Counter-Streaming Electrons in the Near Vicinity of the Moon Observed by Plasma Instruments Onboard NOZOMI

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Abstract. The NOZOMI spacecraft approached the Moon at an altitude of about 2,800 km at 7:34UT on Dec. 18, 1998. Around the time of closest approach, a plasma instrument PSA/ESA detected non-solar-wind electrons in addition to the normal solar wind component. From the characteristics of the electron distribution function, we can categorize these events into two types: (1) backstreaming electrons exhibiting a similar velocity distribution to the solar wind electrons. But its phase space density ratio to the solar wind electrons decreases as a function of velocity. (2) backstreaming electrons that are thermalized and have a comparable or dominant flux to the solar wind electrons. We considered possible source locations as well as possible mechanisms that can produce these backstreaming electrons. After careful investigation of the velocity distribution function of the electrons and the magnetic field orientation, we concluded that their origins are: i) the lunar wake region, where the electrostatic potential drop associated with ambipolar plasma expansion reflects the solar wind electrons and produces backstreaming electrons of the category (1), and ii) the terrestrial bow shock, where the electrons are thermalized downstream and escaping electrons are of category (2).

1. Introduction

In situ plasma and magnetic field measurements around the Moon have been conducted by several spacecraft. The first measurements were made by Explorer 35 in the late 1960s and by Apollo sub-satellites in the early 1970s (see review by Schubert and Lichtenstein[1974], and references therein). They proved that the Moon has no significant intrinsic magnetic field and that no bow shock or magnetosheath is formed around the Moon [Ness et al., 1967]. It was also reported that a void cone of plasma and expanding rarefaction waves should be created behind the Moon by the absorption of solar wind electrons and ions at the lunar surface [Johnson and Midgley, 1968].

The WIND satellite traversed the lunar wake on Dec. 27, 1994 at a distance of ~6.8 R_L from the Moon at the time of closest approach. Ogilvie et al. [1996] found an increase in electron temperature and the appearance of two distinct cold ion beams in the lunar wake region, as predicted by a simple theory. In the upstream region of the wake, intense ULF waves and energetic electron flows were detected [Farrell et al., 1996]. Also electrostatic ion acoustic waves and Langmuir waves were observed in the upstream region of the wake [Bale et al., 1997]. They both concluded that the observations of the wake precursor region revealed similar characteristics to those that can appear the upstream of collisionless bow shocks.

The Lunar Prospector, which was launched on Jan. 16, 1998 and intentionally crashed into the lunar surface on July 31, 1999 to verify the existence of water had a magnetometer and an electron reflectometer (MAG/ER) to investigate the nature and origin of the Moon's magnetic fields. These instruments mapped lunar crustal magnetic fields and observed the interaction between the solar wind and regions of strong crustal fields. Lin et al. [1998] reported that a miniature bow shock system is formed when a strong crustal field interacts with the solar wind.

On July 4, 1998, the NOZOMI spacecraft was successfully launched. The primary objective of this project is to study the Martian aeronomy and plasma environment, with special emphasis on the interaction of the Martian upper atmosphere with the solar wind [Yamamoto and Tsuruda, 1998]. To alter the orbit of the spacecraft, two lunar swing-bys and one terrestrial swing-by were performed. Plasma observations with the PSA/ESA and PSA/ISA onboard NOZOMI were conducted at the closest approach of the second lunar swing-by on Dec. 18, 1998, and data were successfully obtained. This paper presents the observational results and discusses the signature and characteristics of the plasma environment upstream of the lunar wake.

2. Instrumentation

The 3-D electron observations were performed with the Electron Spectrum Analyzer (PSA/ESA) mounted on the NOZOMI spacecraft. The PSA/ESA can measure electrons from 12 eV to 15 keV in 32 energy steps. However, the energy range was limited from 12 eV to 3 keV with 32 logarithmically spaced energy steps during the second lunar swing-by of NOZOMI. With one spin rotation (about 6.5 s at that time), the PSA/ESA could cover a full 4π steradian viewing angle with 22.5×22.5 angular resolution. Because of telemetry limitations, approximately 1/10 of the data (about 1 minute period) were transmitted until 07:37UT, and no data could be obtained from 07:19UT to 07:24UT and from 07:37UT to 07:42UT. Between 07:42UT and 07:47UT, all spin data were obtained. More detailed characteristics of the PSA/ESA can be found in a paper by Machida et al.[1998].

Though magnetic field observations were performed by NOZOMI MPM/MGF, we were unable to use those measurements for the period of lunar swing-by. A three-axis fluxgate magnetometer of the MPM/MGF is installed at the end of a 5-m deployable mast. However, the mast will not be extended until the insertion of the NOZOMI into Mars orbit, so magnetic field data were contaminated by a variety of electromagnetic noise originating from the onboard instruments. On the day of lunar swing-by, the strength of the interplanetary magnetic field was about 3 nT, which is relatively small. Consequently, the relative error in the magnetic field is large. Moreover, the operation of many instruments onboard NOZOMI during the lunar swing-by considerably affected the electromagnetic field environment of NOZOMI and made it difficult to reduce the artificial noise in the magnetic field data. For these reasons, we did not use MPM/MGF data in this analysis. Instead, we estimated the magnetic field orientation from the anisotropy of electron distribution functions obtained by PSA/ESA.

We used WIND and ACE data to evaluate the accuracy of the estimation by PSA/ESA. Taking the distance of the spacecraft as well as the plane surface of the solar wind structure which had a normal angle of $\sim 65^\circ$ with respect to the solar wind velocity vector into account, the magnetic field orientations estimated by PSA/ESA is very similar to those observed by other satellites.

3. Observations

The NOZOMI spacecraft made its second lunar swing-by on Dec. 18, 1998. The time of the closest approach was 7:34 UT and the altitude from the lunar surface was about 1.6 R_L (~2,800 km) where R_L(=1,738 km) is the radius of the Moon. The orbits of the Moon and NOZOMI are shown in Figure 1. In the left panels, the position of the Moon and its orbit are indicated in the GSE coordinate system. Both the Moon and NOZOMI were located in interplanetary space, rather than in the shocked magnetosheath plasma behind the terrestrial bow shock, or within the magnetosphere. The right panels of Figure 1 display the relative position of NOZOMI to the Moon during the interval from 06:00UT to 09:00UT. Here the coordinates are shown in Lunar-Centered GSE (LCGSE), which are centered on the Moon and the orientation of each axis is the same as in the GSE coordinate system.

Figure 1

Plate 1 shows the energy-time diagram of the electrons obtained by PSA/ESA during NOZOMI's lunar swing-by. The three panels indicate the time sequences of the electron counts obtained by three different channels which have the center view angles of 33.75, 146.25, and 168.75° with respect to the spin axis [Machida et al., 1998]. The periodic variation of the count is due to the spin modulation of NOZOMI spacecraft with a spin period of about 6.5 s. It should be noted that the count data of the PSA/ESA were not continuous because of telemetry limitations, and the interval between two sequential data was not constant. The PSA/ESA could observe electrons with energy between 12 eV and 3 keV at that time. Due to instrumental problems the data in the

Plate 1

lower energy steps (< 60eV) need corrections, and electron counts of energies greater than 500 eV are small. We show electron count data in the energy range from $\sim$ 60 eV to $\sim$ 500 eV, which corresponds to the suprathermal component of the solar wind electrons.

We can see enhancements of sunward flowing electrons (CH-1 and 2) around the NOZOMI's closest approach to the Moon as indicated in Plate 1. These enhanced sunward fluxes can be assumed to be parallel to the magnetic field [Feldman et al., 1975], so we estimated the orientation of the magnetic field from the electron velocity distribution function. In the following, we discuss details of the data obtained during 7:08UT and 7:16UT (Solar wind, for reference), 7:25UT and 7:36UT (Event-1), and 7:42UT and 7:43UT (Event-2).

The electron data obtained in the normal solar wind during 7:08UT and 7:16UT are shown in Plate 2. Note that these are average data for eight spin periods of NOZOMI spacecraft. Four left panels in Plate 2 show the full two-dimensional angular distribution of electrons with energies of 358, 239, 160 and 108 eV, observed during 7:08UT and 7:16UT (upper panels) and the pitch-angle-sorted electron counts with the same energy steps (lower panels). Here, we used spacecraft coordinate (SC) system, which has the origin at the spacecraft center, and the z-axis parallel to the spin axis. The x-axis is perpendicular to the z-axis and lying on a plane that contains the z-axis and the sun. The y-axis is define so as to form the right-hand system. In the upper panels, the direction of zero spin angle is defined to contain the sunward flow vector of the electrons. By assuming the solar wind electrons to be gyrotropic, it is possible to

Plate 2

estimate the orientation of the magnetic field from the electron distribution function. In this case, the orientation of the averaged magnetic field (i.e., the elevational angle θ and the spin angle ϕ of the magnetic field) was determined being $\theta = 152°$ and $\phi = 149°$ in the SC coordinate system, which corresponds to the components of the unit vector of the magnetic field to be (-0.85, 0.37, -0.36) in the GSE as well as LCGSE coordinate systems. Pitch angle ($\alpha = \tan^{-1}(v_{\perp}/v_{||})$) contours of 30°, 60°, 90°, 120°, and 150° with respect to the estimated magnetic field orientation are also superimposed on the electron angular distribution data. Using the estimated magnetic field orientation, we obtained the electron pitch angle distribution; the results are shown in the lower panels. The right panel in Plate 2 displays the velocity distribution functions of electrons. The red curve is for the electrons with pitch angle of $0° < \alpha < 30°$, which stream away from the sun along the magnetic field, the blue curve is for those of $150° < \alpha < 180°$, which stream toward the sun along the magnetic field, the dotted line is for those of $90° < \alpha < 120°$, which have velocities perpendicular to the magnetic field line so that are trapped by the magnetic field. The thin black curve shows the one-count level of PSA/ESA. As can be seen, these data had a common solar wind character in that the phase space density of electrons away from the sun was five times larger than that toward the sun, and both had power-law distributions in velocity over ~7,000 km/s.

The observational result around 7:30UT when the first enhancement of electron counts was observed is shown in Plate 3 in the same format as Plate 2. The data in Plate 3 are also eight-spin-period data. Because of the low edit rate of NOZOMI, we could not sum over continuous time interval so that we used data when back streaming

Plate 3

electron flux were apparently enhanced (Plate 1). The magnetic field, which was also estimated from the three-dimensional electron velocity distribution function, was $\theta = 133°$ and $\phi = 139°$ in the SC coordinate system, (the unit vector of the magnetic field had components of (-0.86, 0.52, -0.04) in the GSE and LCGSE coordinate systems), and was slightly different from the previous case in the solar wind. It is obvious that the backstreaming electrons along the magnetic field were broadly enhanced in the color-coded angular distribution maps of Plate 3. This can also be clearly seen in the lower four panels of the pitch angle count data; namely, electron counts with pitch angles of more than 90° were clearly enhanced.

Plate 4

Plate 4 shows the observational results at $\sim$ 7:43UT, when the second electron flux enhancement occurred. The features of electrons look similar to Event-1, but there are some differences from that event. One of the most important differences is that there was no significant flux decrease around 180° pitch angle. The second difference is that the reflected electrons have comparable flux to the ambient solar wind electrons or they dominate the ambient solar wind electrons in the higher energy ranges. This can be clearly seen in the velocity distribution functions. Namely, the backstreaming reflected electrons ($150° < \alpha < 180°$) overwhelm the nominal electrons ($0° < \alpha < 30°$) in the higher energy, i.e., in the higher velocity range ($\gtrsim$ 8000 km/s). This implies some mechanism that thermalized the solar wind electrons and reflected them back along the magnetic field line to the spacecraft location.

Similar events of backstreaming electron enhancement were observed during the time interval from 7:45 to 7:55 UT. Their characteristics are the same to Event-2.

Since the signatures of the electron distribution functions are different in Event-1 and Event-2, it is appropriate to assume that the reflection processes are different for these two cases. We discuss the reflection process in the following section.

4. Discussion

It is essential to determine the location where the electron reflection occurred and to understand the mechanism of the reflection. Since the electrons in the energy range over 60 eV, which are studied in this paper, had velocities much faster than the bulk velocity of solar wind electrons, we can roughly consider that the enhanced electrons simply came back along the magnetic field line.

The locations of the Earth, Moon, and NOZOMI and the magnetic field which crossed the spacecraft and the solar wind ion velocity at 07:11:22UT, when no reflection events were observed, are shown in Figure 2. In each panel, the thick line corresponds to the magnetic field and the arrow almost along -x direction indicates the solar wind ion velocity. The dotted line is a trajectory of the Moon (right panels) and NOZOMI (left panels). The left and right panels are shown in the GSE and LCGSE coordinate systems, respectively. The orientation of the magnetic field was also obtained from the electron data.

Figure 2

Figure 3 shows the results at 07:32:08UT, when Event-1 was occurred in the same format as Figure 2. The magnetic field pointed toward the night side region in the vicinity of the Moon, namely, the lunar wake region. Figure 4 shows the results for Event-2. In this case, the magnetic field line did not seem to traverse the lunar wake

Figure 3

Figure 4

region.

The characteristics of the plasma and the magnetic field in the lunar wake region have been discussed since the late 1960s. Solar wind plasma particles collide with the lunar surface and are simply absorbed, creating a void region in the downtail. The plasma passing the terminator flows into the void region and rarefaction waves are created simultaneously. In the void region the magnetic field is intense in order to maintain the pressure balance with the solar wind [Michel, 1968].

Recently, the plasma measurement in the lunar wake has been conducted, and it was reported that the ions were accelerated along the magnetic field line by ambipolar diffusion process [Ogilvie et al., 1996]. This process was comprehensively shown by computer simulation [Farrell et al., 1998]. The ambipolar electric field accelerates the ion in the direction of the plasma expansion, but it also reflects the electrons in the opposite direction. Those electrons can escape the wake region along the magnetic field line and form the counter-streaming electron distribution in the vicinity of the Moon. This can be a possible mechanism to account for Event-1.

According to this mechanism, an electron with kinetic energy greater than that corresponds to the potential drop cannot be reflected back and travel through the wake. Therefore, we have no reflected electrons in a higher energy range. As can be seen in Plate 3, there are backstreaming antisunward electrons in Event-1 in the velocity range below 8,000 km/s, compare to the solar wind case which is shown in Plate 2. The ratio of the phase space densities for sunward, trapped and antisunward electrons seems to take about the same value to the nominal solar wind case beyond 13,000 km/s. This corresponds to 480 V potential drop, which is close to the value of 400 V obtained by Ogilvie et al. [1996] based on the accelerated ion data from the WIND spacecraft.

As for Event-2, we cannot conclude that the reflection process is due to the ambipolar potential drop in the lunar wake for two reasons. First, the magnetic field did not seem to point toward the lunar wake region, as can be seen in Figure 4. Second, the backstreaming electrons were apparently thermalized differently from Event-1.

An alternative interpretation of this event is that the reflected electrons originated from the terrestrial bow shock. Solar wind electron velocity distributions upstream of the terrestrial bow shock are characterized by a counter-stream structure and a thermalization of backstreaming electrons attributed to the heating at the bow shock [Feldman et al., 1983a]. The orientation of estimated magnetic field is also consistent with this interpretation if we consider ±20° ambiguity of our estimation. This can be applied to the other cases similar to Event-2 observed from 7:45 UT to 7:55 UT which were explained earlier.

One other possibility is that these counter-streaming electrons are created in the interplanetary shock. However, as can be seen in Figure 5, which indicates the magnetic field obtained by the electron data in the GSE coordinate system, no dynamic change in the magnetic field occurred around the time this event was observed. Moreover, interplanetary shocks have a smaller Mach number than the bow shock. Consequently, perpendicular heating is stronger than parallel heating [Feldman et al., 1983b]. Our observational results do not exhibit notable perpendicular heating (Plates 2 and 4).

Figure 5

Another possibility is that backstreaming electrons resulted from the magnetic mirror effect of the lunar crustal field. This idea is compatible with the reduction of the electron flux near 180° pitch angle, which indicates an existence of loss cone as can be seen in Plate 3. From the observations of Apollo Subsatellite and the Lunar Prospector, we know that there are regions on the lunar surface that are characterized by crustal magnetic fields. If the solar wind magnetic field were connected to the magnetized crustal region and this intensified the magnetic field, then the electrons with small pitch angles would be reflected by the mirror force and return along the magnetic field line. This mechanism could produce a similar characteristics in the electron data as Event-1. However, there is a difficulty; namely, the solar wind magnetic field cannot be connected to a spatially confined magnetized crustal region, whose scale size is very small, for at least 6.5 s (one spin period of NOZOMI). The idea of a mini bow shock is related to this mechanism. According to Lin et al.[1998], a mini bow shock can be generated in front of the crustal magnetic field anomaly region. However, this possibility is also excluded by the same reason as the mirror force due to the crustal magnetic field, namely, the mini bow shock is too small to be connected for at least 6.5 s by the magnetic field. Moreover, the non-thermalized velocity distribution in Event-1 also negates this model.

A further possibility for the source of the backstreaming electrons is photoelectrons generated in the tenuous lunar atmosphere or at the lunar surface. In Event-1 (7:24UT $\sim$ 7:36UT), the magnetic field can be said to point to the lunar surface when deviations of the estimated magnetic field are considered. If this configuration really occurred, the photoelectrons could have traveled along the magnetic field to the spacecraft's location. However, the spectrum of the backstreaming electrons of Event-1 (blue curve in the right panel in Plate 3) is very similar to that of the solar wind (that in Plate 2). As for Event-2 ($\sim$ 7:43UT), the magnetic field did not seem to be connected to the lunar surface, and no photoelectrons could be observed.

For Event-2, one may say that the magnetic filed line traversing NOZOMI can also traverse the distant region of the lunar wake, if we consider a possible error of $\pm 20^\circ$ in determining the magnetic field orientation. Further it is expected that there is a region of the ion beam disruption in the central part of the lunar wake beyond the distance of $\sim$20R_L from the center of the Moon [Farrell et al., 1998]. There is a possibility that electrons are heated due to the plasma instability associated with the ion beam disruption, and escape out of the wake having similar characteristics to the backstreaming electrons from the Earth bow shock. This is an attractive idea but we think that there is still not much evidence to support the idea. We would like to address investigating the electrons in the distant wake region as a further study.

5. Conclusions

Observations by the PSA/ESA onboard the NOZOMI spacecraft around the time of the NOZOMI lunar swing-by on Dec. 18, 1998, 7:34UT showed backstreaming electron enhancements in relatively high energy ranges. We classified these events into two types by the characteristics of the electron velocity distribution. Event-1 was observed during 7:24UT and 7:36UT and Event-2 around 7:43UT and 7:45UT $\sim$7:55UT. In Event-1, the spectrum of backstreaming electrons was very similar to that of solar wind electrons. But the ratio of these electors in the phase space density has an energy dependence, which can be interpreted by the electron reflection by the ambipolar potential drop in the lunar wake. In Event-2, the spectrum of backstreaming electrons had a different feature from the solar wind electrons, and we think the backstreaming electrons originated from the thermalized electrons in a downstream region, possibly in the terrestrial bow shock. We considered several possible origins of the backstreaming electrons, e.g., the crustal magnetic field at the lunar surface, lunar photoelectrons, the magnetic field environment around the Moon, interplanetary shocks, and the terrestrial bow shock. After careful inspections of the electron distribution in the energy and velocity phase spaces and the magnetic field orientation estimated from the electron data, we finally concluded that the mechanism of the reflection is the ambipolar potential drop in the lunar wake for Event-1 and the terrestrial bow shock for Event-2.

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Figure 1. Trajectories and locations of the Earth and Moon (left panels) and those of Moon and NOZOMI (right panels) at the time of NOZOMI's closest approach to the Moon (Dec. 18, 1998 7:34 UT). The left panels use the GSE coordinate system and the right panels the Lunar-Centered GSE system. The unit of length is a radius of the Moon (R_L). In the right panels, the position of NOZOMI is indicated by asterisk(*) and the size of the Moon is to scale.

Figure 2. Locations of Earth, Moon, and NOZOMI in the same format as Figure 1 at around 7:11:22UT, when the nominal solar wind were observed. The solid thick line in each panel shows the estimated magnetic field orientation and the arrow shows the direction of the solar wind velocity.

Figure 3. Locations of the Earth, Moon, and NOZOMI at the time Event-1 occurred, (7:32:08UT). The format is the same as in Figure 2. The magnetic field pointed toward the lunar wake region in this case.

Figure 4. Locations of the Earth, Moon and NOZOMI at the time of Event-2 (7:42:34UT). The format is also the same as in Figure 2. The magnetic field did not seem to reach the lunar wake region.

Figure 5. Time series of the magnetic field orientation around the time of NOZOMI's closest approach to the Moon (7:34UT). These data were estimated from the electron data. The time of closest approach (CA), Event-1 (Ev-1), Event-2 (Ev-2), and the solar wind (SW) are superimposed. Because of telemetry limitations, the data are not continuous. No rapid changes in magnetic field occurred during this time period.

Plate 1. Energy-time diagram obtained by PSA/ESA during the NOZOMI lunar swing-by. From top to bottom, counts/sample for CH-7, 2, and 1. Each segment corresponds to one spin data. The measurements are plotted sequentially but the time interval between measurements is not constant across the plot. The black line segments at the bottom of the plot map the measurements samples to a time axis. The mapping reveals the data gaps from 07:19 UT to 07:24 UT and from 07:37 UT to 07:42 UT. After ∼ 07:24 UT, when NOZOMI was very close to the Moon, electron counts in CH-1 and 2 were enhanced.

Plate 2. Detailed electron data obtained at 7:08UT ∼ 7:16UT, when normal solar wind electrons were detected. The data are averaged over 8 spins. The four left panels show the angular distribution of electrons and the pitch-angle-sorted electron counts with energies of 358, 239, 160, and 108 eV. The curves in the upper panels indicate the pitch angle contours of 30°, 60°, 90°, 120°, and 150° with respect to the estimated magnetic field. The right panel shows the velocity distribution functions of electrons. The red curve is for the anti-sunward flowing electrons, the blue curve is for the sunward streaming electrons, and the dotted curve is for the electrons having velocities perpendicular to the magnetic field. The thin solid curve is the one-count level of PSA/ESA.

Plate 3. Detailed electron data at the time of Event-1 occurred (7:24UT ∼ 7:36UT), in the same format as Plate 2. Data are summed over 8 spins. Compared with Plate 2, there are more electrons with pitch angle $\alpha > 90°$, which implies the counter streaming distribution.

Plate 4. Detailed electron data at the time Event-2 was observed (7:42UT $\sim$ 7:43UT). The format is the same as Plate 2. Data are summed for eight spins. In this case, the backstreaming electrons seem to be thermalized.