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Enhanced Ion Sampling Techniques for In-situ Neutral Gas and Low-energy Ions Exploration of Main-belt Comet*

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Abstract One of the detection objectives of the Chinese Asteroid Exploration mission is to investigate the space environment near the Main-belt Comet (MBC, Active Asteroid) 311P/PANSTARRS. This paper outlines the scientific objectives, measurement targets, and measurement requirements for the proposed Gas and Ion Analyzer (GIA). The GIA is designed for in-situ mass spectrometry of neutral gases and low-energy ions, such as hydrogen, carbon, and oxygen, in the vicinity of 311P. Ion sampling techniques are essential for the GIA's Time-of-Flight (TOF) mass analysis capabilities. In this paper, we present an enhanced ion sampling technique through the development of an ion attraction model and an ion source model. The ion attraction model demonstrates that adjusting attraction grid voltage can enhance the detection efficiency of low-energy ions and mitigate the repulsive force of ions during sampling, which is influenced by the satellite's surface positive charging. The ion source model simulates the processes of gas ionization and ion multiplication. Simulation results indicate that the GIA can achieve a lower pressure limit below 10^{-13} Pa and possess a dynamic range exceeding 10^9 . These performances ensure the generation of ions with stable and consistent current, which is crucial for high-resolution and broad dynamic range mass spectrometer analysis. Preliminary testing experiments have verified GIA's capability to detect gas compositions such as H₂O and N₂. In-situ measurements near 311P using GIA are expected to significantly contribute to our understanding of asteroid activity mechanisms, the evolution of the atmospheric and ionized environments of main-belt comets, the interactions with solar wind, and the origin of Earth's water.

Key words Gas and Ion Analyzer (GIA), Main-belt comet, Active asteroid, Ion attraction, Ion extraction, Gas ionization

Classified index P185

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0 Introduction

Small bodies in the solar system include asteroids, comets, meteoroids and others, which preserve the history about early period of the solar system. Main-belt Comet (MBC), also called active asteroid, is located in the inner asteroid belt between Mars and Jupiter. They have both the orbital characteristics of asteroids and the activity characteristics of comets^[1,2]. Observations of their mass loss due to various activities and chemical compositions can provide crucial insights into the evolution of the solar system, or the genesis of life, as they potentially harbor primordial water and organic substances.

Multiple comet exploration missions have performed detailed close-proximity observations, and attained the profound comprehension of the characteristics and rules of comets. However, the close-proximity detection missions of the MBC have not been successfully established. Based on the results of comet exploration, the hypothesis that the water on Earth originated from Jupiter-family comets has been largely precluded, thus indicating that Earth's water may have a higher probability of coming from asteroids^[3]. Active asteroids are expected to have more volatile substances, investigating water molecules in the atmospheric environment of MBC can greatly support the study of the origin water on Earth.

The first MBC-133P/Elst-Pizarro was discovered in 1996, and 311P/PANSTARRS was discovered in 2013^[4,5]. The activity of the comet primarily arises from the sublimation of ice. In contrast to traditional comets, MBCs exhibit a diverse activity properties, including levels of activity, mechanisms, and periods^[6]. The driven mechanisms producing the mass loss processes include the electrostatic repulsion, impact ejections, rotational instabilities, radiation pressure sweeping, dehydration stresses, and thermal fracture, in addition to the sublimation of ice^[7]. So far, observations of MBCs have been primarily limited to remote sensing. These observation results provide fundamental parameters of MBCs, such as orbit, rotational states, shape and size, thermal radiation, and spectral features, *etc*^[2]. There is a lack of direct observational evidence for the chemical and mineral composition, isotopic composition, water and organic content, as well as comprehensive and continuous dynamic variations of MBCs, such as gas releases, dust

emissions, and fragmentation, *etc*. By conducting close-proximity observations of MBCs and obtaining information on their terrain, material composition, and activity patterns, a more accurate and reasonable explanation of their properties, origin, evolution, and activity mechanisms can be illustrated.

Acquiring material composition data of neutral gas and cold plasma is a critical objective within China's asteroid exploration mission. This includes investigation the formation and evolution of the MBC atmospheric and ionized environments, as well as the analysis of the origin and the activity mechanisms. Gas and Ion Analyzer (GIA) is a component of the Charged Particle and Neutral Particle Analyzer which is the Chinese scientific payloads for asteroid exploration. The amplification ion source technology is developed to possess the capability of effectively increasing ion charges and enabling higher sensitivity and resolution. Consequently the payload can accurately distinguish the components of neutral gas and cold plasma ions adjacent to the MBC. When the satellite approaches the MBC 311P, GIA will conduct in-situ exploration of the composition content of neutral gases and low-energy ions. The in-situ measurement data will play a crucial role in supporting the scientific understanding of the properties, origins, and evolution of the atmospheric and ionized environments of the 311P. Additionally, it will provide valuable insights into the driving forces behind MBC activity and contribute to our understanding of the evolution of the solar system and the origins of water on Earth.

In this study, we introduce the measurement requirements of GIA in Section 1. The design scheme of GIA is presented in Section 2 with a focus on the advancements in ion sampling techniques. In Section 3, we present the simulation result and preliminary testing experiment.

1 Measurement Requirements

The Chinese asteroid exploration mission will conduct an orbital investigation around the MBC 311P/PANSTARRS which was discovered in 2013. It has a semi-major axis of 2.189 AU, an eccentricity of 0.115, and an inclination of 5.0°. The absolute magnitude, H_V , is estimated to be 19.14 ± 0.02 , and its diameter is approximately 200 meters. The orbit of 311P/P

ANSTARRS is located near the inner edge of the asteroid belt, where most objects are considered highly metamorphosed S-type asteroids. It is believed to potentially have a connection with LL-group chondrite^[5,7] (one group of ordinary chondrites characterized by low iron and low metal content). The primary volatile components of this type of meteorites include CH₄ and H₂, as well as NH₃, N₂, H₂O, and O, *et al.*^[8]. The Hubble Space Telescope observed an extraordinary set of six linear, comet-like tails of 311P in 2013 September. These observations revealed a unique structures of multiple dust tails, with particles in the tails were ejected at speeds $< 1 \text{ m}\cdot\text{s}^{-1}$. Observational research has shown that the 311P may be an asteroid binaries that are thought to be formed by rotational breakup. It's mass loss suggested that the breakup could even be on-going^[7]. Although current studies show that the mass loss of 311P cannot be driven by ice sublimation, evidence suggests that water ice is buried at depths of about 30 m in numerous small main belt asteroids^[9]. This implies that there is a possibility of rich volatile being present at these depths, which could be released during ongoing breakup processes. Considering the relatively lesser mass loss of active asteroids compared to comets, the potential for 311P to exhibit eruptions of volatile materials containing water ice can be ascertained through in-situ measurements conducted in its vicinity.

Furthermore, in addition to the dominant mass losing process mechanisms, there will also be accompanying other activity mechanisms. Considering the significantly more diverse activity mechanisms in small asteroids compared to comets, the mechanisms of the mass loss of 311P remain an unresolved issue. The activity level of MBCs is generally one order of magnitude weaker compared to comets. Therefore, it is more challenging to observe them, and there is currently no direct observational evidence regarding the gas release. Estimations of MBC volatile content, including water ice, are primarily based on spectroscopic observations of the CN radical using large telescopes, with the assumptions that the $Q(\text{CN}) / Q(\text{H}_2\text{O})$ production ratio of MBC is equivalent to the production ratio of comets. When MBCs approach the Sun, they are influenced by the heat and radiation from the Sun. Sublimation of ice and dust particles around the nucleus forms a bright, outward-

flowing atmosphere, which creates a coma. This process is similar to the sublimation of ice in comets composed of water, dust, and rocks. Neutral gases in the atmosphere become ionized due to solar EUV radiation, charge exchange with solar wind ions, or energetic electron impacts. These processes may lead to the formation of the ionosphere. As the dusts and gases flow outward the space from the nucleus, a dust tail and an ion tail driven by the solar radiation pressure and solar wind are formed^[10,11]. During the mass loss of 311P, it is likely accompanied by the release of the gases, which will form an ionized environment around it. The gases ejected from the neutrons undergoes a free diffusion process without constrained by gravity. The density of neutral gases varies with about $1/r^2$, while the density of low-energy ion varies with about $1/r$, where r is the radial distance from the nucleus^[12]. Conducting in-situ exploration of the atmospheric and ionized environment in close proximity will present exceptional research opportunities to understand the origin, mechanisms and process of for mass-losing in this unique system. So the neutral gases and low-energy ions in the vicinity of 311P will be the primary detection targets for GIA in China's asteroid exploration mission.

Immersed in the solar wind, the atmospheric and ionized environment of MBCs are comprised of abundant H and He. Furthermore, noble gases isotopes are significant importance for the celestial body evolution researches. Therefore, we set the mass number for GIA measurements to be $1 \sim 150 \text{ Da}$ (Here Da represents Dalton. One Dalton is defined as one twelfth of the mass of an unbound neutral atom of carbon-12 in its nuclear and electronic ground state and at rest). And the mass resolution should be set to be better than 1 Da in order to distinguish between CH₄ and NH₃.

The albedo of 311P is about 0.29. According to the Stefan-Boltzmann law, the surface temperature can be calculated by the following equation:

$$T = [P / (4\pi\sigma r^2)]^{1/4}. \quad (1)$$

Here P represents the total power radiated of the celestial body received from the sun, r denotes its radius, and σ is the Stefan-Boltzmann constant. The surface temperature of 311P is about 180 K, and the average velocity v of the thermal motion of the molecule can be calculated accordingly. Assuming gas molecules are diffusing uni-

formly from the surface of a small celestial body, the diffusion velocity is equal to the thermal velocity of the molecules. When a gas column is formed at the average height where molecules move in a unit of time, the atmospheric pressure near the surface of a small celestial body can be calculated using the ideal gas equation:

$$P_a = \frac{1}{3} N m v^2, \quad (2)$$

where N is the molecules number density, m is the mass of the gas molecule. In comet, the typical ratio of water production rates to CN production rates is around $Q(\text{CN}) / Q(\text{H}_2\text{O}) = 350$. The upper limit on the production rate of the MBC CN is about $10^{21} \sim 10^{24} \text{ mol} \cdot \text{s}^{-1}$, based on this, the upper limit of the water production rate is calculated to be about $10^{24} \sim 10^{26} \text{ mol} \cdot \text{s}^{-1}$ [9]. If the primary gas molecules of 311P is assumed to be methane, based on the production rates of typical comet volatile, the upper limit of methane gas production rate can be estimated as about $10^{21} \sim 10^{26} \text{ mol} \cdot \text{s}^{-1}$. Consequently, the upper limit of atmospheric pressure in the vicinity of 311P is expected to be between $10^{-9} \sim 10^{-4} \text{ Pa}$. Furthermore, obtaining the composition and abundance of neutral gases and low-energy ions in the vicinity of 311P, as well as their isotopes, is one of the primary goals of the payload's investigation. Taking into account the abundance of deuterium isotopes in hydrogen (about 0.015%), carbon-13 (about 1.07%), and oxygen-18 (about 0.2%), the minimum detectable pressure by the GIA should be at least 10^{-13} Pa . Then, the dynamic range should exceed 10^9 for detecting pressure variations. According to above, GIA should achieve the following performances.

2 Instrument Description

2.1 Principle and Composition of GIA

GIA will perform in-situ detection to the compositions, concentration, and isotopes of the neutral gases and low-

energy ions during the satellite orbit the 311P. GIA utilizes a Time-of-Flight (TOF) mass analyzer for mass resolution, a technique that is widely applied in deep space exploration and known for its stability. Moreover, this approach holds potentials for development in simultaneously balances low resource requirements and high-quality resolution[13]. The main components of GIA are the ion source and the mass analyzer. It performs neutral gas and low-energy ion detection involves ion sampling and mass analysis. In the case of neutral gas, ion sampling refers to the process of neutral gases ionized in an ion source before being introduced to the ion lens. For low-energy ions, ion sampling refers to the process of introducing low-energy ions in space to the ion lens by an electrostatic attraction device. Afterwards, the ions undergo the processes of acceleration and focusing in the ion lens before entering TOF. Figure 1 illustrates the configuration of GIA. It shows that the electrons ejected from the cathode are accelerated and focused by the electron lens. The neutral gases entering the gas ionization region are ionized by these energetic electrons, while low-energy ions in space are pull in by electrostatic attraction. Subsequently, when the ions are located in the ionization region, they will be extracted by the extraction grid by a periodic pulsed negative voltage. Then they will undergo acceleration and focusing by an ion lens before mass analysis. Ions with the same mass-to-charge ratio will arrive at the ion detection region al-

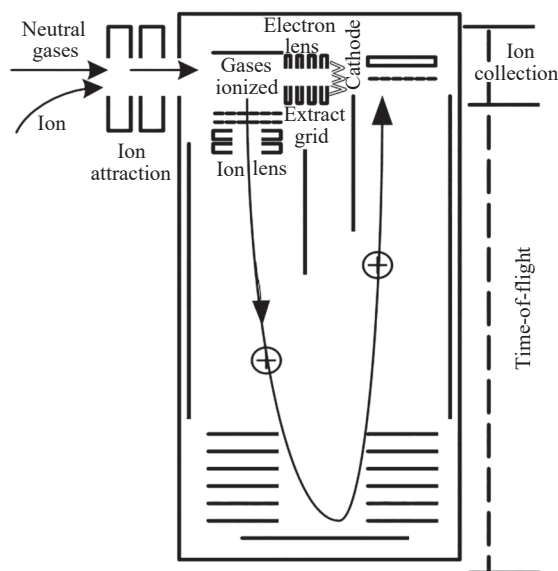


Fig. 1 Configuration of GIA

Table 1 Measurement requirements of GIA

Item	Range or value
Mass range	1 ~ 150 Da
Mass resolution	$\leq 1 \text{ Da}$
Dynamic range	$\geq 10^9$
Time resolution	4~256 s

most simultaneously. The number of such ions can be obtained by the ion collection, and their number density can be calculated. Ion sampling is one of the key steps to achieve high mass number resolution with compact size and large dynamic range. In ion sampling, the existing problems mainly include how to achieve ion attraction when the satellite surface is charged positively, how to achieve ion detection when the pressure limit is as low as 10^{-13} Pa, and the dynamic range should reach 10^9 for TOF mass analysis. In addition, GIA should also be miniaturized. In terms of miniaturization design, GIA adopts the design of neutral gas and low-energy ions sharing the same TOF mass analyzer for time shifting, and the ion lens adopts the design of compact size. These design methods can achieve the miniaturized size of ion attraction, neutral gas ionization and ion pulled in before mass analysis.

2.2 Ion Extraction

When the satellite orbits 311P, due to the influence of solar UV radiation and background plasma, the surface of the satellite should be positively charged on the sunlit side, and negatively charged on the shadow side. This electric field will change the trajectory of low-energy ions (a few eV). The positive potentials on the surface of the satellite will repel positive ions, and in order to facilitate ion detection, an ion attraction grid is set up at the entrance of GIA. According to the observation and simulation results of China's deep space exploration satellite Chang'E-1 and 2^[14,15], the maximum positive potential of the satellite surface can reach about +10 V under the condition of illumination.

During the GIA operation, the satellite will orbit the MBC at an altitude of tens to hundreds of kilometers. And the density of low-energy ions decreases by $10 \sim 100$ times with increasing altitude. Considering that the observed density of low-energy ions near the comet 67P is about 100 cm^{-3} ^[12], and that the activity of MBCs is at least one order of magnitude weaker, the ion density of 311P can be as low as 10 cm^{-3} . The Field of View (FOV) for GIA points to 311P. Assuming that the structure of MBCs is similar to that of comets, when the satellite is outside the contact surface, the newborn ions generated in the solar wind away from the nucleus from the upstream of the satellite will undergo a process of being gradually "picked up" by the solar wind, and

their guiding centers drift along the direction of $\mathbf{E} \times \mathbf{B}$, where the direction of $\mathbf{E} = \mathbf{E}V_{\text{sw}} \times \mathbf{B}_{\text{IMF}}$ is consistent with the direction of the solar wind bulk velocity. Observations from Ulysses^[16] indicate that the solar wind density, magnetic field intensity and temperature vary over the heliocentric range (R) as $1/R^2$, $1/R^{1.5}$ and $1/R$ respectively. However, the solar wind speed shows little variation. At 2.2 AU, the average magnetic field intensity $|\mathbf{B}|$ is approximately $1 \sim 3 \text{ nT}$, and the average solar wind dynamic pressure is about 20.7% of that at 1 AU, which is about $0.1 \sim 1 \text{ nPa}$. At this time, satellite should be outside the wake of the comet, the low-energy ions will come from the local newborn ions that are not pickup and the upstream ions that are partially pickup by the solar wind. When the drift speed of low-energy ions is close to the relative speed of the satellite, and the incident direction is within the sensor FOV of about $70^\circ \times 50^\circ$, they can be observed by GIA, so the measurable low-energy ion density is low. When the satellite is within the contact surface, the influence of the solar wind is almost negligible, and the magnetic field can be considered to be approximately zero. The neutral particles sublimed from the nucleus and was ionized by solar UV radiation, most of the ions still maintain the radial motion. When the direction of motion of low-energy ions is the same as the direction of the FOV, a higher concentration of low-energy ions can be observed. The comets' encountered observations^[17] show that the contact surface of Halley's comet can be thousands of kilometers high. Therefore, it can be assumed that a satellite orbiting 311P can enter the contact surface for observation. Assuming that the low-energy ion is methane, their incident velocity is about $500 \sim 1000 \text{ m s}^{-1}$ ^[18], the satellite length is about 2.0 m, and the solar arrays length is 5 m. According to the above assumptions, the influence of surface charging on ions can be modeled and the effect of ion attraction grid can be studied. The simulation results are shown in Section 3.1.

2.3 Gas Ionization and Ion Multiplication

The satellite orbits 311P with a speed of a few meters per second, and the neutral gas will enter the sensor by diffusion process and then ionized in the energetic electron beam emitted by the cathode before mass analysis are carried out. Mass analysis requires a steady, consistent ion flow that exceeds the lower limit of counting de-

tection. The distribution of these ions is primarily affected by the electron beam, electric field and the geometry structure of the ionization region. In order to achieve high mass number resolution, GIA uses high-precision TOF mass spectrometer, which will determine the ion mass by the time series to the ions arrive at the ion collection. Analogous TOF technology has been successfully applied to the MINPA on Tianwen-1^[19]. It can resolve the ion species as H^+ , He^{2+} , He^+ , C^+ , O^+ , H_2O^+ , etc. For the ion mass is determined by the time series of arrival to the ion collection, it is necessary not only for the species and quantity of initial ions produced after the ionization of identical neutral particles to be consistent, but also for the spatial distribution to be as uniform as possible in order to minimize the temporal and spatial errors existing in their mass analysis. It is shown that the spatial resolution $M_s \propto (s/\Delta s)^2$ of the initial ion affects the mass resolution when using the time-flight method. Where s is the width of the ionization region and Δs is the width of the initial ion distribution, which is also equivalent to the width of the electron beam distribution. The energy resolution of the initial ion that affects the mass resolution is $M_e \propto U_0^{-0.5}$, where U_0 is the energy of the initial ion and represents the velocity of the initial ion, and the total mass resolution M can be expressed as $1/M = 1/M_s + 1/M_e$ ^[13]. In addition, different electron energies have different ionization efficiency for the identical ion. Thus, parallel electron beams with uniform energy and narrow distribution ensure stable, consistent, and small spatial and energy distribution deviations of the ions emitted from the ionization region. The electrons emitted by the cathode traverse the ion source through a slit in an electron-focusing lens composed of four ring electrodes. The electrons emitted by the cathode pass through a slit in an electron-focusing lens composed of four ring electrodes and across the entire ion source. Adjust the potential difference between the electrodes, the distance between the electrodes, and the width of the slot for electron emission, so that the emitted electrons from the cathode can be considered to be an energy-stabilized electron beam with a narrow distribution around 70 eV. The ion extraction grid is arranged at the outlet of the central axis of the ion source, which uses a negative pulse high pressure of about -200 V to introduce ions into the ion lens. The ions ac-

celerated and focused by the ion lens then enter the mass analysis area. Since the direction of ion movement to the mass analysis region is perpendicular to the electron beam, an orthogonal ion source structure is formed, as shown in Figure 1.

High sensitivity of GIA is required for mass spectrometer, because the lower limit of ambient pressure is very low, and the pressure range of neutral gases has a large dynamic range, so there should be enough initial ions in the ionization region to improve the sensitivity of GIA.

At the same ionization rate, temperature, pressure and electron path length, the ion current is I_i , $I_i \propto I_e$, where I_e is the electron current, and the total number of ions current increases when I_e increases. Near the lower pressure limit of 10^{-13} Pa, the I_i is about 6×10^{-20} A without the space charge effect. If the I_e is increased from the initial emission of 50 μA to 1000 μA with time integration up to 256 s, the total ion current generated in the ionization region can be increased to about 3×10^{-16} A. Although the ion current reaches the detection lower limit of the payload, there are still few ions available for analysis and they will be greatly affected by background noise or random errors. Because the charged particles can produce a space charge effect, ions will accumulate in the space electric field created when the energetic electron beam passes. The electrostatic potential generated by the space charge of electrons in the ionization region is shown in Eq. (3) and (4)^[20]:

$$\phi_{out}(R_e \leq r \leq R_a) = I_{el}/(2\pi\epsilon_0) \cdot \sqrt{m_e/(2k_e)} \ln(r/R_a), \quad (3)$$

$$\phi_{in}(0 \leq r \leq R_e) = I_{el}/(2\pi\epsilon_0) \cdot \sqrt{m_e/(2k_e)} [2 \ln(R_e/R_a) + r^2/R_e^2 - 1]. \quad (4)$$

Here, R_e is the radius of the electron beam, I_{el} is the emission electron stream, k_e is the electron energy, m_e is the electron mass, R_a is the half height of the ionization region, and r is the distance between the ionization position of the neutral gas and the center line of the ionization region. It can be seen that the absolute value of the potential ϕ_{in} generated by the space charge is proportional to I_{el} and inversely proportional to the electron energy k_e . The greater the r , the farther the distance from the center line of the ionization region, and the smaller the absolute value of ϕ_{in} . According to Eq.(3)(4), Figure 2

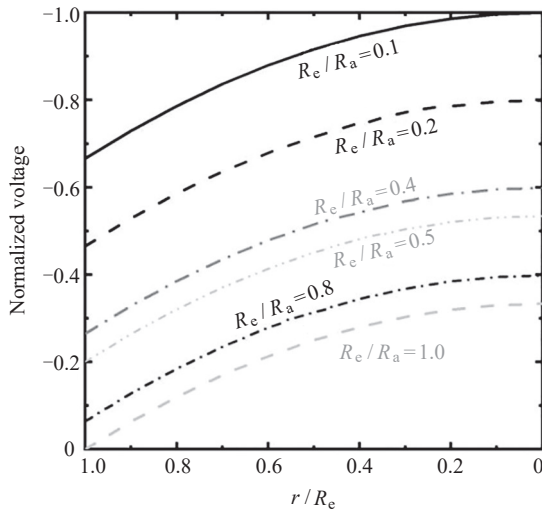


Fig. 2 Effect of the half-high ratio of the electron beam to the ionization region on the electric potentials generated by the spatial charge of the electrons

shows the relationship between R_e/R_a and the potential decreased generated by the space negative charge in the ionization region, as well as the relationship of the gas ionization r , and the potentials decreasing. The results show that the electric potential of the ionization region decreases after the electron beam passes. The narrower the width of the electron beam is compared to the width of the ionization region, the greater the electric potential decrease caused by the space charge. The closer the ionization position is to the center line, the smaller r will be, resulting in a greater potential decrease.

The space charges of the electrons create a potential well that confines the ion. Within this potential well, the ions oscillate in a direction perpendicular to the motion of the electrons. Ions with kinetic energy lower than the potentials established by the space charges are captured and accumulated with the well. This accumulation continues until the charge of the accumulated ions fully neutralizes the electron space charge, thereby filling the potential well. Prior to this neutralization, the extraction grid generates a rapidly rising electrical pulse to accelerate the ions in the ionization region and directs them into the ion lens depicted in Figure 1.

Based on the considerations of mass resolution and the influencing factors in Eq. (3)(4), an appropriate ratio of ionization region width to electron beam width is selected. Furthermore, simulations are employed to determine the electron current intensity and the geometric pa-

rameters of the ionization region. The simulation results are presented in Section 3.2.

3 Simulation Result and Preliminary Testing Experiment

3.1 Ion Attraction

According to Section 2.2, assuming that the satellite's surface charging in sunlight is +2 V, the incident velocity of CH_4^+ ions is about $1000 \text{ m}\cdot\text{s}^{-1}$, and they approach the satellite from a distance of $5\sim 20 \text{ m}$, we conducted a simulation to assess the impact of setting up the ion attraction grid. The results indicate that the presence or absence of solar panels, the initial positions of ions, and the voltage of the attraction grid significantly affect the total number of low-energy ions arriving at the GIA entrance.

The grid voltage is set to -10 V , and the influence of solar panels on the total amount of low-energy ions arriving at the entrance is analysis. Figure 3(a) (b) show the motion paths of ions with initial motion directions toward the GIA entrance, without and with solar panels, respectively. The results show that when there is a solar panel, the total ions count reaching the GIA entrance decreased from 30% to 25%, the CH_4^+ entering the GIA entrance is reduced by 5%, and the larger the solar panels geometry structures, the more significant this effect becomes. In addition, the simulation results also show the effect of the distance between the initial position of the ion and the GIA entrance on the ion's arrival. As shown in Figure 3, the shorter the distance between the initial ion position and the satellite, the easier it is to be pulled by the attract grid to reach the entrance, and the longer the distance, the more difficult for the ion to reach the entrance. If the voltage of the attract grid is increased in the negative direction, the proportion of ions absorbed by the grid will gradually increase. Figure 4(a) shows the motion trajectory of ions under the same initial ion distributions when the grid voltage is set to -25 V . CH_4^+ entering the GIA observation entrance account for 90% of the total ions, which is 65% higher than the percentage at -10 V . Figure 4(b) shows the percentage of ions entering the GIA observation entrance as the grid voltage varies between -10 V and -30 V . The results indicate that when the grid voltage reaches

−25 V, the percentage of ions absorbed by the attracting grid stabilizes at about 90%. And the efficiency of ion measurement can be improved by adjusting the voltage setting.

3.2 Gas Ionization and Ion Extraction

According to Sections 2.1 and 2.3, the simulations of GIA ion source have been established. The simulation is refined by adjusting the geometry of the sensor, the voltage of the electrodes and the emission parameters of the cathode. Additionally, the spatial electric field, the emission electrons and the distribution of ions after gas ionization are calculated.

The electrons in the ionization region should possess uniform energy. As mentioned in Section 2.3, the mass resolution is proportional to $(s/\Delta s)^2$. The average energy of electrons in the ionization region and their spatial distribution characteristics perpendicular to the electron beam direction can be determined by adjusting the geometry and voltage configuration of electrodes around the electron path after the cathode emission, as shown in Figure 5(a)(b). Simulations show that the average energy of electrons in the ionization region is about 70 ± 0.35 eV, with an energy deviation not exceeding 0.5%. When the electron beam traverses the ion outlet in

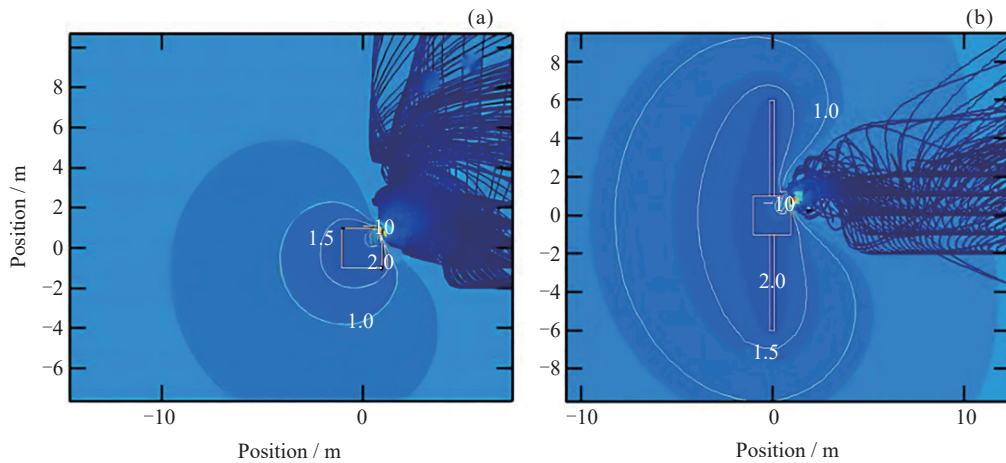


Fig. 3 Effects of the solar panels to the ions moving towards the GIA observation entrance without a solar panel (a) and with a solar panel (b). The voltage of the attract grid is set to −10 V, and the white curves are the contours of the voltage, and the dark blue curves are the path of the particles

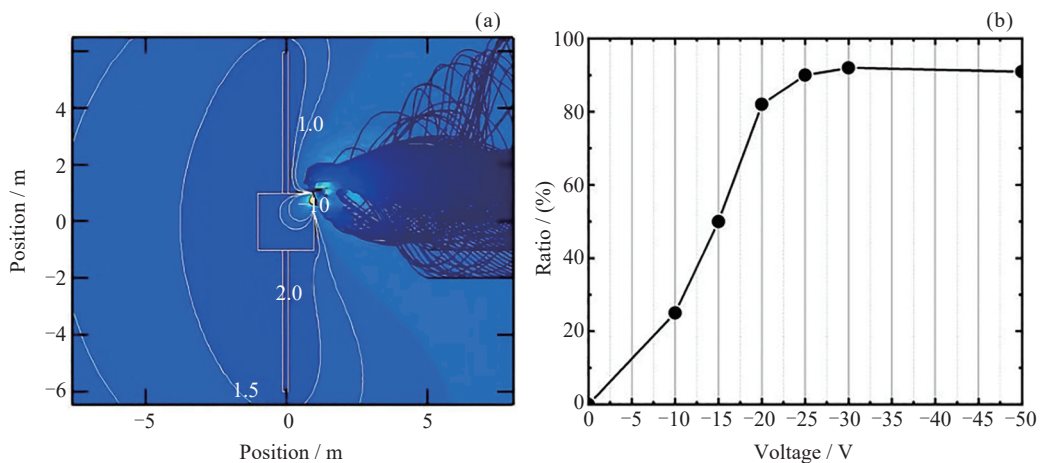


Fig. 4 Effects of the voltage variations of the attraction grid on the total ions arriving at the GIA observation entrance. (a) Effect of the attraction grid voltage set to −25 V on the ions at the GIA observation inlet. The white curves are the contours of the voltage, and the dark blue curves are the path of the particles, (b) the percentage of total ions arrived at the entrance observed by GIA when the grid voltage varies from −10 V to −50 V

the center of the ionization region, 98% of the electrons are confined within a 0.5 mm wide, which is significantly narrower than the width of the ionization region. Consequently, the electrons emitted by the cathode and crossing the ionization region can be regarded as a narrow, parallel electron beam with uniform energy.

As stated in Section 2.3, the potential well formed by space electron charges can bind ions. By this principle, the number of ions in the ionization region can be increased, thereby broadening the dynamic range of detection. Figure 6(a) illustrates the variation of the volt-

age in the central region above the ion outlet parallel to the electron trajectory direction in the ionization region. It suggests that in the absence of an electron beam, the potential distribution within the ionization region exhibits a pronounced peak-shaped structure. This peak reaches its maximum value at the center of the ionization region, thereby exerting a repulsive force on the ions generated. Upon the passage of an electron beam, the potential distribution within the ionization region forms a valley-like structure, in line with the calculated outcome of Eq.(3)(4). Notably, the minimum potential

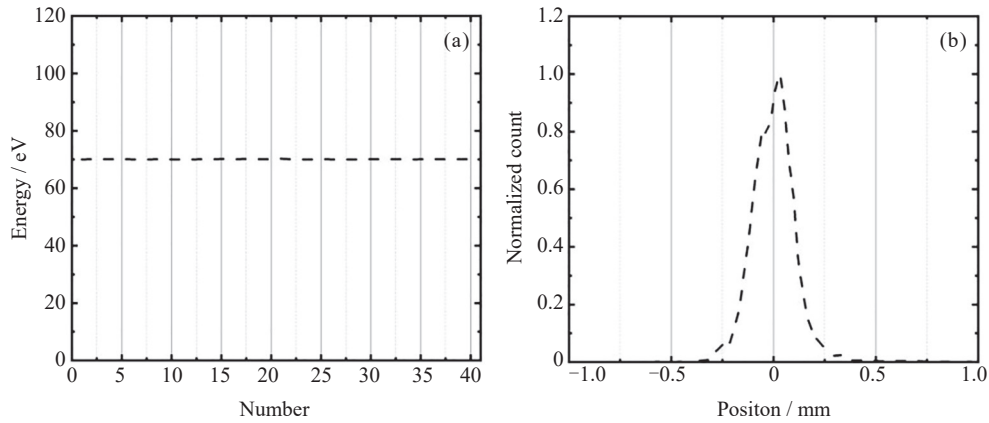


Fig. 5 Electrons distribution in the ionization region. (a) Average kinetic energy of electrons in the ionization region, with the abscissa indicating the electron serial number and the ordinate indicating the electron kinetic energy, (b) electron distribution along the direction of the vertical electron beam at the center of the ionization region. The ordinate represents the normalized value of the total number of electrons, and the abscissa represents the position

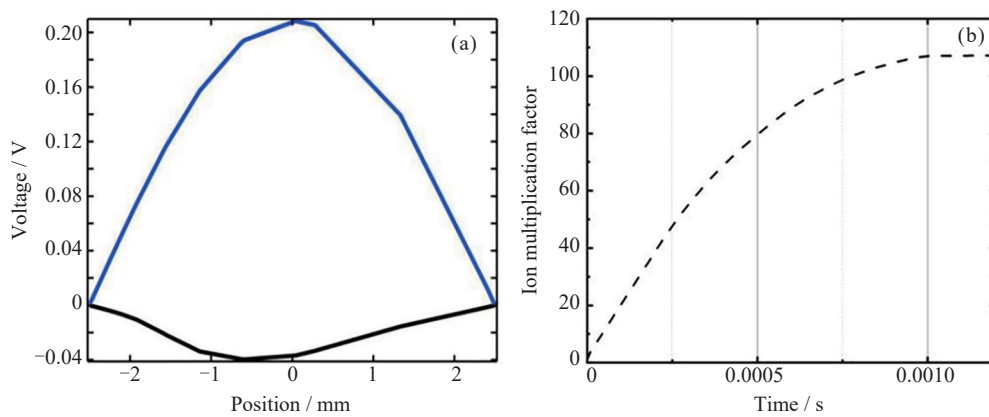


Fig. 6 Electric field distribution and ion multiplication in the ionization region. (a) Profiles of the variation voltage-position in the central region above the ion outlet of the ionization region, aligned to the direction of electron movement. The blue curve represents the voltage variations with position in the absence of electron emission from the cathode. The black curve represents the voltage variations when electron emission from the cathode reaches 50 μA , (b) the variation in the quantity of ions ionized by electrons over the time in ionization region

value occurs at the center of the ionization region. Figure 6(b) illustrates how the electron beam forms a potential well in the ionization region, effectively trapping ions. Consequently, the accumulation of ions within the ionization region exhibits temporal variations. Under influence of the electric field generated by the space electron charges, the number of the bound ions within the ionization region progressively increases over time, ultimately reaching a saturation point at approximately 0.001 s. Subsequently, the total number of ions within the ionization region increased by a factor of about 100. Therefore, we set the ion sampling frequency to 0.001 s. In this time interval, the ion current generated experiences a significant increasing from approximately 3×10^{-16} A to 3×10^{-14} A, thereby substantially enhancing the GIA's lower limits of pressure measurement. This means the dynamic range can reach 10^9 .

3.3 Preliminary Testing Experiment

Preliminary ground testing and verification experiments were conducted for GIA. The experiment was conducted within the ultra-high vacuum system at the National Space Science Center (NSSC), Chinese Academy of Sciences. The calibration uncertainty of the ultra-high vacuum system is better than 4%. The sensor of GIA is mounted in a vacuum tank under test conditions of 20 °C at room temperature, and the atmospheric pressure of the vacuum system is lower than 1×10^{-5} Pa. Figure 7 presents the results of the preliminary test experiment, with the x -axis presenting the flight time of ions (ns), and the y -axis presenting the counts (s^{-1}). The primary gaseous constituents in the test are H_2O and N_2 . The mass spectrum clearly reveals distinct counting peaks

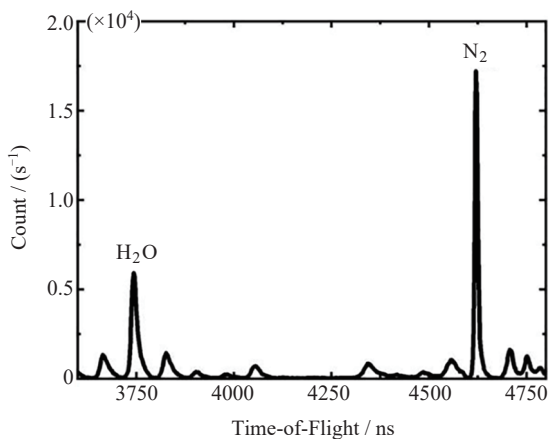


Fig. 7 Preliminary testing experiment result of GIA

corresponding to these gas components, such as H_2O and N_2 . Due to the absence of high-temperature baking, residual water and organic contaminants adsorbed inside the vacuum system were not fully removed, resulting in the appearance of small peaks in the mass spectrum. The preliminary validation experiment confirmed that the GIA is capable of performing mass spectrometry measurements. The ground calibration experiment for the flight model, including detailed quantitative analysis, will be conducted in the future.

4 Summary

The exploration of MBCs is crucial for unraveling the mysteries of the solar system's origin, formation, and evolution trajectories. China's asteroid exploration mission, equipped with the GIA, targets in-situ investigations of the MBC 311P/PANSTARRS. The GIA is designed to obtain data on the composition, abundance, and behavior of atmospheric and ionized environments, surrounding MBCs, such as 311P. This will provide a comprehensive understanding of the dynamic environment around 311P. To achieve precise in-situ detection of neutral particles and low-energy ions, the GIA is designed with the following measurement requirements: a mass range of 1~150 Da, a mass resolution better than 1 Da, and a dynamic range exceeding 1×10^9 .

The instrument utilizes ion attraction, gas ionization, ion multiplication, and Time-of-Flight techniques for in-situ mass spectrometer measurements.

GIA's high-precision mass analysis relies on the ion sampling process, involving ion attraction, gas ionization, and ion multiplication. An ion attraction model has been developed to simulate the entry of ambient ions into the observation entrance through an attracted grid, especially during satellite positive charging. The study of grid voltage and solar panel influence on the incidence of low-energy ions from various initial locations reveals that larger solar panels significantly reduce the number of ions reaching the detection entrance. Moreover, increasing the negative grid voltage boosts the proportion of ions attracted into the GIA sensor until a stable percentage is achieved. This indicates that proper grid voltage adjustment can notably improve the detection efficiency of low-energy ions. An ion source model

has been established to simulate gas ionization and accumulation. Through systematically adjusting the electrode geometry, voltage configuration, and electron current, the model achieves precise simulation of the spatial electric field, electron beam current, and ion distribution. The ionization region's electron energy is stabilized at approximately 70 eV, with fluctuations within 5%. The controllable potential well created by electron space charge traps ions, amplifying their count by about 100 times. This ensures that the ion current generated from neutral particle ionization is stable, consistent, and exceeds the detection threshold within a single sampling period. These advancements greatly improve GIA's ability to sample ionospheric ions and ions from neutral particle ionization, satisfying the requirements for high-resolution and a wide dynamic range in mass spectrometer analysis. Considering the constraints of deep space exploration, such as limited resources, the design employs a time-shifting measurement method to achieve a compact GIA, reducing its size and power consumption.

This study presents three key advancements. First, adjusting the voltage configuration of the attract grid effectively mitigates the impact of satellite surface charging on ion repulsion during sampling. Second, the GIA's ion source has demonstrated the ability to generate ions with stable and consistent current. Third, the space electron charge potential well enables post-ionization accumulation and multiplication of ions, significantly lowering the detection pressure threshold. These conclusions underscore GIA's suitability for in-situ detection of species, abundance, and isotopes of neutral gases and low-energy ions near 311P. A preliminary ground testing and verification experiments were conducted to validate GIA's capability in perceiving gas compositions.

Beyond the key ion sampling techniques discussed above, the mass resolution of GIA is primarily determined by its TOF mass analyzer, where the flight time of ions is directly related to their mass-to-charge ratio. A detailed discussion of the GIA flight model performance, including TOF mass analysis technology and comprehensive ground calibration experiments for the integrated payload, will be provided in subsequent papers to ensure optimal performance during the asteroid exploration mission. Anticipated GIA observations are expected to yield invaluable insights into the mechanisms of

asteroid activity, the evolution of MBCs' atmospheric and ionized environments, the interaction between solar wind and MBCs, and the origin of Earth's water. Furthermore, the breakthrough technologies developed for GIA have the potential to be applied in the exploration of atmospheric and ionized environments of other planets and moons in the solar system.

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