In-flight performance and preliminary observational results of Solar Wind Ion Detectors (SWIDs) on Chang’E-1

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\textbf{A R T I C L E I N F O}

Article history:
Received 21 July 2011
Received in revised form 30 November 2011
Accepted 3 December 2011
Available online 14 December 2011

Keywords:
Moon
Solar wind
Plasma
Electrostatic analyzer
Double ion beams

\textbf{A B S T R A C T}

SWIDs (Solar Wind Ion Detectors, SWID-A and SWID-B) are two of the scientific instruments on Chang’E-1, the first Chinese lunar mission. SWIDs utilize top-hat electrostatic analyzer to measure the low energy (< 20 keV/q) ion distribution of solar wind and the plasma environment around the Moon. SWIDs consist of two identical instruments with two perpendicular fan shaped field-of-views of $180^\circ \times 6^\circ$. The preliminary observational results of SWIDs show that SWIDs were sufficient to measure the basic characteristics of the Moon-plasma interaction. A typical event about the Moon and solar wind interaction is discussed in this paper. Another new observational result near the Moon reported in this paper is the double proton beams coupled with a single alpha beam in solar wind. This is the first double ion beams event reported near the Moon. The double ion beams appeared having relatively anisotropic characteristics due to the interaction between solar wind and the Moon.

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1. Introduction

The plasma environment around the moon has been measured by many orbiters and rovers since 1960s. The basic views about the lunar plasma environment had been achieved by Explorer and Apollo missions in 1960s and 1970s (Ness, 1972; Schubert and Lichtenstein, 1974). After that, Wind, Lunar Prospector, Geotail and Nozomi made some new progress about lunar plasma environment and updated people’s knowledge about lunar plasma environment (Ogilvie et al., 1996; Lin et al., 1998; Nakagawa et al., 2003; Futaana et al., 2001, 2003). The plasma environment around the Moon and the mechanism of interaction between solar wind and the Moon are more complicated than what we expected. In recent years, people pay more attention to the lunar exploration again. Several lunar orbiters such as Japanese Kaguya, Chinese Chang’E-1 and -2 and Indian Chandrayaan have been launched in 21st century. From all the observations before, it seems that we have learned much about the lunar plasma environment. However, there are still some fundamental aspects of the Moon–plasma interaction and how it affects (and is affected by) other aspects of the lunar plasma environment, which need to be learned by human beings (Halekas et al., 2010).

Chang’E-1 (CE-1) is a Chinese lunar orbiter launched in 2007 to study the origin and evolution of the Moon by means of global mapping of element abundances and mineralogical composition, and surface geographical mapping. The 3-axis stabilized satellite CE-1 had a circular polar orbit with an altitude of 200 km before December 2008 and 100 km after that until it hit the Moon on 1 March, 2009. There were eight scientific instruments onboard CE-1. To study and explore the lunar particle environment was one of the four scientific objectives of CE-1 (Ouyang et al., 2010). As two of the scientific instruments, Solar Wind Ion Detectors (SWIDs) were developed to measure the solar wind and also the plasma environment around the Moon.

2. Scientific objectives of SWIDs

The main scientific objectives of SWIDs are to explore the solar wind and to study the mechanism of the Moon–plasma interaction.

2.1. Solar wind characteristics

CE-1 immerged in solar wind for most of its lifetime. So, detection of the characteristics of solar wind around the Moon is
the first main scientific objective of SWIDs. The solar wind characteristics in different areas have been explored by many satellites, such as WIND, Cluster, Interball, IMP series, ACE, Ulysses and so on.

Besides the basic characteristics of the solar wind, an interesting phenomenon, the solar wind double ion beams, has been detected by IMP7, IMP8 and Ulysses (Feldman et al., 1993; Bame et al., 1992; Hammond et al., 1995). There are two kinds of double ion beams. One is double proton beams coupled with a single alpha beam. The other is double proton beams with double alpha beams. Feldman et al. (1993) have shown that the double proton beams coupled with a single alpha beam are nearly always seen in the high-speed solar wind and are the results of reconnection near the coronal base. Hammond et al. (1995) found that the double proton beams coupled with double alpha beams are associated with the heliospheric current sheet from the cases of Ulysses. The double ion beams are always present on either side of the current sheet and are not observed inside the heliospheric current sheet (Hammond et al., 1995). Hammond et al. (1996) have also found that the double ion beams are associated with coronal mass ejections from the data of Ulysses (Hammond et al., 1996).

The double ion beams have also been observed in the terrestrial magnetosheath, which are interpreted as direct evidence for magnetic reconnection (Gosling et al., 1991; Pashmann et al., 1989; Hammond et al., 1995).

2.2. Moon–plasma interaction

The mechanism of the Moon–plasma interaction interests many scientists recently. To study the mechanism of the Moon–plasma interaction is the other scientific objective of SWIDs.

There are two main aspects for the Moon–plasma interaction: dayside interaction and lunar plasma wake. For the dayside interaction, the solar wind interacts relatively weakly with the dayside lunar surface, with most ions impacting and implanting into the surface. The ion scattering/reflection forms an important part of the dayside lunar surface. For the lunar plasma wake, particles can enter the wake by some mechanism. The wake has a number of modes of particle entry, many of which have only recently been observed and properly appreciated (Saito et al., 2011; Halekas et al., 2010 and references therein).

3. Instrumentation of SWIDs

The SWIDs on CE-1 consist of two identical instruments, which are identified as SWID-A and SWID-B. Each instrument of SWIDs utilizes a typical top-hat electrostatic analyzer (ESA) with a fan shaped field-of-view of about 180° × 6° (see Fig. 1). The typical top-hat electrostatic analyzer is a symmetric hemisphere with a uniform response over 360° of elevation angle. The inner and outer hemisphere radii are 40.5 mm and 42.5 mm, respectively. The space between the inner and outer hemisphere is 2 mm. The collimator and outer hemisphere are held at ground potential. In order to reduce the count rate when measuring the solar wind, the aperture is covered by a grid with 10% transmission efficiency. The inner hemisphere is applied with a sweeping voltage from −6.5 V to −2690 V, in 48 logarithmically spaced steps, as shown in Fig. 2. Each voltage step lasts for 61 ms. A beam of parallel ions entering the aperture is focused to a certain location at the exit plane of ESA. This location determines the incident elevation angle of the ions beam. For SWIDs, chevron type micro channel plates (MCPs) are used as particle sensor at the exit plane of ESA. The MCPs have bias angles of about 8°, pore size of 15 μm, and opening area larger than 60%. The ions exiting ESA are accelerated by a −2.3 kV voltage applied to the foreside of MCPs. The anode behind the MCPs responds to 180° of elevation angle, and is divided into 12 sectors. So each instrument has 12 measurement channels, which can be defined as C1 to C12.

The installation geometry of SWIDs is illustrated in Fig. 3 in selenocentric solar ecliptic coordinate system (SSE). The two perpendicular fans indicate the field-of-views of SWID-A and SWID-B. The field-of-views of SWIDs are also shown in Fig. 4 with more details in the spacecraft coordinate system: +X is the flying direction and +Z directs to the center of the Moon. The cross line of the two fans lies in the C8 measurement channel of SWID-A and SWID-B.

4. Pre-flight calibration of SWIDs

The two plasma instruments on CE-1, SWID-A and SWID-B were calibrated by the ion beam facility at IRAP (former CESR) of Toulouse in France (Institut de Recherche en Astrophysique et
The ion beam energy is adjustable from 5 eV to 800 eV with a diameter of 30 mm. Fig. 5 shows the schematic configuration of the pre-flight calibration experiment.

SWID-A/SWID-B was installed on a turn table with one rotation axis parallel to the instrument symmetric axis, which can be defined as $\beta$ angle sweeping. The turn table can also rotate with another axis vertical to the instrument symmetric axis, which can be defined as $\alpha$ angle sweeping. Therefore, the ion beam can cover the whole field of view by the rotation of the turn table.

During the calibration process of each instrument, ten energy points were chosen for the calibration. At each energy point, the ion beam energy was kept constant while sweeping the high voltage of the inner hemisphere. Fig. 6 shows two examples of the $\beta$ angle sweeping characteristics of C5 for SWID-A and SWID-B, respectively. The ion beam intensity during SWID-B calibration process was around 3 times higher than that during SWID-A calibration. The average angle acceptance of each measurement channel for SWIDs is around 15°.

Fig. 7 shows two examples of the energy-$\alpha$ characteristics of SWID-A and SWID-B, respectively. The contour lines in Fig. 7 show the normalized count rate distribution. The energy in Fig. 7 is calculated from the sweeping voltage of inner hemisphere. The geometry factors are calculated based on the characteristics in Figs. 6 and 7.

From the pre-flight calibration, the performances of SWID-A and SWID-B are derived and listed in Table 1.

5. In-flight performance of SWIDs

5.1. Performance of UV rejection

In order to reduce the UV contamination, the inner side of the outer hemisphere of ESA was serrated. As the installation
geometries of SWID-A and SWID-B were different, the UV contaminations of SWID-A and SWID-B appeared different in-flight. For the SWID-A, the UV contamination appeared when the SWID-A saw the sun directly in each orbit and lasted less than 3 min. For the SWID-B, the UV contamination depended on the angle of the sun relative to the orbital plane. The UV contamination of SWID-B appeared scarcely and lasted less than 3 min when the UV contamination appeared.

The count rate caused by the UV contamination in SWID-A and SWID-B was much lower than the count rate of the solar wind. In general, the ratio of the UV contamination count rate and the solar wind count rate was lower than 0.3%, which is acceptable.

5.2. Functional performance

In general, the SWID-A and SWID-B performed well during the whole life of CE-1 in orbit.

Due to the installation geometry, the measurement channels C11 and C12 of SWID-A, the C12 of SWID-B were blocked by the satellite body. The data of these three blocked measurement channels were discarded. The C9 response of SWID-B was about one magnitude lower than the other channels than expected. Maybe there were some problems that occurred in the amplifier gain of C9. Thus, the C9 measurement data of SWID-B should be used carefully.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Performances of SWID-A and SWID-B.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SWID-A</td>
</tr>
<tr>
<td>Energy range</td>
<td>40 eV/q–16.48 keV/q</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>8.1% (FWHM)</td>
</tr>
<tr>
<td>Energy sweep steps</td>
<td>48</td>
</tr>
<tr>
<td>Field-of-view</td>
<td>180° × 5.7° (FWHM)</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>15° × 5.7° (FWHM)</td>
</tr>
<tr>
<td>Time resolution</td>
<td>2.9 s</td>
</tr>
<tr>
<td>G-factor</td>
<td>4.6 × 10⁻⁴ cm² sr eV/eV</td>
</tr>
</tbody>
</table>

* Average G-factor of 12 measurement channels. Efficiency is not included here.
For the electric noise of SWIDs, the average count rate was less than 3 counts/61 ms. This was very low for the solar wind measurement and is acceptable.

6. Preliminary observational results of SWIDs

The preliminary observational results shown below are related to three days, which are 2007-12-11, 2007-12-18 and 2008-05-28, respectively. In order to understand the observational results better, the locations of the Moon relative to the magnetopause (Shue et al., 1998) and bow shock (Fairfield, 1971) are plotted in Fig. 8.

The following definitions are introduced for convenience. The lunar longitude 0° crosses through the intersection of the Earth–Moon connection line and the lunar surface. The positive longitude value lies in the eastern hemisphere, while the negative value lies in the western hemisphere. The sun incident angle is defined as the angle between the symmetric axis of the measurement channel and the Sun–Moon connection line. The figures below use the same definition of longitude and the sun incident angle.

6.1. Solar wind spectrum

From the installation geometry of SWID-A and SWID-B, SWID-A measured the solar wind with only one measurement channel, which was C9 for the most operational time in orbit. SWID-B measured the solar wind in a sequence of C12 to C1. Fig. 9 shows the solar wind E-t spectrogram measured by SWID-A on 2007-12-18 shortly after CE-1 was launched. SWID-A swept over the solar wind along the α angle and only C9 measured the solar wind. When C9 of SWID-A measuring the solar wind, the spacecraft was near the equator of the Moon and the longitude was about +70°.

Two obvious peaks are shown in the energy spectrum in Fig. 9, which are indicated by two white arrows. The energy of the two peaks is around 1.8 keV and 3.6 keV, respectively, which can be identified as H⁺ and He²⁺ by the ratio of energy and charge. The bulk velocity calculated from the energy spectrum of the solar wind was about 580 km/s. This velocity was consistent with the solar wind data from ACE satellite by a time shift method of about 1 h delay. Another interesting phenomenon in this figure is the low intensity ions at around 03:25 UT, which may have come from the accelerated solar wind ions reflected by the lunar surface, since the spacecraft was located around the south pole (Saito et al., 2010; Wang et al., 2010).

Fig. 10 shows the solar wind E-t spectrogram measured by SWID-B on 2007-12-11. The Moon lied almost on the Sun–Earth line, which indicates that the spacecraft was totally immersed in the solar wind. There are ten panels in Fig. 10, showing the SWID-B measurement of the solar wind, which are in a sequence C1–C8, C10 and C11 from the top to the bottom. SWID-B swept over the solar wind along the β angle. So each measurement channel of SWID-B could see the solar wind one by one. The solar wind velocity during the observational time in Fig. 10 increased from 510 km/s to 580 km/s, which was consistent with the solar wind monitor data from ACE satellite by a time shift method. In some panels of Fig. 10, the solar wind intensity appeared small variations during the observational time.
6.2. Accelerated ions near the Moon

From the measurements of SWID-B, the accelerated solar wind protons were detected and one case about the acceleration of backscattered solar wind close to the terminator of the Moon was discussed. (Wang et al., 2010)

Here, a case of accelerated ions near the Moon on 2008-05-28 is shown in Fig. 11. Two populations of ions in addition to the solar wind ions were observed in this case. One population of ions had a lower flux intensity and lower energy, lasted from 02:35 to 03:25 and from 04:30 to 04:42 and marked with horizontal dark line, which is named as type A accelerated ions in this paper hereafter. The other population of ions had a higher flux intensity and energy that lasted from 02:52 to 04:01 and marked with horizontal red line, which is named as type B accelerated ions in this paper hereafter. The solar wind occurred from 03:25 to 03:45, marked with horizontal blue line. There are four typical positions identified in Fig. 11, which are P1–P4: P1 locates at the north pole; P2 locates at the equator of the dayside; P3 locates at the south pole and P4 locates at the night side of the south pole. For the type A ions, the energy was sustained around 350 eV. For the type B ions, the energy first increased from 350 eV to 4 keV, then decreased from 4 keV to 2.5 keV. During the observational time in Fig. 11, the three components of IMF from time-shifted ACE satellite data are plotted in the bottom panel.

From the map of near side lunar surface magnetic field anomalies (Richmond and Hood, 2007; Tsunakawa et al., 2010), CE-1 flew over three typical strong magnetic anomalies Reiner Gamma (RG), Rima Sirsalis (RS) and Hartwig (HW) when the spacecraft was near the equator of the Moon. The spacecraft orbit footprint in dashed line and the three typical locations P1, P2 and P3 in Fig. 11 are plotted on the map of the near side Moon in Fig. 12. The locations of the three typical strong magnetic field anomalies are shown schematically by diamonds. RG, RS and HW are the three typical magnetic field anomalies, which are Reiner Gamma, Rima Sirsalis and Hartwig, respectively. The dashed curve indicates the footprint of CE-1.

6.3. Solar wind double ion beams

The proton and alpha particle peaks were simultaneously observed many times by SWIDs during the whole mission.
Besides, for some high speed solar wind, SWIDs also measured a kind of double ion beams. Fig. 13(a) shows a case of solar wind double ion beams observed by SWID-B at 12:54:48 UT on 2007-12-18, which was a double proton beams coupled with a single alpha beam. Fig. 13(b) shows the observational geometry relative to the Moon in selenocentric solar ecliptic (SSE) coordinate system. CE-1 was immersed in solar wind and located near the north pole of the Moon when the double ion beams were observed. Since there was no magnetometer on CE-1, we use the IMF data from ACE satellite by a time shift method. The three components Bx, By and Bz of IMF were around −4 nT, −0.3 nT and −4 nT, respectively, when the double ion beams occurred.

In Fig. 13(a), three measurement channels C2, C3 and C4 measured the solar wind simultaneously. But the three spectra curves show different characteristics from each other. That means the solar wind had a quite anisotropic property for the double ion streams. Each curve has three peaks. The first two peaks show the double proton beams, which are indicated approximately as vertical arrows between 500 km/s and 700 km/s. The single alpha particle beam is indicated approximately as vertical arrows between 800 km/s and 950 km/s. No distinct two alpha beams are seen in the three curves in Fig. 13(a).

The first proton beam velocity is defined as $V_{HL}$. The second proton beam velocity is defined as $V_{HH}$. The alpha beam velocity is defined as $V_{HE}$. For all the three curves measured by C2, C3 and C4 in Fig. 13(a), the higher speed proton beam’s velocity $V_{HH}$ is around the same as the alpha beam velocity $V_{HE}$ and about 63 km/s higher than the lower speed proton beam’s velocity $V_{HL}$. C3 and C4 have almost the same $V_{HL}$, $V_{HH}$ and $V_{HE}$, which are about 30 km/s higher than those values in C2 curve. For the curves of C3 and C4, $V_{HE}$ is estimated around 575 km/s and $V_{HH}$ is 638 km/s, respectively.

The local Alfven velocity, calculated using the IMF $B_0$ value of 5.6 nT and solar wind density of 3 cm$^{-3}$ from ACE satellite with a time shift, is about 70 km/s. The velocity difference of 63 km/s between the two proton beams was approximately the same as the local Alfven velocity of 70 km/s. Accounting for the error of IMF and solar wind density values by time shift method from ACE satellite, the result above is reasonable.

7. Discussion and conclusion

In general, SWIDs, as two scientific instruments of CE-1, were sufficient to measure the solar wind and the plasma environment near the Moon.

Besides the normal in-flight observations, SWIDs also measured some interesting phenomena in the near Moon plasma environment, such as the cases of accelerated ions in Fig. 11 and double ion beams in Fig. 13 reported in this paper. Since it is not easy to interpret the two cases clearly in one paper, more work need to do in the future. Here, some speculations are given here about the accelerated ions and double ion beams.

7.1. Accelerated ions near the Moon

In order to better understanding the observational result in Fig. 11, the observational geometry of SWID-B at the four typical locations are plotted in Fig. 11(a) in selenocentric solar ecliptic coordinate system. As what is shown in Fig. 11(c), the type B accelerated ions energy and intensity increased dramatically around the P2 position, while the spacecraft was near the equator and met with the three typical magnetic anomalies in Fig. 12. A speculation can be given that the magnetic anomalies may have a great influence on the accelerated ions. The magnetic anomalies influence maybe appeared in two possible ways, which were self-pickup acceleration and mini-magnetosphere.

For the self-pickup acceleration, the solar wind ions can be backscattered by the lunar surface or reflected by the magnetic anomaly field. The backscattered or reflected ions can be accelerated by the solar wind, which can be called self-pickup ions. The maximum acceleration energy is nine times of the solar wind energy (Saito et al., 2010).

The mini-magnetosphere near the Moon has been confirmed by simulation and observational results (Harnett and Winglee, 2002; Kurata et al., 2005; Weiser et al., 2010). Kurata et al. (2005) also reported the presence of a mini-magnetosphere above the Reiner Gamma magnetic anomaly (RG). From the particle simulation results with no interplanetary magnetic field done by Harnett and Winglee (2002), the solar wind can be deflected by
the magnetic anomaly filed and accelerated primarily in the downstream region. The solar wind energy can be enhanced by more than an order of magnitude and the solar wind intensity can be increased by a factor of 3 to 5.

The type A and type B accelerated ions maybe the results of the self-pickup acceleration, mini-magnetosphere effect or some other effects. During the observational time in Fig. 11, the By component of IMF kept negative and the magnitude increased from about $-5 \text{nT}$ to $-10 \text{nT}$. So, the IMF may be another important factor that needs to be evaluated. The influence of the IMF on the size and the shape of the mini-magnetosphere was reported by Harnett and Wingle (2002).

In order to understand and interpret the phenomenon well, much more work needs to be done in the future.

7.2. Solar wind double ion beams

The solar wind double ion beams are a new result of SWID-B. It is a kind of two proton beams coupled with a single alpha beam. Feldman et al. (1993) made an interpretation of this kind observation of IMP7 and IMP8. It was linked to coronal heating and acceleration. The acceleration was associated with the direct conversion of magnetic energy flux to plasma convection and enlathly flux through the process of magnetic reconnection.

There is some difference between SWIDs observations and IMP7/IMP8/Ulysses observations. The double ion beams measured by SWIDs show distinct anisotropic characteristics. Accounting for the orbit of CE-1 and IMP7/IMP8, CE-1 had a circular orbit with 200 km altitude from the Moon. IMP7 and IMP8 had a circular orbit with nearly 200,000 km altitude from the Earth. Ulysses had an interplanetary orbit. CE-1, IMP7/IMP8 and Ulysses measured the double ion beams in three different areas and the double ion beams shown different characteristics. So, we can make a speculation that the Moon–plasma interaction may have an influence on the anisotropic property of the double ion beams. In this paper, we just show the phenomenon of double ion beams measured by SWIDs. There is still some more work needed to interpret the anisotropic double ion beams near the Moon.

Acknowledgments

We thank all the members of SWIDs work team. We acknowledge Professor Henri Reme to provide the opportunity to calibrate the SWIDs at IRAP of Toulouse in France (Institut de Recherche en Astrophysique et Planétologie). We thank the ACE team to provide the solar wind plasma and IMF data. We thank professor Li Lei and Dr. Zhang Yiteng for helpful suggestions. This research is supported by National High-Technology Research and Development Program of China (No. 2010AA122205).

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