Analysis of Electric Sensor for Space Detectors: Mass Spectrometer, Particle Detector and CMOS/CCD Sensor

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Abstract. As a matter of fact, with the participation of government agencies and the exploration of private enterprises, space exploration is undergoing rapid development as well as change in recent years. With this in mind, these trends will continue to promote human exploration and utilization of space, providing more opportunities for scientific research, commercial applications and exploration. In order to realize accuracy observation, high precision detectors are necessary to be developed and implemented. To be specific, a large number of electric sensors are applied on the space detectors, including mass spectrometer, particle detector as well as CMOS/CCD image sensor, etc. On this basis, this paper presents the principles, structures and applications of these three electric sensors in detail. According to the analysis, this study also analyzes the existing shortcomings of the state-of-art facilities as well as proposes future developments. Overall, these results shed light on guiding further exploration of space detectors.

Keywords: Space exploration; electric sensor; mass spectrometer; particle detector; CMOS/CCD.

1. Introduction

The development history of space probes can be traced back to the beginning of the 20th century, with the increasing human interest and exploration of space, space probes played a key role in scientific research, earth observation, planetary exploration and cosmic exploration. In 1957, the Soviet Union launched the world's first artificial satellite, named Spotnik. This event marked the beginning of the era of space probes. A year later, since 1915, the National Aviation Advisory Board (National Advisory Committee for Aeronautics) has changed to the National Aeronautics and Space Administration (National Aeronautical and Space Administration) [1]. In the 1960s, the United States and the Soviet Union conducted a series of lunar exploration missions, the most famous of which was the Apollo program, where the Apollo 11 astronauts successfully landed on the moon in 1969. In the 1980s, the European Space Agency (ESA) was established and began participating in space exploration missions, such as the Gaia satellite. At this time, international cooperation became more common in space exploration. In 1990, the Hubble Space Telescope was launched, becoming the first optical telescope to continue in orbit, providing stunning images and data of deep space in the universe. Currently, several countries and private companies are planning to explore the moon and Mars around the late 2020s, including the Project Artemis and Starman missions in the United States, as well as China's Chang' e probe series. In the 50 years since the launch of the satellite on October 4,1957, more than 6,000 operational satellites have been launched to Earth orbit and beyond, some of them to, the farthest point in our solar system [2]. After 50 years of rocket launch, there are now more than 10,000 human-made materials located in Earth orbit alone [3].

The history of space probes is full of scientific discoveries, technological breakthroughs and international cooperation. They provide valuable data and insights in the study of the solar system, the origin and evolution of the universe, the Earth's climate and environment, and the physical phenomena in outer space, driving our understanding of the universe. As technology continues to evolve, space probes will continue to play an important role in helping us solve more unsolved mysteries.

Spectroscopy is based on different chemical structures of gas molecules with different light absorption wavelength or excitation itself to obtain specific spectra for analysis. It has also been used

in space, such as the Mars Atmospheric Characteristics Research Spectrum (SPICA) on the Mars Express satellite, launched in 2003. The mass spectrometer (MS) analyzes the gas composition by separating the ions with different mass-charge ratios. It can obtain information about the composition, atomic weight or molecular weight, molecular structure and molecular arrangement in the material. This information is difficult to obtain for by other means [4].

A particle detector is an instrument used for measuring and analyzing high-energy particles (such as electrons, protons, neutrons, heavy ions, etc.). They play important roles in physics, nuclear physics, astronomy, cosmology, as well as in particle physics experiments. The particle detectors work essentially by measuring and identifying the properties of the particles by detecting the electrical signals generated when they interact with matter. The following is the basic working principle of the particle detector [5]:

Particles interact with matter. When high-energy particles enter the active material (usually solid, liquid or gas), they interact with the nuclei or electrons in the material. These interactions may include ionization, scattering, Compton scattering, Compton effect, Auger scattering, etc.

Ionization and excitation. particles interacting with matter lead to ionization or excitation of atoms in the material. These processes produce charged particles such as free electrons, positive ions, and photons (such as X-rays and γ -rays).

Charge collection. The detector usually contains an electrode system used to collect free electrons and positive ions generated during particle interaction. These charges are attracted to the electrodes, generating electric current or charge clouds.

Signal amplification. The collected charge is sent to an electrics amplifier to increase the amplitude of the electrical signal for measurement and analysis. The amplified signal can be either a voltage pulse or a current pulse.

Signal processing and analysis. The amplified signal is transmitted to a data acquisition system, usually a computer, used to record, analyze, and store information about particle interactions. This includes measuring the particle energy, trajectory, species, and direction of incident, etc.

Particle recognition. Through the analysis of the generated electrical signals, the properties of the particles can be determined, such as the charge, energy, mass, and species. Depending on the different types of particle detectors, different techniques and methods can be used to achieve the identification. Both the CMOS (complementary metal oxide semiconductor) and the CCD (charge-coupled device) photo sensors have a wide range of applications in space probes to capture images and data in the universe [6]. It includes capturing images of galaxies, stars and planets, and analyzing the spectra of different wavelengths in the universe.

This paper reviews the examples of principle, structures and applications of mass spectrometer, particle detector and CMOS/CCD image sensor, and highlights the shortcomings of existing electric sensors. Finally, the development of electric sensors is discussed. The first chapter describes the current state of space exploration and the common electric sensors used for space detectors. Chapter two introduces the specific classification of electric sensors, and some of the main application functions. Chapter three to chapter five respectively introduce the principle, composition and application of mass spectrometer, particle detector and CMOS/CCD image sensor. Chapter 6 analyzes the limitations and development prospects of electric sensors. The seventh chapter summarizes the full text.

2. Basic Descriptions

A variety of electric detectors are applied on space detectors, which can have different functions and characteristics depending on the mission and the targets and phenomena to be studied. The following are the electric detectors used on some common types of space detectors:

Mass spectrometer. The spectrometer is used to analyze the spectrum of light to determine the composition, temperature and velocity of the light source. They are widely used in the study of stars, planetary atmospheres, and cosmic rays.

Particle detector. These detectors are used to measure high-energy particles in space, such as electrons, protons, heavy ions, and cosmic rays, to understand their properties and origins.

CMOS/CCD image sensor. These detectors are used to capture images and can be used for astrophotography, Earth observation, planetary surface images, etc. They often include cameras of different wavelengths, such as visible, infrared, and UV cameras.

Radiometer. The radiometer is used to measure radiation in space, including cosmic rays, solar radiation, and charged particles, to assess radiation exposure to space vehicles and astronauts.

Plasma instruments. These instruments are used to measure the properties of the space plasma, such as density, temperature, and velocity, to study the solar wind, the planetary magnetosphere, and the interstellar medium.

Magnetometer. Magnetometer is used to measure the strength and direction of the magnetic field in space, and it is helpful to study the phenomenon of planetary magnetic field, solar wind and magnetosphere.

The choice of these electric detectors depends on the specific mission objectives and scientific research questions. Space detectors are typically equipped with multiple different types of detectors to collect multidimensional data, so that scientists can have a more comprehensive understanding of the various phenomena in space and planetary systems.

3. Mass Spectrometer

According to working principle, the Mass spectrometer(MS) can be segmented into magnetic sector MS, quadrupole mass spectrometer(QMS), ion trap MS and time-of-flight MS. QMS have fast response, high sensitivity, wide mass range and simple structure. In QMS, the four electrode poles are divided into two groups, on which the radio frequency reverse intersection variable voltage is applied. In such an electric field environment, the ions will oscillate according to the electric field. However, only ions with a specific charge-to-mass ratio can be stabilized through the electric field. When the voltage on the pole rod is specified, the ion with small mass will be affected by the voltage, resulting in a very intense shock, resulting in the loss of the touch pole charge and being removed by the vacuum system; the large mass ion cannot touch the pole or fly out of the electric field. For ions located in this potential field, the selected partial stabilized field can reach the detector or enter the subsequent space for subsequent analysis [7]. Charge ions of a certain mass cross the quadrupole field in a stable manner at a certain frequency. The scanning of ions of all masses can be achieved when the frequency changes [8]. A QMS consisting of two ion sources, a quadrupole mass analyzer using the Microsaic system, and two secondary electron-doubling detectors as shown in Fig. 1.

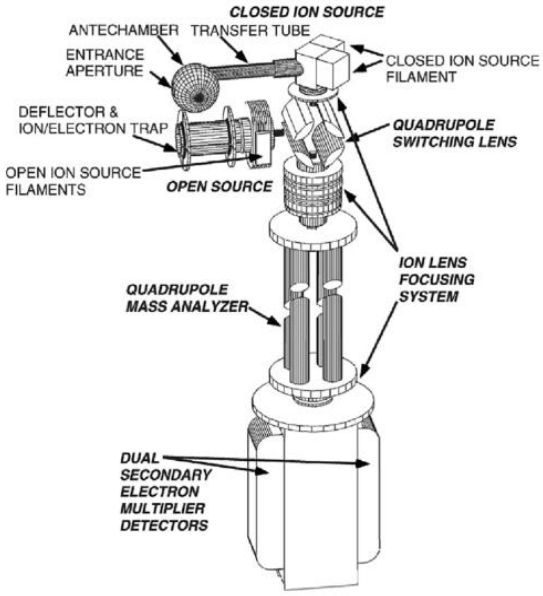


Fig. 1 The key components of QMS

QMS has important applications in space exploration, which can be used to analyze and detect gas, particles and cosmic dust in space, providing key information about the chemical composition of cosmic space and planetary surface. Here are some of the main application scenarios of QMS in space exploration. QMS is used to analyze the composition of gas in the planetary atmosphere, such as the atmosphere of the Mars, Venus and Saturn moons. By measuring ions with different mass-charge ratios, the composition of the atmosphere, such as hydrogen, oxygen, nitrogen, carbon dioxide, etc. This helps to understand the climate and chemical environment of the planet. QMS is used in comet detection missions to analyze gas and dust from comet tails. By measuring the gases emitted from comets, the composition and chemical reactions of comets can be studied, thus increasing the understanding of the formation and evolution of the solar system. In interstellar space, QMS is used to analyze the chemical composition of the interstellar medium, such as interstellar gas clouds, interstellar dust, and media near stars. This helps scientists study the chemical evolution of interstellar space and the origin of interstellar matter.

In 2004, the European Space Agency (ESA) launched the Rosetta Mission (Rosetta Mission), a decade-long deep space exploration mission designed to study the properties of comet 67P/Churyumov to improve understanding of the formation and evolution of comets and the solar system. The Rosetta spacecraft was launched on March 2,2004, and reached comet 67P in August 2014. It was the first spacecraft to successfully land on the comet's surface. The Rosetta spacecraft carries a variety of scientific instruments, including magnetic field, gas and dust analyzer (ROSINA), QMS, and infrared imaging spectrometer (VIRTIS), to analyze the comet composition, atmosphere, dust, activity and other information. September 30 September 2016. During the mission, it sent large amounts of valuable data on the evolution of the solar system, giving the scientific community an opportunity to gain insight into comets.

In addition, the Cassini-Huygens mission, the Mars Science Laboratory (Curiosity) mission, the New Vision mission, and the International Space Station [9]. In conclusion, the application of QMS in space exploration helps scientists to gain insight into the chemical composition and properties of matter in space, thus driving the exploration and understanding of the universe. It plays a key role in the study of space science, providing us with valuable data to reveal the mysteries of the universe.

4. Particle Detector

The particle detector is a scientific instrument for detecting and measuring the properties of charged or uncharged particles produced in cosmic rays, particle beams, or particle collisions, including their species, energies, velocities, trajectories, etc. The principle of particle detectors is based on the properties of the interactions between different particles and matter that can produce measurable signals.

The working principle of the particle detector can be divided into five steps [10]. Particle detector work begins with a particle incident. Particles can be derived from cosmic rays, accelerator experiments, nuclear reactions, or other particle sources. When a particle passes through the detector's detection component, it interacts with the nucleus and electrons in the component, causing the particle to lose energy. This process is called the energy loss. Due to energy loss, particles can excite, ionize, or hit the nucleus or electrons, thus creating a charge in the detector. These charges can be positive or negative, depending on the nature and energy of the particle.T he charge signal in the detector is detected and recorded. Typically, the detector contains various detection elements (gas chambers, semiconductor detectors, scintillators, ionization chambers, etc.), for the capture and recording of charge signals. The properties of the charge signal (e. g., amplitude, time, and position) are measured and recorded. These data can be used to determine the energy, trajectory, speed, and species of the particles. Fig. 2 shows the structure diagram of the energetic particle detector (EPD), which mainly includes the following parts: Ultra thermal electron and Proton (STEP), electric Proton Telescope (EPT), high temperature ion spectrometer (SIS), High Energy Telescope (HET), instrument control unit (ICU) [11].

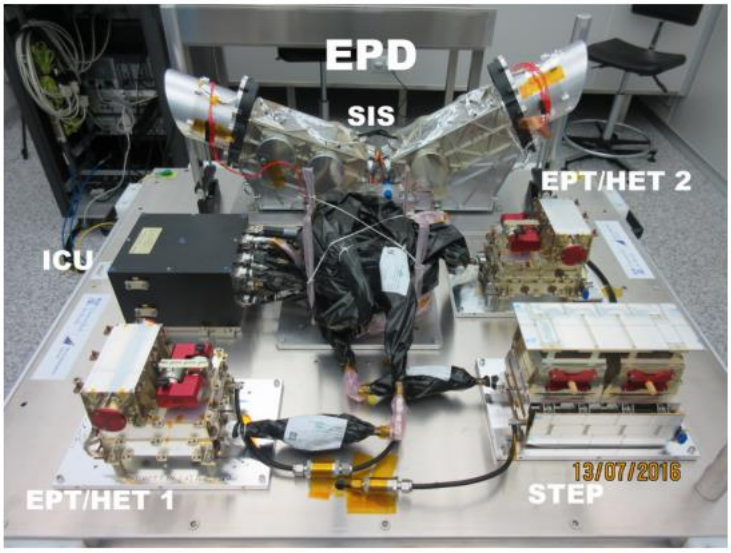


Fig. 2 The components of EPD

Particle detectors have important applications in space exploration. They are used to study and measure various particles and radiations such as cosmic rays, solar wind, planetary atmosphere and planetary surface in space, including cosmic ray research, solar wind analysis, planetary atmosphere research, radiation zone research and dark matter search. So far, there have been several space detectors, such as the DAMPE (Dark Matter Particle Explorer) satellite, also known as "Wukong" (NASA) (Wukong), designed to search for the presence of dark matter particles. It carries particle detectors for measuring high-energy particles from the universe. In addition, the US National Aeronautics and Space Administration (NASA) launched the Parker Solar Probe in 2018. It also carries particle detectors for measuring electrons, protons, and α particles in the solar wind to study the heating and acceleration mechanisms of the solar wind [12].

5. CMOS / CCD Image Sensor

CMOS (complementary metal oxide semiconductors) and CCD (charge-coupled devices) are two common photosensitive photographic elements that are used in digital cameras, camcorders, and other imaging devices. They work slightly differently. Each pixel of the CMOS image sensor contains a photosensitive element, usually a photosensitive diode or a photosensitive transistor. When the light hits the pixel, the amount of charge in the photosensitive element is affected. When the light hits a pixel, the photosensitive element transforms the light energy into electrons. The greater the light intensity, the more the number of electrons produced is [13]. The amplifier and the A/D converter in the CMOS photosensitive photographic element amplify and convert the generated electric signal into a digital signal. Digital signals undergo subsequent signal processing and encoding to form the final image. CMOS photo sensors can read all pixels simultaneously, so they have an advantage in image capture speed. A sketch of CMOS is shown in Fig. 3.

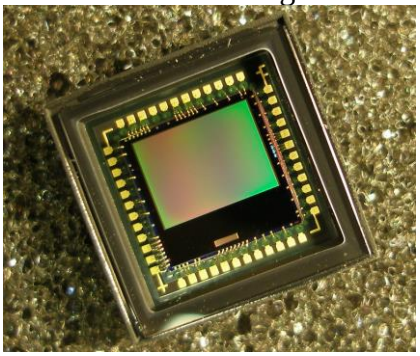


Fig. 3 CMOS Image Sensors

The pixels of the CCD image sensor are a series of charge-coupled devices that are able to accumulate the charge in the pixels. When the light hits the pixel, the photosensitive element generates a charge. The charge is transmitted in the CCD, passing through the entire photosensitive area, and finally reaching the output of the photosensor. The charge is read at the output end and then converted into a voltage signal. These voltage signals are directly proportional to the intensity of the light rays. The voltage signal output by the CCD is signal processing and encoded to form the final image [14]. The reading of the CCD photographic element is serial, line by line, and therefore slower in image capture. A sketch of CCD is shown in Fig. 4.

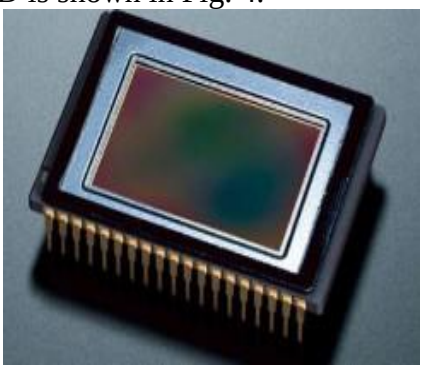


Fig. 4 CCD Image Sensors

Overall, CMOS and CCD image sensors differ in working principle and performance. CMOS has the advantages of parallel reading, low power consumption and high integration, and CCD performs well in terms of image quality and low noise. They are widely used in planetary probes and satellites to capture images of planetary surfaces, atmospheres, moons, and comets. For example, the CCD camera on the Hubble Space Telescope is used to capture images of Earth's exoplanets. In addition, in planetary and satellite land missions, they were used to image the surface to study features such as landforms, rocks and soil.

6. Limitations and Prospects

Spatial probe electric sensor research faces several limitations and challenges that may affect detector performance and reliability as following.

Radiation. There is intense radiation in space, such as cosmic rays and solar radiation. These radiation can cause damage to the electric sensors, leading to the degradation or failure of the electric components.

Temperature change. The temperature range in space is extremely wide, ranging from extremely low temperatures to extremely high temperatures. electric sensors must be able to operate properly under such extreme temperature conditions, which requires sophisticated temperature control and thermal management systems.

Long runs. Space missions often take long operations, possibly years or longer. Therefore, the electric sensors must have a high degree of reliability and durability to maintain a stable performance.

Communication delay. There is a communication delay between space probes and the Earth, which may have an impact on control and data transmission. The real-time performance and responsiveness of the sensor need to consider the communication delay.

Energy supply. Electric sensors need electricity, and energy supplies, such as solar energy and battery technology in space are limited. Energy supply issues may limit the sensor performance and running time.

Space constraints. Space probes typically have strict size and weight limits. electric sensors must be installed in a limited space, and must be lightweight to reduce the load on the task.

Cost constraints. Space exploration missions are typically very expensive. The research and manufacture of electric sensors requires substantial funding, and therefore must be studied under cost constraints.

Addressing these limitations requires research in depth and innovation in areas such as engineering design and materials science. Scientists and engineers constantly strive to improve and adapt electric sensor technology to meet the changing needs of space exploration. At the same time, these limitations need to be fully considered in the planning and implementation of space missions to ensure the success of the mission. The field of space detection of electric sensors has a broad development prospect. For example, the resolution and performance of electric sensors will continue to improve, making it possible to obtain higher quality and more detailed data in space. This is very important for tasks such as planetary exploration, astronomical observation and Earth observation. electric sensors will also be more miniaturized and lightweight to accommodate small satellites and multi-satellite missions. Moreover, energy-saving technologies for electric sensors will be improved to extend the life of the detector and reduce dependence on energy supply. Solar energy and high-efficiency battery technologies will drive the development in this direction.

7. Conclusion

As a matter of fact, the electric sensors in space detectors are diverse. To sum up, this study describes the principle, composition and application scope of mass spectrometer, particle detector and CMOS / CCD image sensor. The existing electric sensors have some limitations, but with the progress of science and technology, there are broad development prospects for the electric sensors for space detection. Overall, these results offer a guideline for future development of the detectors.

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