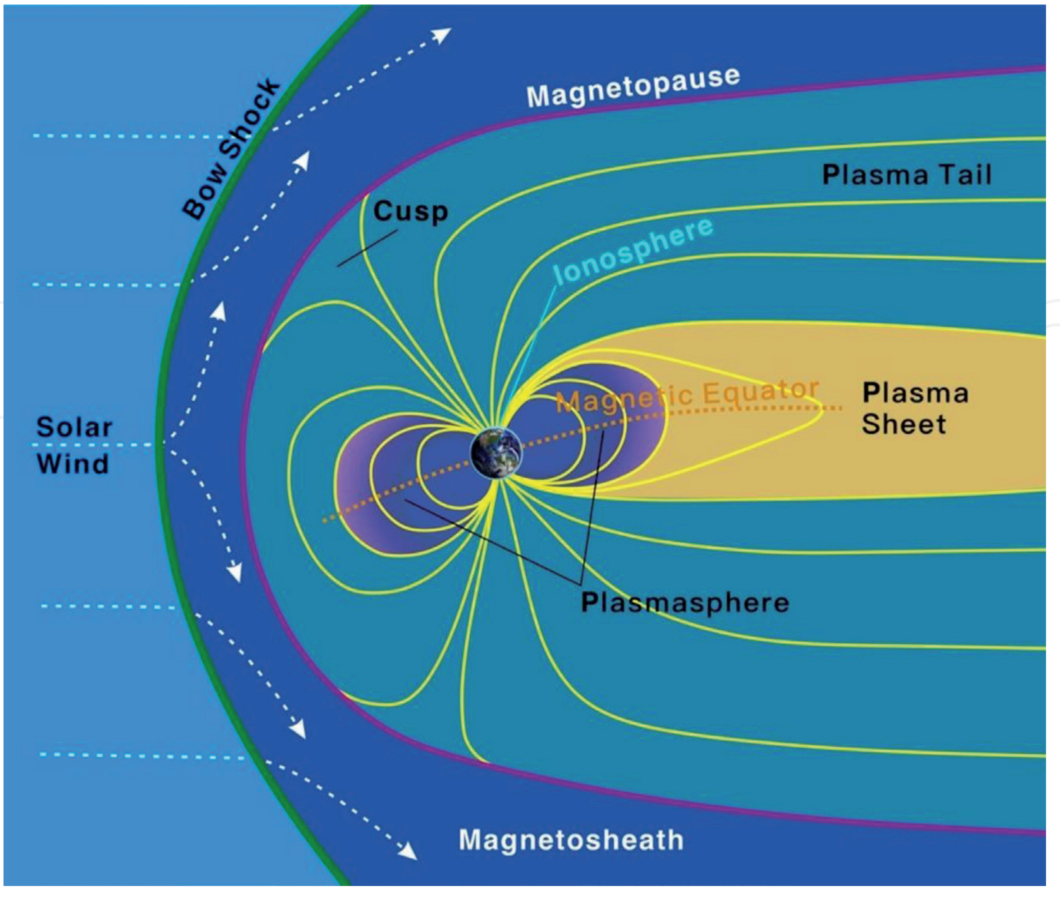

Figure 1.
Illustration of the Earth's space environment.

Parameters	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Distance (AU)[a]	0.31–0.47	0.723	1	1.524	5.2	9.5	19	30
Radius, R_P (km)	2,439	6,051	6,373	3,390	71,398	60,330	25,559	24,764
Surface pressure (atm)[b]	<10–14	90	1	0.006	> > 1000	> > 1000	> > 1000	> > 1000
Magnetic moment (M_{Earth})[c]	4 × 10–4	—	1	—	20,000	600	50	25
Surface magnetic field, B_0 (nT)	3×10^2	<2	3.1×10^4	<10	4.28×10^5	0.22×10^5	0.23×10^5	0.14×10^5
Solar wind density, ρ_{SW} (cm^{-3})	35–80	16	8	3.5	0.3	0.1	0.02	0.008
Magnetopause nose distance (R_{MP})[d]	1.4–1.6	—	10	—	42	19	25	24
Plasma density (cm^{-3})	~1	—	1–4000	—	>3000	~100	3	2
Composition	H+	—	O+/H+	—	O^{n+}/S^{n+}	$O^+/H_2O^+/H^+$	H+	N+/H+
Dominant source	Solar wind	—	Ionosphere [e]	—	Io	Rings and moons[f]	Atmosphere	Triton
Time scale	Minutes	—	Days/Hours [e]	—	10 ~ 100 days	30 days–years	1–30 days	~ 1 day
Plasma motion	Solar wind drivent	—	Rotation/Convection [e]	—	Rotation	Rotation	Solar wind/rotation	Rotation

[a] *1 AU = 1.5 × 10^8 km.*
[b] *Refence to planetary fact sheet: https://nssdc.gsfc.nasa.gov/planetary/planetfact.html.*
[c] *Normalized to the magnetic moment of the Earth, $M_{Earth} = 7.906 \times 10^{15}$ T m^3.*
[d] *$R_{MP} = (B2\ 0/2\mu_0\rho_{SW}u^2)^{1/6}$ for typical solar wind conditions of ρ_{SW} given above and u ~ 400 km s^{-1}. For outer planet magnetospheres, this is usually an underestimate of the actual distance.*
[e] *The dominant source inside the plasmapause is the ionosphere [3] and is mainly controlled by the corotation electric field with time scale of days. Outside the plasmapause, the dominant source is solar wind and is controlled by solar wind-driven convection electric field with time scale of hours.*
[f] *Enceladus, Tethys, and Dione.*

Table 1.
Parameters of planetary magnetosphere in solar system.

The dipolar configuration of the Earth's magnetic field acts like a huge magnetic bottle, within which many charged particles are confined [2]. The motion of charged particles in the geomagnetic field is complicated, but can generally be divided into three types, namely gyration around a field line, bouncing between mirror points on the opposite side of the magnetic equator, and drifting around the Earth – westward for ions and eastward for electrons – due to the longitudinal gradient of the field lines. According to the energy and origin of the particles, the magnetosphere can be divided into several typical regions, namely, from inner to outer, the plasmasphere, radiation belt, ring current, plasma sheet, plasma tail in the case of Earth (**Figure 1**).

3. Optical remote sensing

3.1 Principle of optical remote sensing

Optical remote sensing is a remote detection method that studies an object through its optical emissions without coming into direct contact with it. Generally, optical remote sensing can generally be categorized into three types, i.e., imaging, spectrometry, and spectrographic imaging, as illustrated in **Figure 2**. The imaging, just likes we see the world through our eyes, directly project the radiations in the three-dimensional (3D) space to a two-dimensional (2D) detector. A filter with narrow band or wide band is used to select the wavelengths that can be recorded by the detector. The advantage of imaging is to separate the spatial and temporal variations in a certain time scale, and the spatial distribution of a specific composition that emit radiations at specific wavelength can be captured in a large scope of space. Therefore, imaging is the preferred method to investigate global spatiotemporal evolutions. The spectrometry, which split the incident radiations into single wavelengths through a dispersion element (e.g., prism) or an interferometer to measure the wavelength dependence of the incident radiations. Generally, such observation does not have spatial resolution and only single 'point' (Here, 'point' means a spatial region covered by the field of view of the spectrometer but not a geometrical point.) measurement can be realized, but the advantage is to identify different compositions or different

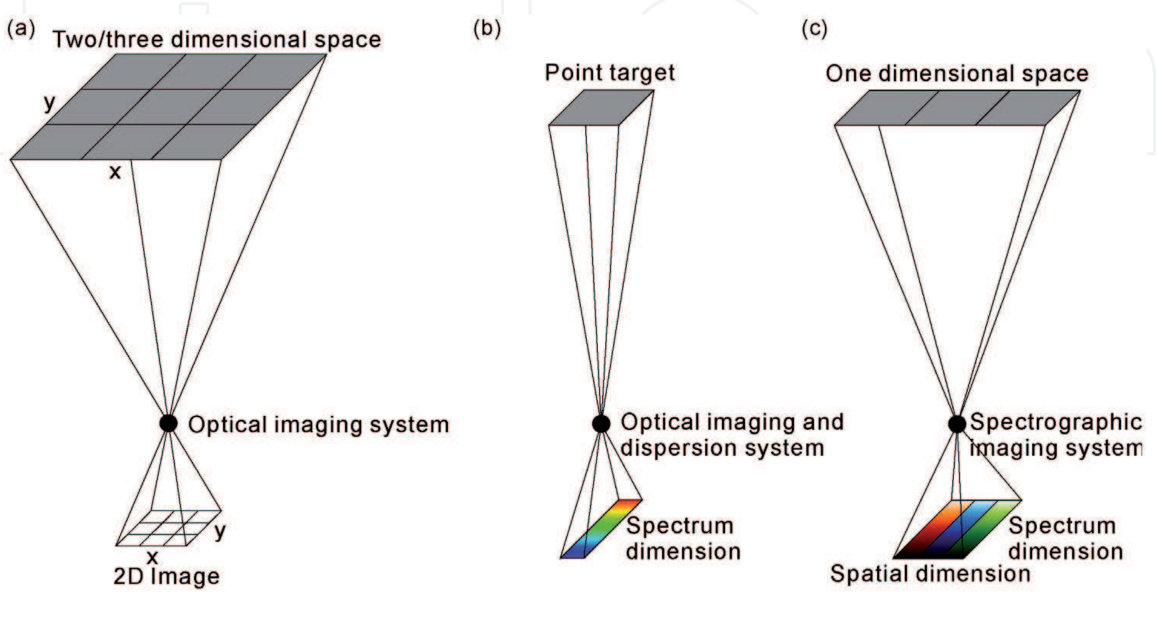

Figure 2.
Three typical methods of optical remote sensing (adapted from He, 2020). (a) Imaging. (b) Spectrometry. (c) Spectrographic imaging.

states (such as temperature and velocity) of a specific composition. Therefore, spectrometry is the primary measure to detect chemical composition and property in space. The spectrographic imaging, which integrated the advantages of imaging and spectrometry, can capture both spatial information (usually a line of view) and spectral information. Equipped with scanning mechanism, spatial coverage can be realized. In a global view, although the temporal resolution is reduced, the quasi-simultaneously captured spatial and spectral information is critical in global large-scale investigations.

The optical remote sensor is usually composed of an optical system that collect radiations and a detector that record the radiation through a photoelectric conversion, so we can analyze the digitalized signals to retrieve the physical information of the targets. The main performance indicators for an optical remote sensor include (not limited to the following indicators depending on different applications):

Field of View (FOV): the object space covered by the sensor. The larger the field of view, the larger spatial coverage. The spatial coverage can be calculated once the field of view and the distance to object are known.

Focal Length (*f*): the distance between the image point of infinity object and the principal plane of the optical system.

Operation Wavelength (λ): the wavelength range that the sensor can response. It is usually determined by a combination of the reflectivity of the mirrors, the transmission of the filters, and quantum efficiency of the detector. For spectrometric instrument, it depends also on the property of the dispersion elements (e.g., grating and prism).

Angular Resolution ($\Delta\theta$): the ability of the optical system to distinguish the image speckles of two objects. The diffraction-limited angular resolution $\Delta\theta$ is determined by the Rayleigh Criterion, $\Delta\theta=1.22\lambda/D$, where D is the aperture of entrance pupil.

Pixel Resolution (Δp): the angle corresponding to a pixel of the detector, $\Delta p = 2\tan(d/2f)$, where d is the size of the pixel and f is the focal length of the optical system. The angular resolution refers to the spatial resolving power of the optical system, while the pixel resolution is based on the physical pixel size of the detector. In actually optical design, the angular resolution and pixel resolution should be matched according to the radiation intensity and the requirement of signal-to-noise ratio (SNR). According to the Nyquist Criterion, two physical pixels are usually needed to resolve an optical resolution unit.

Area of Entrance Pupil (A): the area of the image of the aperture stop to the preceding optical system. The entrance pupil determines the size of the aperture of incident beam and thus determines the radiation energy that enter the optical system.

Spectral Resolution ($\Delta\lambda$): the ability to resolve radiations at different wavelengths.

Illumination Uniformity: the uniformity of the response of optical system (including the detector) to uniform incident radiations. Due to the aberration of optical system and manufacturing error of the optical elements, the detector response is nonuniform though out the image plane, and such nonuniformity should be measured during calibration process of the sensor. The calibrated matrix can be used to correct the scientific data.

Pixel Sensitivity (S): the ability of the response of the sensor to radiation intensity change. Commonly, the definition of S (in unit of count s^{-1} Rayleigh^{-1} pixel^{-1}) in space environment remote sensing is that, for an incident beam that fulfill entrance pupil with unit intensity (in Rayleigh, 1 Rayleigh = $10^6/4\pi$ photon cm^{-2} s^{-1} sr^{-1}), the count number or signal strength on the detector is $S(\lambda) = 10^6 A\Omega\eta(\lambda)/4\pi$, where A is the area of entrance pupil in cm^2, is the solid angle corresponding to a pixel in sr, and $\eta(\lambda)$ is the transmission efficiency of the system.

Exposure Time (ΔT): the integration time to acquire image with sufficient SNR.

Calibration Accuracy: the calibration of an optical sensor includes geometric calibration and radiometric calibration. The geometric error of an optical sensor originates from both the distortion of the optical system and the alignment error. The objective of geometric calibration is to accurately determine the projection relationship between pixel and geometric space. Usually, this can be achieved by imaging standard grid in laboratory. Radiometric calibration includes relative radiometric calibration and absolute radiometric calibration. The relative calibration is to measure the illumination uniformity of the sensor and the absolute calibration is to measure the pixel sensitivity of the sensor. Both are critical to retrieve the emission intensity of target from the optical images.

The above-mentioned indicators are common in general planetary optical remote sensing missions, some specific environmental adaptation indicators must be considered in specific application scenario, for example, the level of stray light, the ability of energetic particle shielding, and temperature dependence.

3.2 Optical radiation mechanisms

Optical emissions in space environment are the basis of remote sensing. Variations of the emissions reflect the physical property of the radiator. Understanding of the physical process of optical emission is developed after the establishment of quantum mechanics. The typical emission mechanisms for atoms, molecules, and ions are illustrated in **Figure 3**. The trigger of the emission is external energy, including optical radiation, particle collision, vibration and rotation (molecules and molecular ions), that excite the electron from ground state to higher energy state, the subsequent transition of electron to ground state emit a photon with the wavelength determined by the energy difference between the two states. The transition rate, intensity of spectral line, shifting of spectral line and broaden of spectral line can be determined by the density, temperature, and velocity of the radiator. It is noted that the mechanisms illustrated in **Figure 3a-h** mainly occur in the sunlit region. In the dark region, the emissions are primarily due to chemical reactions between different compositions. The collision charge-exchange process usually occurs in planetary magnetosheath region, between the energetic ions and low energy neutral atoms. For example, the collision between the hot solar wind charges particles (e.g., He^{2+}, O^{6+}) and the geocoronal neutral hydrogen generated EUV and soft X-ray emissions in the terrestrial magnetosheath and cusp regions [5], and in the dayside Martian ionosphere [6]. Besides, there is a special emission mechanism in the cusp region of the Earth's magnetosphere, the bremsstrahlung, also called the braking radiation, which happens when energetic electrons brake in an increasing magnetic field. Specific radiation properties in planetary space environment will be introduced in the following sections.

3.3 Radiations of planetary atmosphere

Planetary atmosphere, which originates from the planet, is controlled in different degrees by external sources (e.g., solar activity) and internal sources (e.g., surface and interior) and exhibits diverse complicated variations. Planetary atmosphere is composed of different gases of atomic, molecular, and ionic states, some are active under the effect of sun light and thermal radiation, some are noble compounds (e.g., noble gas), some are chemical active (react with other chemical compositions), and some are compressible gases. The spatiotemporal variations of the atmospheric composition depend on a variety of factors, and this determines the distribution of energy sources within the atmosphere, for example, deposition of solar radiations induce vertical heating, infrared thermal radiations induce cooling, albedo difference due to land or sea results in horizontal distribution.

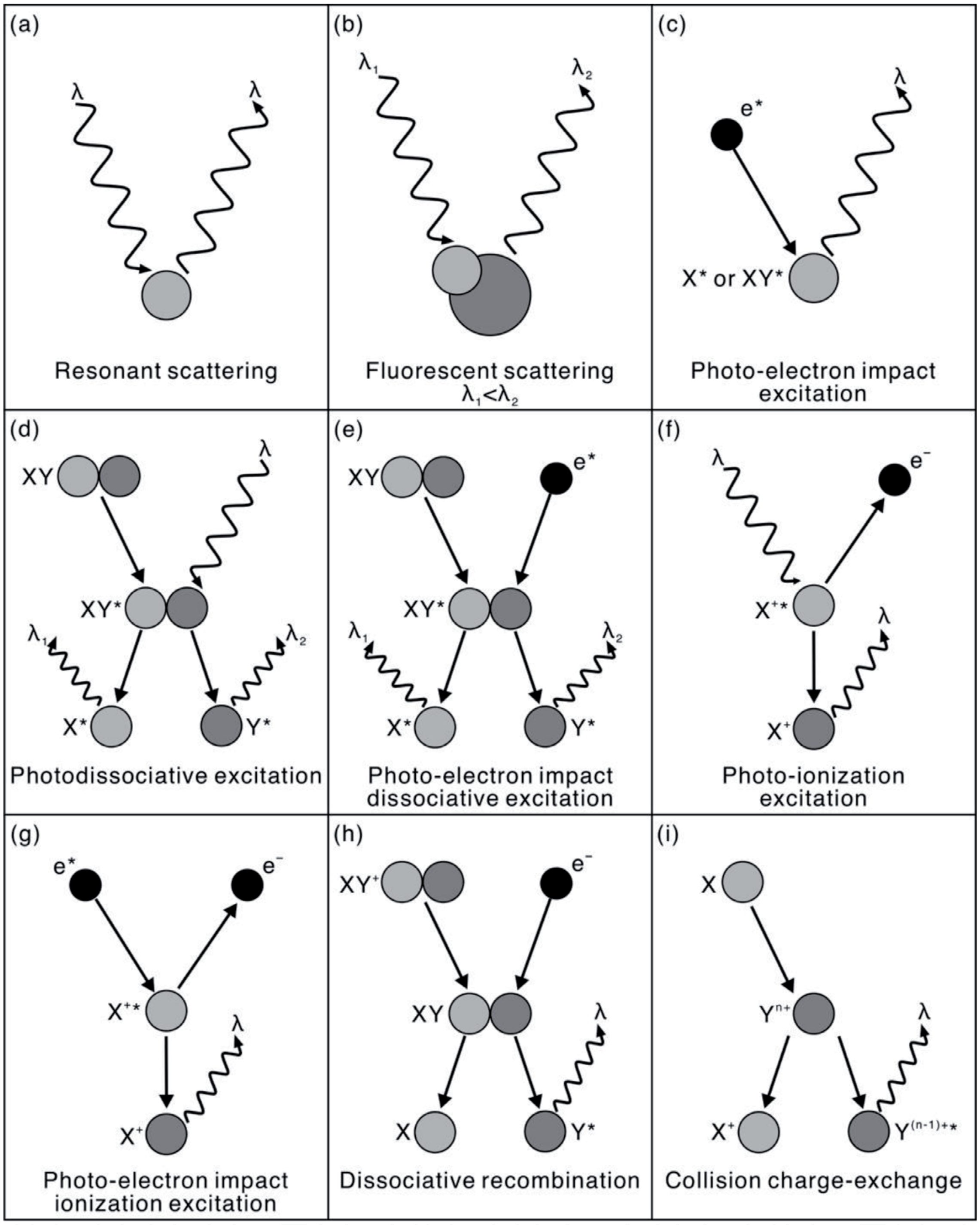

Figure 3.
Typical emission mechanisms in space environment. λ, λ_1, and λ_2 are the wavelength of the incident or emitted photons. X and Y are atoms; XY is a molecule; X^+, Y^{n+}, or $Y^{(n-1)+}$ is an positive ion; and e- and e are electrons and photon electrons, respectively. X*, Y*, XY*, X^{+*}, and $Y^{(n-1)+*}$ is an atom/molecule/ion in an excited state. Modified from reference [4]. From a to i, shown are emission mechanisms of resonant scattering, fluorescent scattering, photo-electron impact excitation, photodissociative excitation, photo-electron impact dissociative excitation, photo-ionization excitation, photo-electron impact ionization excitation, dissociative recombination, and collision charge-exchange excitation, respectively.*

Based on ground-based telescopes, circling or flyby spacecraft, using spectrometric and occultation technologies (solar occultation, star occultation or spacecraft occultation), the atmospheric composition can be determined. In combination of *in-situ* mass spectrometer, the composition of planetary atmosphere can be accurately determined (even the isotopic level). When sufficient observation samples are obtained, the spatiotemporal distribution of the active compounds in the atmosphere can be determined. Using more advanced spectrographic imaging technology, the atmospheric compositions and their spatiotemporal variations can be obtained simultaneously to investigate the atmospheric dynamics. The basis for optical remote sensing is the continuous spectrum and discrete spectrum of the planetary atmosphere.

The continuum spectrum of a planet, from X-rays to radio wavelength, originates from a combination of its surface, atmosphere, and space plasma. The continuum spectrum is composed of two parts. The first part is the reflected spectrum of the sunlight radiation (or from star for exoplanets) by the gases and particles in the atmosphere and by the surface with typical wavelengths ranging from UV to near infrared (0.4–10.0 μm), where the Sun and stars have their emission peak according to the Wien's Displacement Law. The second part is the thermal radiation spectrum originated from the radiative flux emitted by the planet with typical wavelengths ranging from infrared to microwave (>1–10 μm), depending on the body temperature. The continuum spectrum can be obtained by the summation of a diffuse blackbody mirror of the star spectrum and the blackbody of the thermal spectrum. Typical spectrum of a planet is shown in **Figure 4**. The spectrum for various planets are significantly different due to the factors such as the distant to the star, the atmospheric composition, and the temperature of the planet. At short wavelengths (mainly UV and visible), excitations of atoms, molecules, or ions in the atmosphere by the absorption of solar photons or the precipitation of particles generate emission spectrum (e.g., fluorescent emission and aurora phenomena). At radiofrequencies, the planetary emission is dominated by nonthermal processes occurring in planetary magnetic field, mainly by electrons gyrating in spirals along magnetic field lines, for example, the synchrotron emission in the case of Jupiter.

The discrete spectrum also contains two parts. On the one hand, emission lines are produced by atoms, molecules, and ions excited by a variety of physical and chemical processes. On the other hand, the absorption lines and bands are produced by atoms and molecules. The emission lines and absorption lines and bands are the 'fingerprint' of atmosphere. Specific lines may indicate the existence of corresponding chemical compounds or certain states of atoms and molecules. Therefore, such 'fingerprint' is usually used to discovery and identify the specific composition

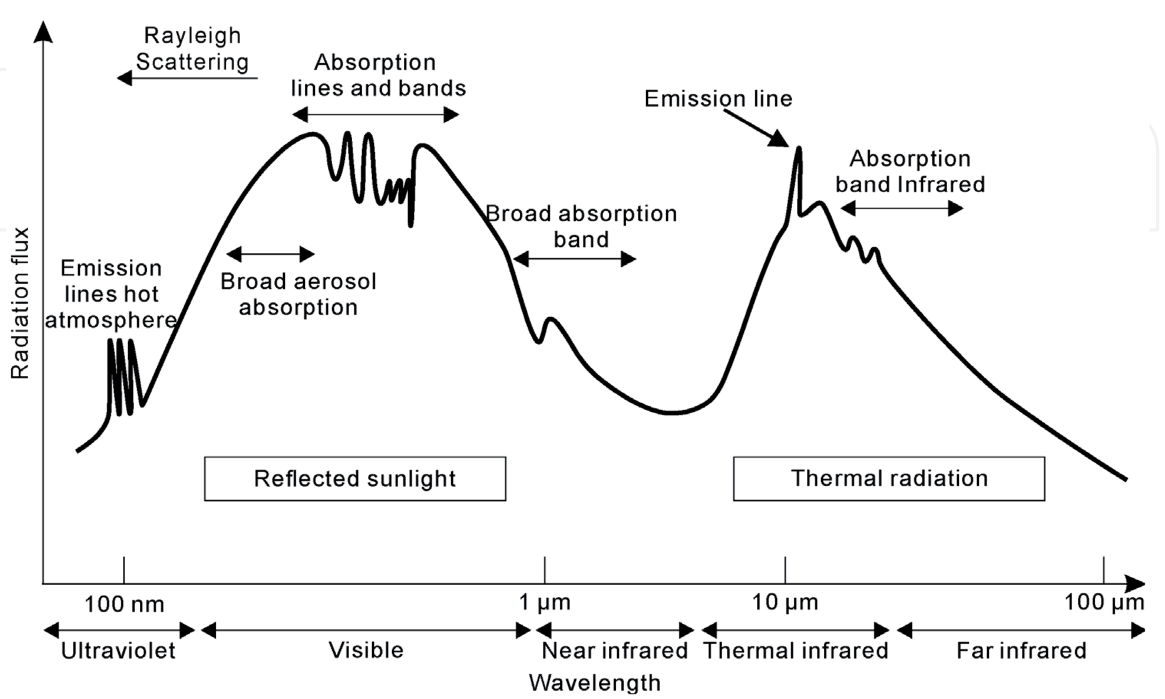

Figure 4.
Typical spectrum of a planet with atmosphere [7].

and its amount in an atmosphere. For example, the discovery of H_2O and CH_4 in Martian atmosphere.

Specifically, the spatiotemporal distribution of certain tracer composition can be obtained through imaging at corresponding narrow band emission lines to investigate planetary atmospheric dynamics. For example, the airglow emissions of atomic oxygen at 557.7 nm and 630.0 nm are widely used to investigate the dynamics of thermosphere and ionosphere and the auroral physics.

3.4 Radiations of planetary space plasmas

The X-ray and UV radiations from the Sun or the stars ionize the upper atmosphere of a planet, the ions and electrons form a quasi-stable plasma distribution in planetary space (e.g., ionosphere, plasmasphere, radiation belt, and plasma sheet in the case of Earth) under the combined effects of solar wind, planetary rotation, intrinsic magnetic field, and other factors. Due to the different physical properties of planets, especially the different configurations of intrinsic magnetic field and the different distances to the Sun or the stars, the plasma composition, energy, distribution, and activity exhibit large distinction (**Table 1**). The most significant manifestation of such distinction is that, under the drives of solar wind disturbances and/or internal sources of planetary system, the plasmas exhibit global or local flow, acceleration, and loss, and thus resulting in mass transportation, energy deposition/dissipation processes with different temporal/spatial scales. The strong interaction between the plasmas trapped by planetary magnetic field and the atmosphere leads to the heating of upper atmosphere, generation of neutral wind, ionization of neutral gasses. Energetic ions and electrons that precipitate into the atmosphere remarkably modify the atmospheric chemistry. During the evolution process of a planet, interaction between plasma and neutral atmosphere significantly contributes to the isotopic fractionation. Bombardment of energetic particles on the surface of planet and its moons will obviously modify the surface property and change the albedo and spectrum characteristics. Traditional *in-situ* field and particle detections are difficult to capture the global view of the mass and energy transportation and are also hard to separate the temporal and spatial variations of the space plasmas, thus limited our understanding of the global coupling dynamics. Optical remote sensing is an important method to overcome these difficulties.

In geospace, in most of the magnetospheric region from the ionosphere to the magnetosheath, plasmas of different property have their characteristic optical radiation. Optical imaging at different wavelengths can be used to answer different scientific questions. For example:

1. EUV and soft X-ray emissions in the terrestrial magnetosheath and cusp regions. Collision charge exchange between the solar wind He^{2+} and geocoronal atomic hydrogen emits photons at 30.4 nm, and when the same process happens between the highly charged heavy solar wind ions (e.g., O^{7+} and C^{6+}) and geocoronal atomic hydrogen photons in X-ray are emitted [5]. Global imaging of the magnetosheath at 30.4 nm and X-ray can visualize the three-dimensional structure of the bow shock and magnetopause, reveal the dynamical process of the entry of solar wind mass and energy into the magnetosphere through the solar wind-magnetosphere interaction, and provide accurate input for the prediction of near-Earth space weather.

2. EUV emissions in the magnetosphere. The plasmaspheric He^+ and the magnetospheric O^+ resonantly scatter the sunlight at 30.4 nm 83.4 nm,

respectively [3, 5, 8]. Global imaging of the plasmasphere and the magnetosphere at 30.4 nm and 83.4 nm can visualize the large-scale convection in the magnetosphere and reveal the dynamic variation terrestrial matter.

3. Auroral emissions in polar region. The auroral oval is a projection of solar wind/magnetosphere energetic particles along the geomagnetic field lines. The precipitated energetic particles collide with atoms, molecules and ions in the upper atmosphere and generate auroral emissions in wavelengths from X-ray to near infrared (the X-ray is generated by energetic electrons through bremsstrahlung) [8]. Multi-wavelength global imaging of the aurora oval can be used to establish the relationship between auroral activity and space mass/energy transportation, break through the limitations of *in-situ* measurements.

In the space environment of other planets, optical remote sensing can also be used to obtain the global image. For example:

1. The solar wind particles bombard the Mercury surface to sputter out sodium atoms. The following interaction with the solar wind generates a sodium exosphere and a sodium tail downstream of Mercury as long as 1,400 Mercury radii. Global images at the sodium doublet (589.0 nm and 589.6 nm) [9] can be used to investigate the solar wind sputtering process and the global dynamics sodium exosphere and tail.

2. Under the effects of solar radiations and energetic particles, photochemical, collision, and other processes excite EUV-UV–Visible emissions in Venusian atmosphere and ionosphere [10], which can be used to investigate the evolution characteristics of Venusian space environment and the interaction between solar wind and planet without intrinsic magnetic field but dense atmosphere.

3. In the case of Mars, the charge exchange collision between solar wind energetic protons and neutral hydrogens emits photons at 121.6 nm, other emission mechanisms illustrated in **Figure 3** can generate O^+ 135.6 nm line, CO+ 2 UV emission bands, O 557.7 nm line, and other bands [6, 11], which can be used to investigate the interaction between solar wind and planet with local crustal magnetic field and thin atmosphere and the global view of Martian atmospheric escape.

4. The mass released from the volcanic activity of Io, the first moon of Jupiter, forms a plasma torus at ~7 R_J (Jupiter radii) in Jovian magnetosphere. The Io plasma torus controls the dynamics of Jupiter's magnetosphere and only optical imaging can capture its global evolution picture. Coordinated with X-ray and far UV imaging of Jupiter aurora, we can investigate how Io's volcanic activity affects the magnetospheric plasma source, as well as the subsequent evolutions. The operational wavelengths include 673.1 nm (S^+), 68.5 nm and 953.1 nm (S^{2+}) in Io plasma torus, sodium doublet in Jupiter's neutral nebula, and the X-ray to far UV auroral emissions [12–15].

5. Like the Jupiter system, the space environment of Saturn system is also affected by geological activities of its moons. The rings and the water erupted from Enceladus are the main plasma sources in Saturn's magnetosphere. Optical imaging of the O^+, H_2O^+, and other water-based ions at EUV-UV wavelengths can be used to investigate how Enceladus's geological activity affects the magnetospheric plasma source, as well as the subsequent evolutions.

3.5 Radiations of planetary geological activities

Geological activity of planet and its moons plays a key role in the evolution of the planetary system. Planetary geology research helps to understand the formation and evolution of celestial bodies in the solar system, deeply understand the evolution of the Earth, and reveal the origin and evolution of life on the Earth [16]. Compared with traditional geological techniques, such as sample analysis, analogy study, and simulation, remote sensing is of great importance to the acquisition of matter composition, structural characteristics, geological history and so on.

Measurements of the planetary thermal radiation intensity in infrared can be used to obtain the temperature and composition of planetary atmosphere and surface, the thermal moment, and the property and evolution of planetary surface. The reflected spectrum in visible to infrared range can be used to obtain the chemistry, mineralogy (silicate) and regolith maturity of surface, the surface geology, and the degree of planetary differentiation. Imaging and spectrographic imaging at UV, visible and infrared can be used to obtain surface properties, relative age, surface action, and history of the planet. With a laser altimeter or a synthetic aperture radar, the surface relief can be acquired. In combination with gravitation data, the isostatic action can be inferred. With a UV–visible photometer, the matter property of planetary surface can be obtained, and the surface composition and differentiation can be induced. The X-ray and gamma ray spectra can be used to measure the abundance of K, U, Th, and other elements that are bombarded by cosmic rays to induce the surface composition, property, thermal history, and differentiation of a planet. Finally, the combination of spectrum and imaging of different wavebands can provide a more detailed study of the geology, origin, and evolution history of planets.

3.6 Optical signals of life

As an important research field in planetary science, the astrobiology mainly focuses on the origin and evolution of life on Earth and other solar system bodies and the exploration of potential distribution and future trend of life in the universe. This field involves astronomy, geology, life science, and other disciplines, and the subjects include the origin and early evolution of life on Earth, search and study of habitable planets (environment) and potential life forms, co-evolution of life and environment, and artificial construction of habitable environment [16–18]. Search for signs of life on planet always lies in the core of planetary science. The most direct way, of course, is collection of life samples. However, no life sample was found on the extraterrestrial celestial bodies that human spacecraft have visited. Discoveries of water and methane on Mars have greatly stimulated the desire of search for life on Mars in the past decades. The paleolakes or paleo-oceans on the Mars and liquid oceans on Europa and Enceladus have pushed the search for extraterrestrial life to the core of planetary exploration.

Beyond the solar system, in places where human spacecraft cannot currently reach, such as exoplanets, the only reliable way to search for signs of life is remote sensing. For thousands of years, human beings have been trying to figure out whether they are the only intelligent beings alone in the universe. The 2019 Nobel Prize in physics awarded M. Mayor and D. Queloz who discovered a planet outside our solar system, known as an exoplanet, around a sun-like star in October 1995. This discovery is a firm step for the exploration of life on exoplanets, and it opens the door to the detection of life on exoplanets. By the end of 2020, 4,374 exoplanets have been discovered from 3,234 planetary systems. Exoplanet life can only be detected by searching for signs of life, such as organic molecules or other indicators of the presence and activity of lives, on the planet's surface or in the atmosphere. The detection of exoplanet atmosphere mainly relies on optical, UV and near-infrared bands, among which molecules related to life activities and relatively easy to be detected include O_2, O_3, H_2O, CO_2, CH_4, NO_2 and so on. Of course, even these signals are detected, other information such as the nature of the planet itself, the nature of the star, and the properties of planetary systems are needed to make a comprehensive decision. Currently, acquisition of these information mainly relies on optical methods, such as radial velocity, microlensing, transit, and imaging [19].

The radial velocity method measures the change of the radial velocity of the host star caused by the gravitational force of the planet (a Doppler effect of light) to estimate the mass of the planet. Until the Kepler space telescope was launched, it was the most effective way to identify exoplanets, including Pegasus 51b, the first exoplanet orbiting a sun-like star.

The microlensing method measures the bending and amplification of light in gravitational fields to detect objects, including exoplanets. Gravitational lensing is an optical effect predicted by Einstein's general theory of relativity. Since the foreground object passing through the background star is accidental, the application of microlensing method is also accidental and unrepeatable, which has a great impact on the accuracy of exoplanet detection. This method is particularly sensitive to the detection of cold planets (i.e., large orbital radii).

The transit method detects exoplanets and determines their size by measuring the periodically dimming brightness of a star due to the obscuration of the exoplanet in line of sight. By measuring the tiny changes in the brightness of the target star, we can detect telltale signs of an exoplanet in the light curve. The first exoplanet discovered by this method is HD 209458b, a hot Jupiter discovered in 1999. With the launch of the Kepler space telescope, transit method has become the most prolix method of finding exoplanets. By the end of 2020, more than 3,100 exoplanets have been discovered through transit method.

Direct Imaging, as the name suggests, is the direct optical imaging of exoplanets. For general main-sequence stars, the thermal radiation is mainly concentrated in the UV to near-infrared band and the peak value is between visible and UV band according to Stepan-Boltzmann's Law and Wien's Displacement Law. Exoplanets, however, do not have sufficient and stable energy sources, generally have low temperatures, and their thermal radiation is mainly concentrated in the infrared band. So, in the case of exoplanet with large radiation fluxes, we can distinguish two exoplanets by looking at infrared wavelength. On the other hand, the observation requires high performance instrument, a coronograph to block the light from the stars, and the observation system needs to be maintained at a very low temperature to reduce the infrared radiation from the instrument. In general, the direct imaging method is used to search for young Jovian planets with temperatures between 600 and 2000 K, and the peak wavelength of thermal radiation is between 1.4 and 4.8 μm. Such planets are usually far enough from their parent star with large enough surface areas and radiation fluxes and can be observed in the near-infrared to mid-infrared wavelengths.

The first exoplanet was discovered using the radial velocity method, but the method that discovered the largest number of exoplanets is transit. It is expected that transit will continue to be the most effective observation method in the next 15 years. In order to further study the nature of the atmospheres of exoplanets, especially terrestrial exoplanets, both transit and direct imaging are necessary, and the latter will be the most promising observation method in the future.

4. Strategy and plan in China

From the development of planetary science and planetary exploration for more than 400 years, no matter it is space-based or ground-based, optical remote sensing has always occupied an important position. With the development of optical, mechanical and electronic technologies, the aperture of ground-based optical remote sensing equipment has developed from a few centimeters to tens of meters, and its resolution and sensitivity have been improved by orders of magnitude. Advanced remote sensing and *in-situ* detectors carried by various satellites have made our understanding of the planetary environment reach an unprecedented height. However, it is not hard to see that in this development process, especially in the six decades since the Space Age, there has been little presence or voice of China. With the deep space exploration becoming a national strategy, planetary exploration and planetary science will become the hot spot of scientific and technological development in the future.

On January 6, 2019, the Degree Evaluation Committee of University of Chinese Academy of Sciences (UCAS) approved the plan to set up the planetary science as a first-level discipline, as proposed by the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). This plan has also been submitted to the State Council Academic Degrees Committee, who will finally approve the establishment of the new first-level discipline in China. This marks a new period of historical opportunity for the development of planetary science in China. On July 2, 2019, sponsored by the College of Earth and Planetary Science, UCAS, colleges of 27 universities established a China University Planetary Science Alliance in Beijing, targeted at establishing and improving the layout of planetary science discipline in China, perfecting the talent training and scientific research system of planetary science, promoting the coordinated development of planetary science and exploration technology. Taking this as an opportunity and relying on China's intensive deep space exploration missions to carry out ground-based, aero-based and space-based optical remote sensing of planetary space environment, it will greatly promote the integrated development of science and education in planetary science in China [20–23].

4.1 Lenghu observatory for planetary science

In order to support the science and education integration strategy of planetary science in China, it is urgent to build planetary observation facilities. Under the current situation, it is of practical significance to develop ground-based optical remote sensing for planetary science to quickly gather planetary research teams and train planetary exploration and scientific research personnel. At present, almost all optical telescopes in the world are built by astronomers, and there is no ground-based telescope dedicated to planetary science. It is imperative to build dedicated planetary telescopes in China. In China's planetary exploration roadmap, ground-based optical observation is also clearly taken as the first step [20]. To support the development of planetary science exploration and research, the IGGCAS established the Lenghu Observatory for Planetary Science (IGGCAS-LOPS) in the Lenghu Astronomical Observation Base (LAOB) in 2020. Based on the high-quality site conditions of LAOB on Saishiteng Mountain, Lenghu Town, Qinghai Province [24], the IGGCAS-LOPS will build planetary optical telescopes to carry out ground-based observation. The IGGCAS-LOPS currently has two meter-sized telescopes, the 0.8 m Planetary Atmosphere Spectroscopic Telescope (PAST) and the 1.8 m Io geological activity observatory (TINTIN).

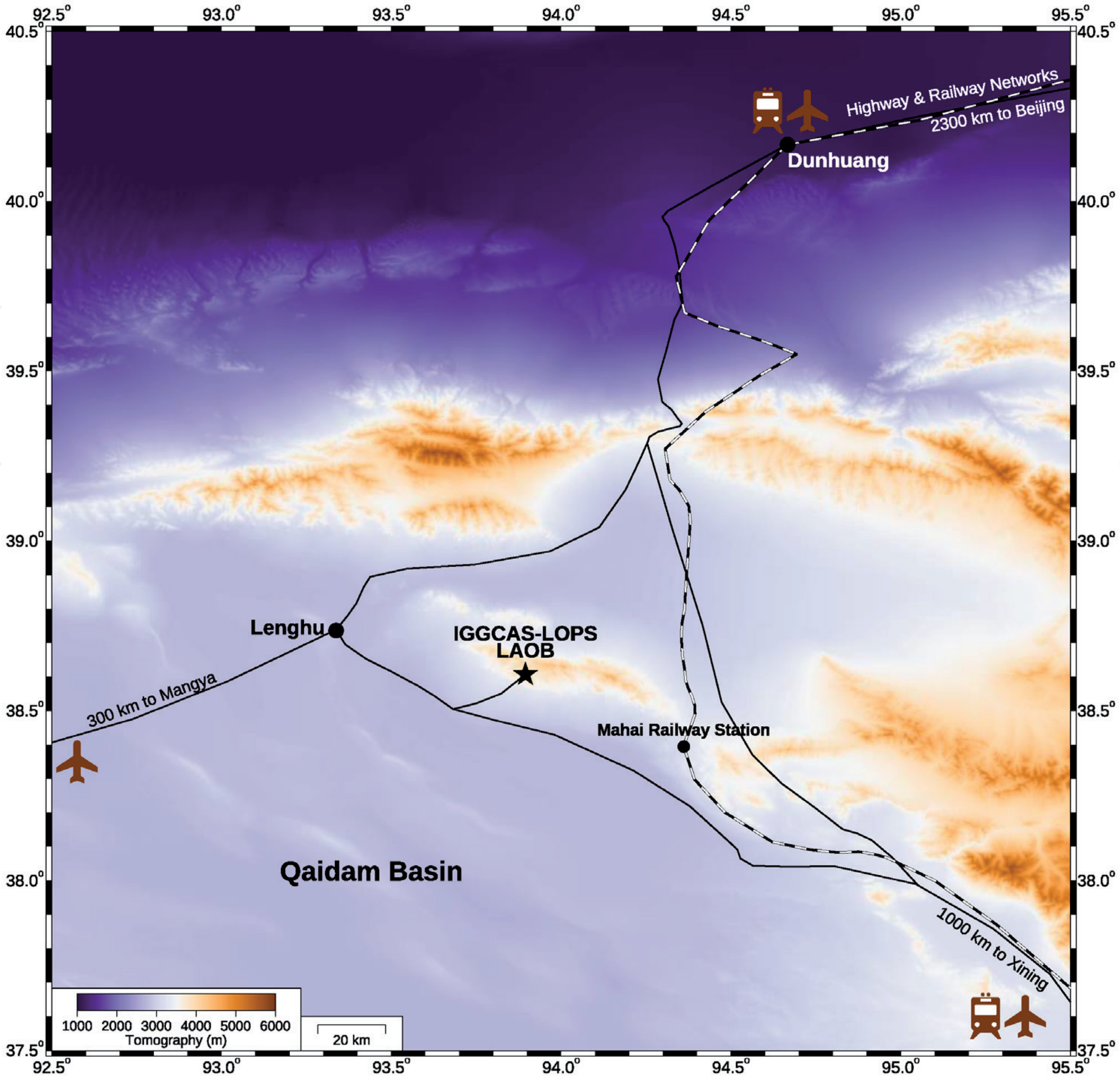

Figure 5.
Basic geographic information for the IGGCAS-LOPS in the LOAB (modified from reference [24]).

The IGGCAS-LOPS is located on the 4,200 m altitude platform of Saishiteng Mountain, about 80 km east of Lenghu Town (as shown in **Figure 5**). The environmental monitoring data since 2018 show that the platform has excellent atmospheric visibility and very good nighttime seeing [24], and it is one of the few sites in the world that can be used for optical imaging of planetary space environment. The site is also an astronomical observation base built by Qinghai Province with great efforts. Astronomy and planetary science will become the two core business cards of the base.

4.2 Telescopes at IGGCAS-LOPS

The two telescopes currently planned for the IGGCAS-LOPS are PAST and TINTIN. The PAST (shown in **Figure 6**) was a 0.8 m UV–visible telescope built with the support of the strategic priority research program of CAS, the near space science experiment system, and was developed by the Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences. The main scientific objectives of the telescope are the orbital motion characteristics, atmospheric and plasma distribution characteristics, and spectral radiation characteristics of the celestial bodies within the orbit of Jupiter in the solar system. The telescope is planned to operate on both a balloon platform and a ground station. Through

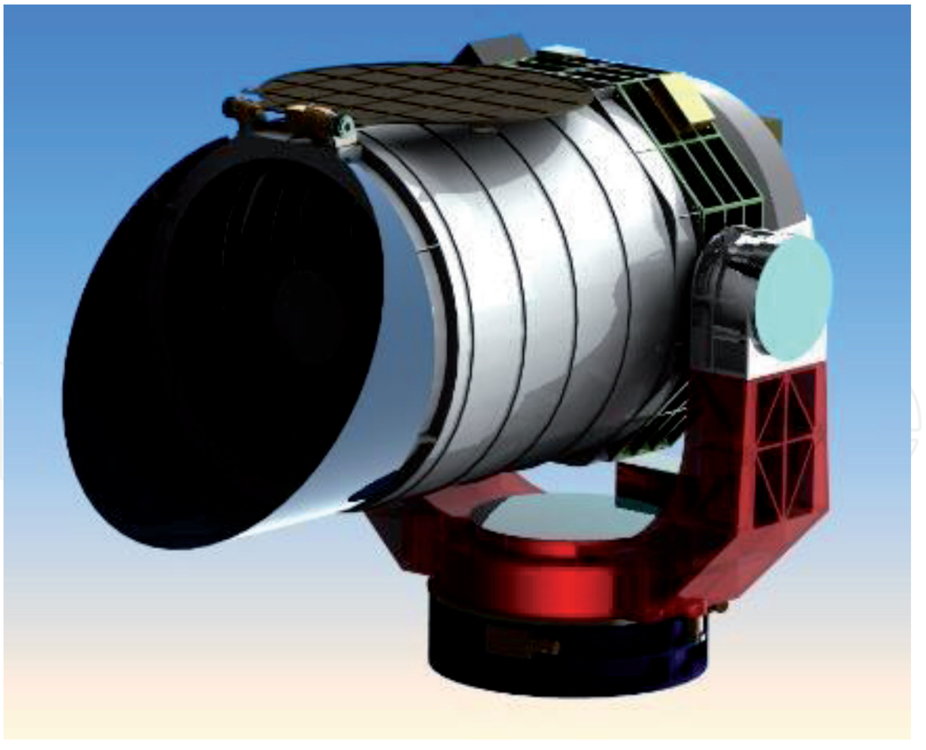

Figure 6.
Illustration of PAST.

comprehensive consideration, the key parameters of the system are determined. The aperture of the telescope is 0.8 m, the operating waveband is 280–680 nm (multiple narrowband filters), the field of view is 15′, the angular resolution is 0.5″. The telescope was also equipped with a Jupiter coronagraph, which will be able to greatly attenuate the intense radiation from Jupiter itself and observe the faint atmosphere and plasma radiation around the planet. The PAST is scheduled to be installed at the station in June 2021. Upon installation, observations of the Jupiter system will begin immediately. At the same time, it can also carry out observations of comets and small celestial bodies.

Another telescope, TINTIN, will be purchased from Germany company Astelco. The aperture of TINTIN is 1.8 m, with a spectral range of 392–1100 nm (as shown in **Figure 7**). The telescope is equipped with a scientific camera, a Jupiter coronagraph, and an echelle spectrograph. The telescope's core goals are to monitor Io's atmospheric escape from volcanic activity and the evolution of Io's plasma torus. The telescope will also be equipped with a coronagraph with a pixel resolution of 0.25″ and a FOV of 5′. The multi-scale monitoring of the evolution of mass and energy from Io's geological activity to plasma torus in Jupiter's space will be performed for the first time. The observations can be used to investigate how a moon's geological activity couples with the planetary space environment, in combination with current/future international/China's Jupiter exploration programs. The construction of the observation tower and dome will begin in summer of 2021. The overall construction of TINTIN project will be completed by the end of 2022, when scheduled observations will also begin.

The routine observations of the two telescopes will mainly be realized by remote control, which is locate at IGGCAS, Beijing. At the same time, we will also set offices in the Lenghu Town with the help of local government to support the regular and irregular operation and maintenance of the telescopes. In response to the large amount of data flow of the telescopes, two data centers will be established at IGGCAS and Lenghu Town, respectively. Both data centers will be connected to the server of the telescopes via high-speed networks to ensure that the observations can be timely delivered to the scientific teams to achieve timely scientific impact.

Figure 7.
Illustration of TINTIN.

5. Optical remote sensing images of planetary space

In this section, optical remote sensing images of planetary space environment will be briefly introduced to demonstrate different applications on different planets. Not all the planets in the solar system will be introduced here, only the Earth and Jupiter are taken as examples. For other planets, one can refer to Section 3 for detailed information.

Imaging of the Earth's ionosphere, aurora, and plasmasphere have been developed for decades. **Figure 8a-d** shows examples of the most recent ionospheric image from the Global-scale Observations of the Limb and Disk UV spectrograph (GOLD UVS), the auroral image in far UV from the wide-angle auroral imager onboard the Chinese Fengyun-3D satellite (Fengyun-3D WAI), and the plasmaspheric images at 30.4 nm from the Extreme Ultraviolet Imager onboard the Inner Magnetosphere-Aurora Global Explore (IMAGE EUVI) and the Moon-based Extreme UV Camera onboard the Chinese Chang'e-3 lunar lander (Chang'e-3 EUVC), respectively. Principles of these optical emissions have been introduced in Section 3.4. The nighttime ionospheric disk image can be used to investigate the structure and

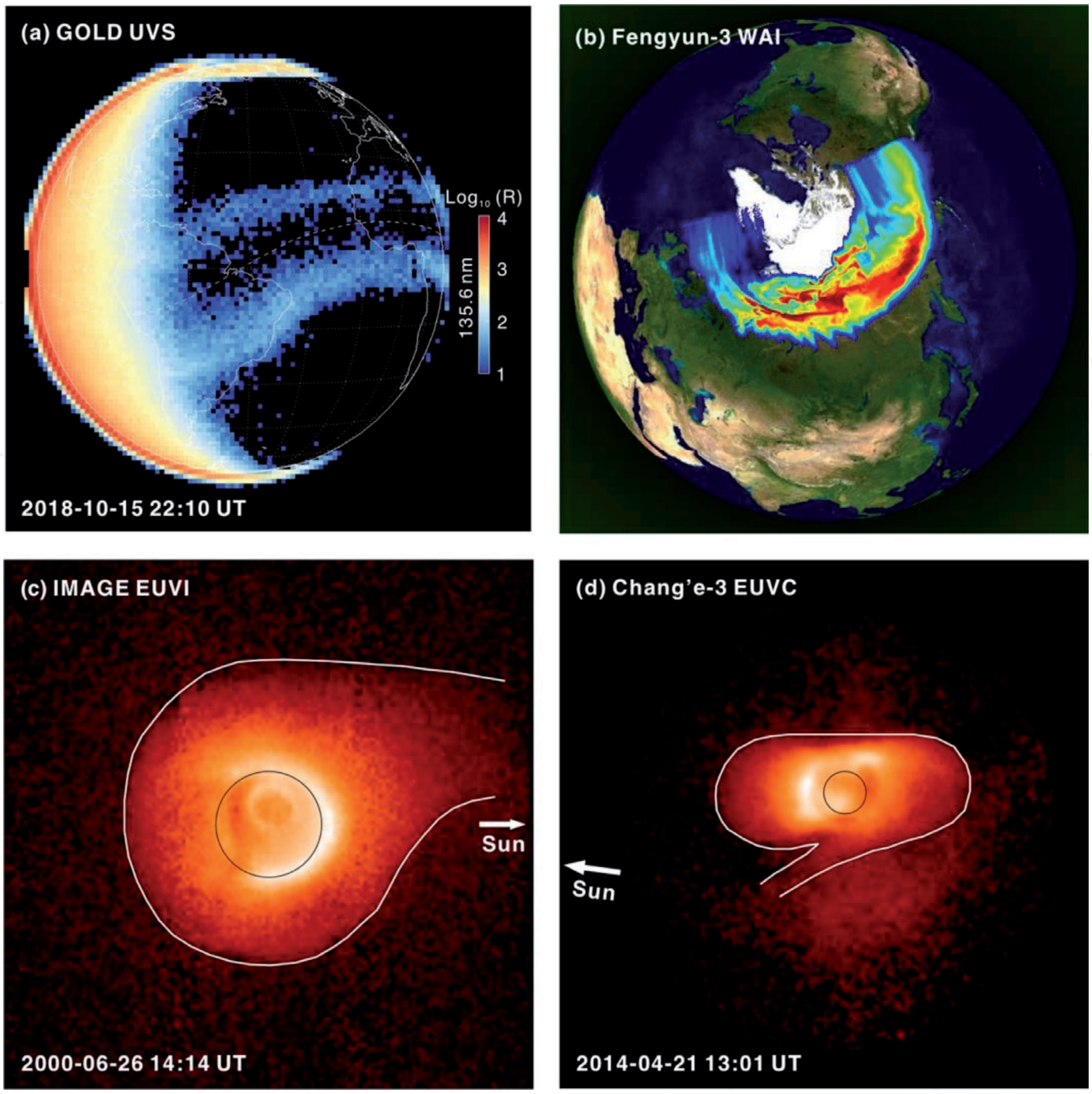

Figure 8.
Optical remote sensing images of Earth's space environment. Shown are (a) nighttime ionospheric disk image at OI 135.6 nm obtained by GOLD UVS (adapted from reference [25]), (b) auroral disk image at N_2 LBH band obtained by Fengyun-3D WAI, and plasmaspheric images at 30.4 nm obtained by (c) the IMAGE EUVI and (d) the Chang'e-3 EUVC.

evolution of equatorial ionization anomaly [25]. The auroral image can be used to manifest the thermal plasma transportation in the Earth's magnetosphere and to denote the substorm activity in Earth's space [26]. The plasmaspheric images can be used to characterize the large-scale convections in the Earth's magnetosphere [27, 28]. When the Chinese Academy of Science (CAS) and European Space Agency (ESA) collaborative science mission – Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) – is launched in the following years, X-ray imaging of the magnetosheath and polar cusp region will be realized. Until then, comprehensive investigations with all the optical remote sensing images will significantly enhance our understandings on the global dynamics of the Earth's magnetosphere.

Figure 9 shows examples of optical remote sensing images in Jovian magnetosphere. The major plasma source in the Jovian magnetosphere is the Io plasma torus, while the major driver for fundamental plasma processes is planetary rotation, very different from the case in terrestrial magnetosphere. Neutral gases released during the volcanic eruptions on Io escape into Jupiter's space. These gases are then ionized by solar radiations. Finally, the ions are trapped by the strong magnetic field of Jupiter and form a plasma torus due to the fast planetary rotation, as shown at the bottom of

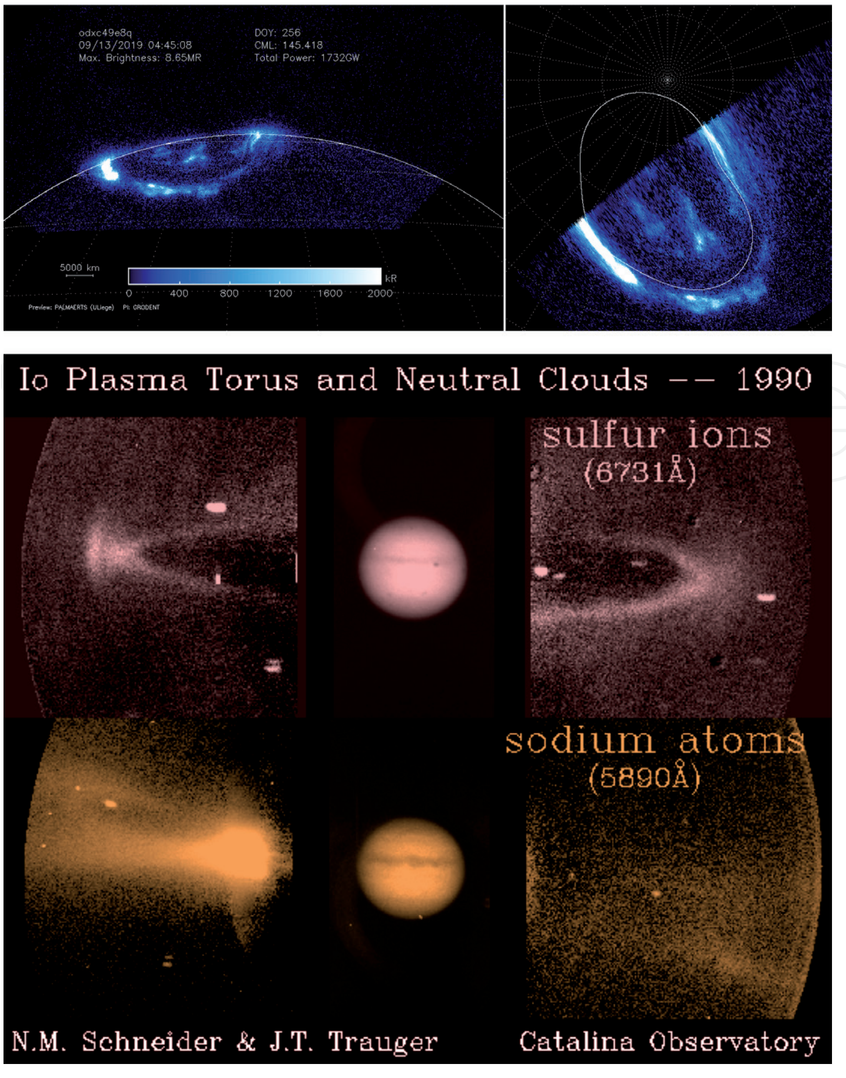

Figure 9.
Optical remote sensing images of Jupiter space environment. The top panel shows UV auroral images captured by the Hubble space telescope (modified from reference [29]). (left) the view from earth orbit and (right) a projection to the northern polar region. The middle and bottom panels show images of the global structure of the Io plasma torus at S^+ 673.1 nm and Na 589.0 nm (credit: University of Colorado/Catalina Observatory/N. Schneider).

Figure 9, in which the Io plasma torus is imaged at 673.1 nm emitted by singly ionized sulfur. The planetary rotation-driven plasma processes then transport the plasmas into the polar region along dipolar magnetic field lines to form the most powerful aurorae in the solar system, as shown at the top of **Figure 9**, in which the UV aurora is observed by the Hubble Space Telescope (HST) [29]. Coordinated observations of the Io plasma torus (e.g., the two telescopes at LOPS) and the Jovian aurorae (e.g., the HST or the Juno spacecraft) in different temporal and spatial scales will help reveal the mass and energy transportation patterns in Jovian space environment.

6. Summary and outlook

As we all know, forward-looking and feasible scientific objectives are the core factors to ensure that a research project can achieve high scientific output. Currently, the IGGCAS-LOPS is preparing a scientific team to set scientific objectives for future observations. In order to ensure that the scientific team is cutting-edge and experienced, the team will be composed of well-known domestic and international planetary scientists, whose research fields cover planetary space physics, planetary geology, astronomical observation and optical remote sensing technology. Through regular scientific team meetings, the telescope's observation schedules are adjusted in time, with particular attention paid to observation objects with scientific timeliness and social impact. In addition, the international team will organize special sessions at major international conferences, such as the annual meetings of the American Geophysical Union and the European Geosciences Union, to expand the international influence of the IGGCAS-LOPS.

The PAST is expected to begin regular observations in June 2021, and the TINTIN will begin regular observations in 2023. The long-term coordinated observations with PAST and TINTIN will ensure the investigation of the evolution of Io plasma torus in Jupiter's magnetosphere at different temporal and spatial scales. Apart from the primary object of Jupiter system, the secondary object is Mars. The airglow of Martian atmosphere/ionosphere in near UV and visible will be imaged according to Mars phase. Both telescopes can also be used to monitor comets, asteroids, and other celestial bodies in the solar system.

In the future, we will further upgrade the performance of the telescopes and add new instruments to expand the observable targets of the telescope. Compared with other astronomical survey telescopes at Lenghu, the PAST and TINTIN can be considered as precision photometric telescopes, which can cooperate with other astronomical survey telescopes at Lenghu to track and observe their survey targets. The diameter of the two telescopes is also large enough to observe exoplanets, and the radial velocity and transit methods can be used to carry out the search and identification of exoplanets.

In addition to providing first-hand data from autonomic planetary observations for related scientific research, the IGGCAS-LOPS is also an important scientific and educational practice base. Considering that the Qaidam Basin near Lenghu is the largest Mars-like geomorphologic environment in the world, the IGGCAS-LOPS and its surrounding geographical environment will become a comprehensive practice site for planetary geology and planetary space science. In July 2020, the College of Earth and Planetary Sciences, UCAS and the government of Haixi Mongolia and Tibetan Autonomous Region of Qinghai Province have signed an agreement on a planetary science practice base. Upon the completion of the telescopes, the IGGCAS-LOPS will provide important scientific practice support. In addition, the IGGCAS-LOPS is also considering building planetary practice bases with other universities.

In the long run, there is still a lack of comprehensive earth and planetary space environment observation station in the vast western region of China. Based on the IGGCAS-LOPS, further deployment of atmospheric, ionospheric, geomagnetic, seismic, and other observation equipment is planned. The excellent atmospheric optical conditions and extremely low light pollution at LAOB are very suitable for the monitoring of upper atmospheric glow in the mid-latitude region and the study of the dynamics of the middle and upper atmosphere. At the same time, together with ionospheric vertical detection (altimeter, radar, etc.) and geomagnetic field detectors, we can comprehensively study the dynamics of atmospheric and ionospheric vertical coupling and cooperate with a series of stations in eastern China to form a more complete coverage of China's space environment.

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Conflict of interest

The author declares no conflict of interest.

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References

[1] Wu FY, Wei Y, Song YH, et al. From fusion of research and teaching to leading of science: Strategy to build planetary science program with Chinese characteristics. Bulletin of Chinese Academy of Sciences. 2019; 34(7): 741-747 (in Chinese). DOI: 10.16418/j.issn.1000-3045.2019.07.002

[2] Kivelson MG, Bagenal F. Planetary magnetosphere. In: McFadden LA, Weissman PR, Johnson TV, editors. Encyclopedia of the Solar System. New York: Academic Press, 2007. p. 519-540. DOI: 10.1016/B978-0-12-415845-0.00007-4

[3] He F, Zhang X X, Chen B, Fok MC, Zou YL. Moon-based EUV imaging of the Earth's plasmasphere: Model simulations. Journal of Geophysical Research: Space Physics, 2011; 118:7085-7103. DOI: 10.1002/2013JA018962

[4] McClintock WE, Schneider NM, Holsclaw GM, Clarke JT, Hoskins AC, et al. The Imaging Ultraviolet Spectrograph (IUVS) for the MAVEN mission. Space Science Reviews, 2015; 195:75-124. DOI: 10.1007/s11214-014-0098-7

[5] He F, Zhang XX, Wang XY, Chen B. EUV emissions from solar wind charge exchange in the Earth's magnetosheath: Three-dimensional global hybrid simulation. Journal of Geophysical Research: Space Physics, 2015; 120: 138-156. DOI: 10.1002/2014JA020521

[6] Deighan JI, Jain SK, Chaffin MS, Fang X, Halekas JS, Clarke JT, et al. Discovery of a proton aurora at Mars. Nature Astronomy, 2018; 2:802-807. DOI: 10.1038/s41550-018-0538-5

[7] Sánchez-Lavega A. An introduction to planetary atmosphere. Boca Raton: Taylor & Francis. 2011. p. 115-164. DOI: 10.1201/9781439894668

[8] Meier RR. Ultraviolet spectroscopy and remote sensing of the upper atmosphere. Space Science Reviews, 1991; 58:1-158. DOI: 10.1007/BF01206000

[9] Baumgardner J, Wilson J, Mendillo M. Imaging the sources and full extent of the sodium tail of the planet Mercury. Geophysical Research Letters, 2008; 35:L03201. DOI: 10.1029/2007GL032337

[10] Nara Y, Yoshikawa I, Yoshioka K, et al. Extreme ultraviolet spectra of Venusian airglow observed by EXCEED. Icarus, 2018, 307:207-215. DOI: 10.1016/j.icarus.2017.10.028

[11] Gérard JC, Aoki S, Willame Y, et al. Detection of green line emission in the dayside atmosphere of Mars from NOMAD-TGO observations. Nature Astronomy, 2020; 4:1049-1052. DOI: 10.1038/s41550-020-1123-2

[12] Schneider NM, Trauger JT, Wilson JK, et al. Molecular origin of Io's fast sodium. Science, 1991; 253:1394-1397. DOI: 10.1126/science.253.5026.1394

[13] Mendillo M, Flynn B, Baumgardner J. Imaging observations of Jupiter's sodium magneto-nebula during the Ulysses encounter. Science, 1992. 257:1510-1512. DOI: 10.1126/science.257.5076.1510

[14] Gladstone GR, Waite Jr JH, Grodent D, et al. A pulsating auroral X-ray hot spot on Jupiter. Nature, 2002; 415:1000-1003. DOI: 10.1038/4151000a

[15] Grodent D, Bonfond B, Yao Z, et al. Jupiter's aurora observed with HST during Juno orbits 3 to 7. Journal of Geophysical Research: Space Physics, 2018; 123(5):3299-3319. DOI: 10.1002/2017JA025046

[16] Li X, Lin W, Xiao Z, et al. Planetary geology: "Extraterrestrial" mode of

geology. Bulletin of Chinese Academy of Sciences, 2019; 34(7):776-784 (in Chinese). DOI: 10.16418/j.issn.1000-3045.2019.07.007

[17] Lin W. Life in the near space and implications for astrobiology. Chinese Science Bulletin, 2020; 65(14):1297-1304 (in Chinese). DOI: 10.1360/TB-2019-0805

[18] Lin W, Li Y, Wang G, et al. Overview and perspective of astrobiology. Chinese Science Bulletin, 2020; 65(5):380-391 (in Chinese). DOI: 10.1360/TB-2019-0396

[19] Doyle LR, Deeg HJ. The way to circumbinary planets. In: Deeg HJ, Belmonte JA, editors. Handbook of Exoplanets. Switzerland: Springer, 2018. p. 65-84. DOI: 10.1007/978-3-319-55333-7

[20] Wei Y, Yao Z, Wan W. China's roadmap for planetary exploration. Nature Astronomy, 2018; 2:346-348. DOI: 10.1038/s41550-018-0456-6

[21] Rong Z J, Cui J, He F, et al. Status and prospect for Chinese planetary physics. Bulletin of Chinese Academy of Sciences, 2019; 34(7):760-768 (in Chinese). DOI: 10.16418/j.issn.1000-3045.2019.07.005

[22] Wan W, Wei Y, Guo Z, et al. Toward a power of planetary science from a giant of deep space exploration. Bulletin of Chinese Academy of Sciences, 2019; 34(7):748-755 (in Chinese). DOI: 10.16418/j.issn.1000-3045.2019.07.003

[23] Wei Y, Zhu R. Planetary science: Frontier of science and national strategy. Bulletin of Chinese Academy of Sciences, 2019; 34(7):756-759 (in Chinese). DOI: 10.16418/j.issn.1000-3045.2019.07.004

[24] Deng L, Yang F, Chen X, He F, Liu Q, Zhang B, Zhang C, Wang K, Liu N, Ren A, Luo Z, Yan Z, Tian J, Pan J. Lenghu on the Tibetan Plateau as an astronomical observing site. Nature, 2021; accepted. DOI: xxxx

[25] Eastes RW, Solomon SC, Daniell RE, Anderson DN, Burns AG, England SL, Martinis CR, McClintock WE. Global-scale observations of the equatorial ionization anomaly. Geophysical Research Letters, 2019; 46:9318-9326. DOI: 10.1029/2019GL084199

[26] He F, Guo RL, Dunn WR, Yao ZH, Zhang HS, Hao YX, Shi QQ, Rong ZJ, Liu J, Tian AM, Zhang XX, Wei Y, Zhang YL, Zong QG, Pu ZY, Wan WX. Plasmapause surface wave oscillates the magnetosphere and diffuse aurora. Nature Communications. 2020; 11:1668. DOI: 10.1038/s41467-020-15506-3

[27] Sandel BR, Goldstein J, Gallagher DL, Spasojević M. Extreme ultraviolet imager observations of the structure and dynamics of the plasmasphere. Space Science Reviews, 2003; 109(1):25-46. DOI: 10.1023/B:SPAC.0000007511.47727.5b

[28] He F, Zhang XX, Chen B, Fok MC, Nakano S. Determination of the Earth's plasmapause location from the CE-3 EUVC images. Journal of Geophysical Research: Space Physics, 2016; 121:296-304. DOI:10.1002/2015JA021863

[29] Yao Z H, Bonfond B, Clark G, Grodent D, Dunn WR, Vogt MF, Guo RL, Mauk BH, Connerney JEP, Levin SM, Bolton SJ. Reconnection- and dipolarization-driven auroral dawn storms and injections. Journal of Geophysical Research: Space Physics, 2020; 125:e2019JA027663. DOI: 10.1029/2019JA027663