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Modelling of the electrostatic environment of the moon on the day side and the night side under various solar wind flux conditions

Nandana. H [b], Nayana. H [b], Sibi K S [a] ,Rakesh Chandran S. B [b*]

[a] *Department of Physics,University of Kerala, Karivattom Campus, Thiruvananthapuram, Kerala, India,695007*

[b] *PG Department of Physics, Sanatana Dharma College, University of Kerala, Alappuzha, Kerala, India, 688003*

Abstract

The moon is the fifth largest satellite in the solar system and the brightest object in the night sky. The moon possesses mild, dispersed, localized magnetic anomalies but no inherent magnetic field. The lunar surface is subject to a variety of charged particles and radiation. As a result, the lunar surface is electrically charged and immersed in streaming plasma (solar wind). A lunar wake zone faces away from the sun as a result of solar wind interactions with the lunar surface. Due to the dominating current from the electron photoemission induced by solar UV radiation, the lunar surface usually charges to a positive electric potential with regard to the surrounding plasma, whereas the night side surface charges to a negative electric potential. Due to the lack of electron photoemission, plasma electron currents often predominate on the night side of the Moon. Most environments have equal temperatures and concentrations of electrons and ions, but because lighter electrons move more quickly, they provide a greater amount of electron flux to the surface. The solar wind fluxes cause the lunar surface to become charged. varied solar wind conditions result in varied charging behaviours. For both solar energetic particle occurrences and average solar wind circumstances, there are differences in the electron number density and energy of the solar wind electrons. Potential The satellite data will be used to predict the current lunar surface properties under various solar wind circumstances on both the day and night sides of the moon. Additionally, we will examine how fluctuations in surface potential are reflected in the region of the lunar terminator. where the potential changes from having a positive value to a negative value. It is possible to identify a transition region at the terminator, where the charging phenomenon will not occur and the potential value will be negligible.

Keywords:Lunar surface charging, Sunspots and solar activity, Solar Corona and origin of solar wind

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1.1 Introduction

Nearly a century ago, research on electrical discharges in gases gave rise to the field of plasma physics. Because of the high temperature, the component atoms may split into mobile electrons and ions that are distinct from one another. Quasi-neutrality is the state in which plasma is nearly electrically neutral due to roughly equal ion and electron concentrations. Because most of the particles in plasma are charged, when they are exposed to strong electrostatic and electromagnetic field forces, they behave in a very complex and intriguing way. Since more than 99 percent of matter in the cosmos is in the plasma state, there are a plethora of applications for plasma research in the fields of geophysics, space physics, and astrophysics. Plasma is present throughout the solar wind, solar corona, and even outside of the solar system. The solar wind is a stream of supersonic plasma that emanates radially from the Sun and contains the solar magnetic field. The magnetic field that the solar wind carries is called the Interplanetary Magnetic Field (IMF). (Halekas JS, 2007) The source is the total magnetic field of the Sun. The IMF transported by the solar wind assumes a spiral structure due to the Sun's spin. The magnetosphere, which is formed around the Earth by the interaction of the solar wind and the earth's magnetic field, shields humans from these intense particles. The Moon orbits Earth at a distance of 384000 km, with a diameter of 3476 km and a mean density of 3. It lacks a core of molten iron and no intrinsic magnetic field, causing weak magnetic anomalies. The

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* Corresponding author: rakwin@gmail.com

Moon's gravitational force is one sixth of Earth's and has no atmosphere, causing extreme temperature extremes. (Andolz FJ,1998).

The Moon’s Day is equal to its year, and its synodic period is about days. The Moon's axis of rotation is inclined at 1.5 to its orbital plane around the Sun, resulting in low Sun visibility at lunar poles and permanent shadow of polar craters. The Moon's surface, lacking a global magnetic field or atmosphere, is an ideal laboratory for studying charged particle and photon interactions. It interacts with supersonic solar wind flow, creating a void or wake. The Moon is not always in the solar wind, but in the tenuous plasma of magnetospheric tail lobes or geomagnetic plasma sheets. The lunar surface becomes electrically charged due to interaction with ambient plasma and solar ultraviolet radiation. This creates complex environments on the sunlit and shadowed sides of the Moon. On the dayside, solar UV radiation dominates, resulting in a positive charge. On the night side, ambient plasma electrons dominate, causing a negative charge. The surface of the Moon charges to an electric potential such that the total incident current is zero (Manka, 1973). The charging currents come from four main sources: (1) photoemission of electrons, (2) plasma electrons, (3) plasma ions and (4) secondary electrons (arising due to surface ionization by highly energetic plasma electrons). The ratio of the emitted secondary electrons to the incident ones called secondary yield. Photo electrons generated by solar UV radiation and secondary electrons constitute an escaping negative current or an equivalent incident positive current. Due to photoionization, the lunar day side typically charges to a few volts positive with a photoelectron sheath extending to $1\mathrm{m}$ in altitude. On the night side, interaction with the charged particles in the solar wind causes the surface to charge to several hundred volts negative, with a Debye sheath extending up to 1 km in altitude. During solar activity time, the negative potential reaches to a large value of several thousand volts negative due to extreme plasma condition prevailed at that time. Plasma environment of the Moon was widely studied by LUNAR PROSPECTOR mission (NASA), Lunar Reconnaissance Orbiter mission (NASA), ARTEMIS mission (NASA), Lunar Lander mission (ESA), etc. The Moon exposed to currents, which vary over many orders of magnitude during its orbit around the Earth. In the solar wind, the day side of the Moon is exposed to relatively low temperature plasma, while the night side lies in the lunar plasma wake is exposed to much more rarefied plasma at a higher temperature (Halekas et al., 2005). In the terrestrial magnetosphere, the Moon exposed to both very rarefied plasma in the magneto tail lobes and more energetic and turbulent plasma in the plasma sheet and the magneto sheath. Meanwhile, solar illumination varies as a function of solar zenith angle on the day side but is absent in the night side. Finally, transient solar events such as solar energetic particle events (SEPs) can contribute very energetic plasma currents to the surface. Because of this extreme variability, the lunar surface should charge to potentials that vary over orders of magnitude. During SEPs secondary electron current plays a vital role in charging processes and the spacecraft observations do indeed support these expectations. (Halekas JS, 2008).

1.2 Data and theory

The Lunar Prospector was a low-cost lunar exploration spacecraft designed for low-cost exploration. It collected high-resolution data on the Moon's gravity, magnetic, compositional, and charging. The mission was the first to be peer evaluated and competitively selected in NASA's Discovery programme. The mission used various instruments to map the Moon's surface layer, investigate lunar dust structure, and detect radon outgassing events. The Moon is an unmagnetized dielectric body that interacts with solar wind, creating a wake in the antisunward direction. Electrons fill the wake region due to their higher thermal velocity than ions. On the night side, plasma electrons dominate due to the absence of photoemission. The lunar surface charges to a negative potential, repelling most electrons, and a Debye sheath shields it (Crook WR, 1984).

These potentials create electric fields near the Moon, which transport dust grains above the surface. These potentials could pose significant threats for robotic and human lunar surface exploration. The study used the Electron Reflectometer (ER) on the Lunar Prospector (LP) spacecraft to measure electron concentration and temperature. The ER was designed to measure the distribution of electrons adiabatically reflected from lunar crustal magnetic fields, determining the magnitude of magnetic anomalies on the lunar surface. (Stroud R, 2009).

The data from the 19-month mission improved our understanding of the Moon's origin, evolution, and current state. The study found that negative lunar surface charges affect the electron distribution by altering the loss cone boundary and producing low-energy secondary electrons.

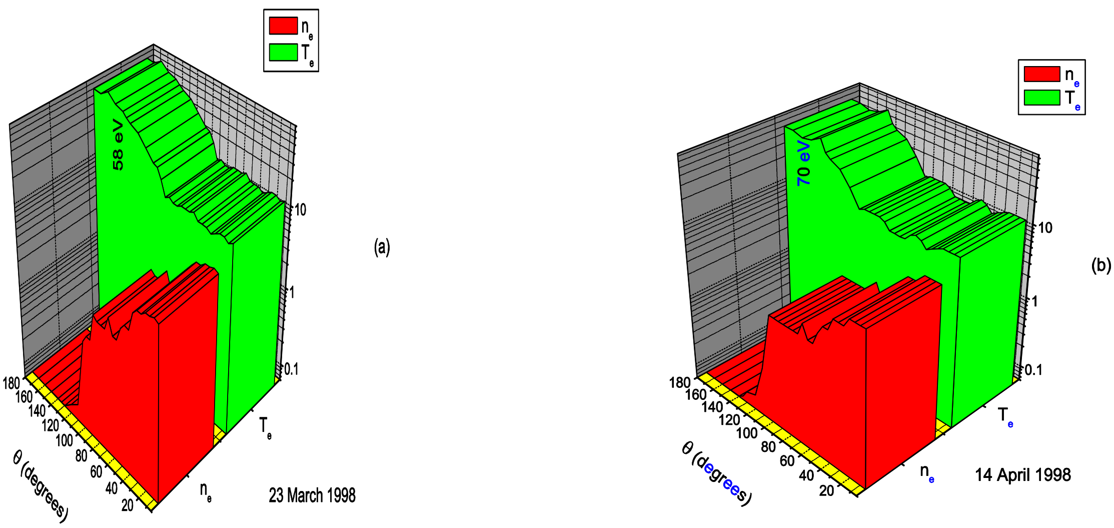

Figure 1.1 LP/ER data on $n_e(cm^{-3})$ and $T_e(eV)$ on 23 March 1998 (a) and on 14 April 1998 (b)

The data from the ER instrument shows variations in electron temperature values on the equator and terminator over two days. The dayside values are consistent, while night side values show some variation. The data is influenced by the lunar night side region, which was not studied before the LP mission. The data was analysed during a massive SEP event on 6 May 1998.

On 6 May 1998, LP data showed electron energy variations due to SEP events, with the space craft in the wake region at an altitude of 50 km above the surface. Secondary electrons produced at the surface were measured by ER, demonstrating the concept of parallel electric fields accelerating secondary electrons. (Charbonneau P,2014) .The lunar surface was covered by the LP mission from 1998 to 1999, providing 18 months of data in various plasma environments, conditions, and solar zenith angles. The reflected flux at energy and pitch angle cannot exceed the incident flux, but upward going flux significantly exceeds the corresponding downward going flux, indicating a secondary electron population. This study uses basic probe equations assuming spherical symmetry to obtain the equilibrium potential of the lunar surface. The equations were simulated using data from the LPER instrument to study global variations in potential and electric field over the lunar surface under different plasma conditions. The solution is easily obtained for isotropic plasma surrounding a spherical probe, but a special expression for plasma current is needed for flowing solar wind. The potential of the lunar surface can be calculated as if the equilibrium condition existed over the entire surface.(Bhardwaj A,2015)

In this work, basic probe equations assuming spherical symmetry first derived by Langmuir and Mott – Smith (1926) and later summarized by Manka (1973) were used to obtain the equilibrium potential. These equations were simulated using the data measured by LPER instrument to study the global variation of potential and electric field over the lunar surface under different plasma conditions encountered by the Moon – at average solar wind (SW) condition and during solar energetic particle events (SEPs).

The solution is readily obtained for the isotropic plasma surrounding a spherical probe (stationary plasma solution). However, in the case of a flowing solar wind, a special expression for the plasma current must be used. In general, these equations are a good approximation to obtain the equilibrium lunar surface potential (Manka 1973). The sheath can be assumed thin in comparison to lunar radius and in addition, the dc conductivity at the lunar surface can be assumed to be very small so that the potential of the lunar surface can be calculated as if the equilibrium condition at that point existed over the entire surface. i.e., the solution at any point is independent of what occurs elsewhere. The flowing plasma conditions used to obtain the potential in lunar dayside and stationary plasma conditions used in the night side.

The lunar surface will reach a potential such that the net current to it is zero. i.e.,

$$I_i + I_e + I_s + I_p = 0 \tag{1}$$

where I_e is electron current, I_i is ion current, I_p is photoelectron current and I_s is secondary electron current. Since these currents depend on the surface potential, the equations can be solved for the equilibrium potential (ϕ_s).The form of the expressions for current as a function of potential depends on whether the species are attracted or repelled.

When the thermal electron current exceeds the ejected electron currents the potential becomes increasingly negative until the remaining repelled electron current reaching the surface equals the positive current to the surface.

The repelled electron current density is

$$J_e = \frac{-n_e e v_{me}}{2\sqrt{\pi}} \exp\left(\frac{-e\varphi}{kT_e}\right) \tag{2}$$

The attracted ion current density is

$$\begin{aligned} J_i &= \frac{n_i e v_{mi}}{2\sqrt{\pi}}\left(1 + \frac{1.66\lambda (R/\lambda)^{1/3}}{R}\frac{e\varphi}{kT_i}\right) \\ &\sim J_{io}\left(1 + \frac{1.66\lambda (R/\lambda)^{1/3}}{R}\frac{e\varphi}{kT_i}\right) \end{aligned} \tag{3}$$

The emitted photoelectron current density is

$$J_p = j_p \cos\theta$$

The secondary electron current density is

$$J_s = J_e \delta_e + J_i \delta_i \tag{4}$$

For the shadowed lunar surface, the most important currents are those due to ions (I_I), electrons (I_e) and secondary electrons (I_S) produced due to the bombardment of highly energetic electrons to the surface. At average SW condition, the incident electron current dominates and the surface charges to a negative potential on the order of the electron temperature (Manka, 1973; Rakesh Chandran et al., 2013). But during SEPs, electron temperature is ~1000ev and secondary electron emission is very important. Secondary electron current represents an important positive current source. During SEPs, the lunar surface charges to floating potential such that net current incident on it is zero. In the night side region, current due to photo electron is zero. i.e.,

$$I_i + I_e + I_s = 0 \tag{5}$$

$$J_S = J_e \delta_E$$

$$\delta_{(E)} = 7.4\, \delta_m\, (E / E_m) \exp[-2(E / E_m)] \tag{6}$$

$$J_e + J_i + J_S = 0 \tag{7}$$

Substitute

$$\tilde{a} = ne / (2\sqrt{\pi}) \sqrt{2KT}$$

$$= ne \sqrt{(KT)} / 2\pi$$

$$\tilde{b} = 1.66\lambda(R / \lambda)^{1/3} / R$$

Divide Equation (1.7) with Je

$$1 + (J_i / J_e) + \delta E = 0$$

$$1 - \sqrt{(m_e / m_i)} \exp e\phi_s / KT_e \{ 1 + \tilde{b}\, e\phi_s / KT_e \} + \delta E = 0$$

$$1 - 0.023 \exp e\phi_s / KT - 0.023\tilde{b}\, e\phi_s / KT \exp (e\phi_s / KT) + \delta E = 0$$

$$\text{Put } e\phi_s / KT = x$$

$$1 - 0.023 \exp x - 0.023\tilde{b}x \exp(x) + \delta E = 0$$

$$0.023 \exp x + 0.023\tilde{b}x \exp x - (1 + \delta E) = 0 \qquad (8)$$

The equation (1.8) is solved to get lunar surface potential during SEP events.

$$\lambda = 69 \sqrt{(T / n)}$$

For average condition, $\delta E = 0$ and equation (1.9) becomes

$$1 - 0.023 \exp x - 0.023\tilde{b}x \exp (x) = 0 \qquad (9)$$

This equation (1.9) is solved to get lunar surface potential under average condition.

Equations (1.8),(1.9) can be numerically solved by bisection method using MATLAB programming for getting lunar potential under different solar fluxes.

The electric field developed over the surface is given by

$$E = \frac{\varphi}{\lambda} \qquad (10)$$

1.3 Results and discussion

Determining the significant charging currents to the body as a function of potential and identifying the potential at which the total current disappears are the two challenges involved in computing the equilibrium potential of a body in a particular environment. Using electron data from LP spacecraft, we computed the equilibrium surface potential and charging currents of the lunar surface under typical solar wind circumstances. (Stubbs TJ, 2007).The Potential – Current characteristic of the sheath region in day side and night side of the lunar surface was also obtained.

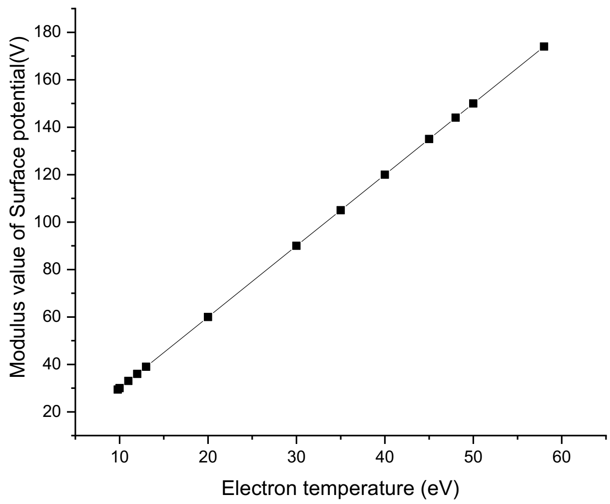

Figure 1.2 Variation of lunar surface potential with electron temperature (23 March 1998)

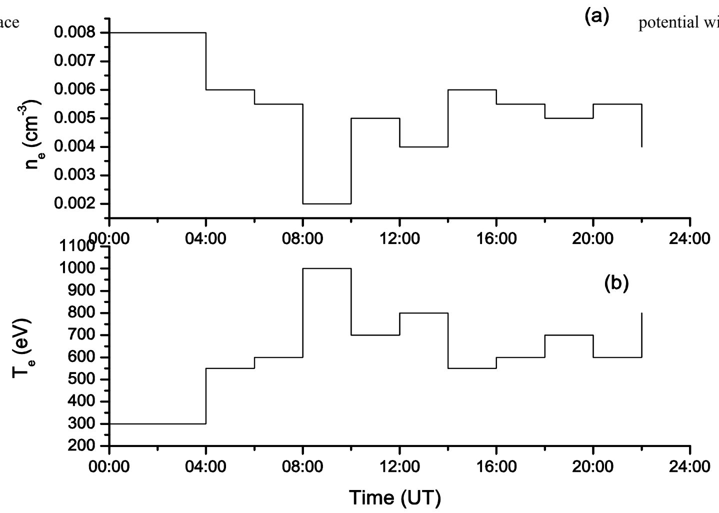

Figure 1.3 Variation of lunar surface potential with electron temperature (14 April 1998)

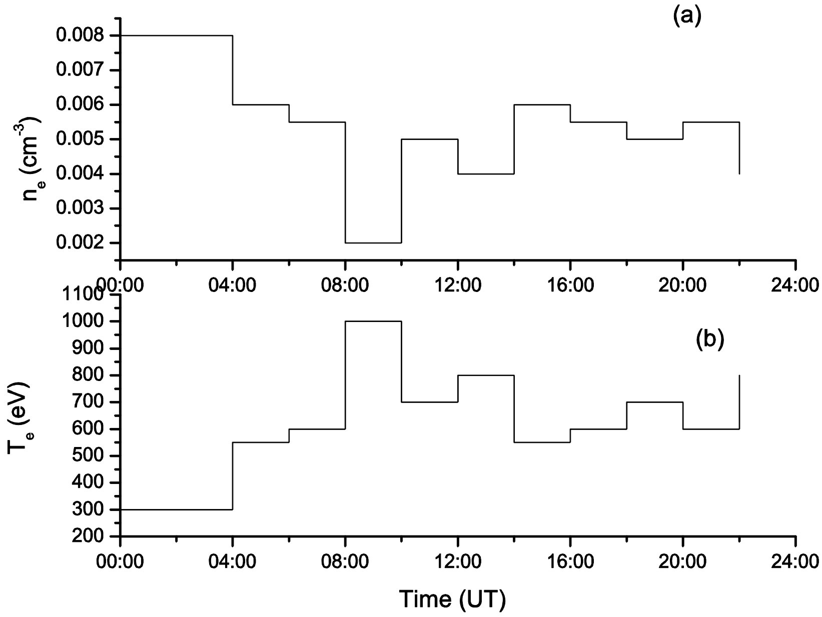

Figure 1.4 LP/ER night side data a) $n_e(cm^{-3})$ and b) $T_e(eV)$ on 06 May 1998.

From two results shown in Figures (1.2) and (1.3), it is clear that night side lunar surface potential has a strong dependence on plasma electron temperature. On 23 March 1998 we got a maximum negative potential of -173 V at T_e = 58 eV . On 14 April 1998 the energy of the incident plasma electron is higher than that in the previous case. This variation is also seen in the potential curve such that night side potential value peaks at -210 V. On 14 April 1998, electron temperature is 70 eV. In both cases potential shows a maximum value at ɵ ~150 and then it decreases towards the wake region. These calculations are for average conditions, which suggests that during periods of enhanced solar activity, lunar surface potentials could be much greater. Photo electron current was ignored to predict potential in nightside region. Figure 1.5 represents Potential-Current density characteristics in nightside region on 23 March 1998. **(**Leer E and Holzer TE, 1980).

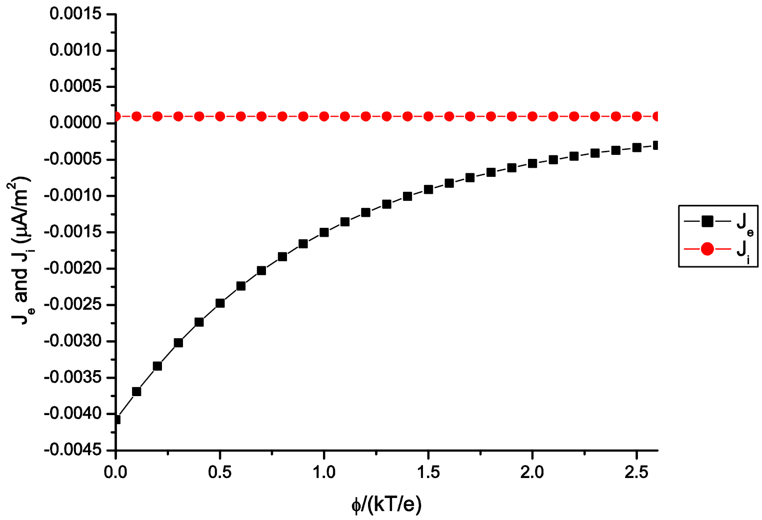

Figure 1.5 Potential – current density characteristics of the nightside region.

Ion current remains constant with negative nightside potential. But electron current shows an exponential decay with nightside potential. This is due to the decrease in the number of electrons reaching the nightside region. In the night side region average values of J_e and J_i are -1.48×10^{-9} Am^{-2} and 9.48×10^{-11} Am^{-2} respectively. Here J_i remains constant irrespective of the nightside potential. (Horz F, 1991)

For the calculation in dayside, we used data in which θ varies from 0^0 to 90^0. Photocurrent density from normally incident sunlight is assumed to be 4×10^{-6} Am^{-2}. In two cases we got a maximum potential of $\approx$ 5 V in the lunar day side. A variation in surface potential is seen in the dayside due to the decrease in solar illumination and the surface photo current, as the terminator is approached.

We compared our results with the potential values measured by Electron Reflectometer instrument in LP spacecraft. The measured data of LP/ER show an uncertainty of 3.13 % and the uncertainty correspond to standard error for energy sweep of 3eV. (Long K, 1998).The predicted values agree well with the experimental values. A small deviation is noticed in lunar dayside, and this is due to the variation in photocurrent density of lunar surface. Since the photoelectron temperature data is not available from LP/ER instrument, it is assumed to be constant as 1.5eV. As the terminator region is approached, the predicted values behave exactly like the experimental plot in both cases. Another important observation is that on the global scale, the transition from positive to negative surface potential is established well in the dayside of the Moon. This transition occurs at ɵ ~75 . This means that under average conditions ~13% of the lunar surface in the day side has a negative surface potential.

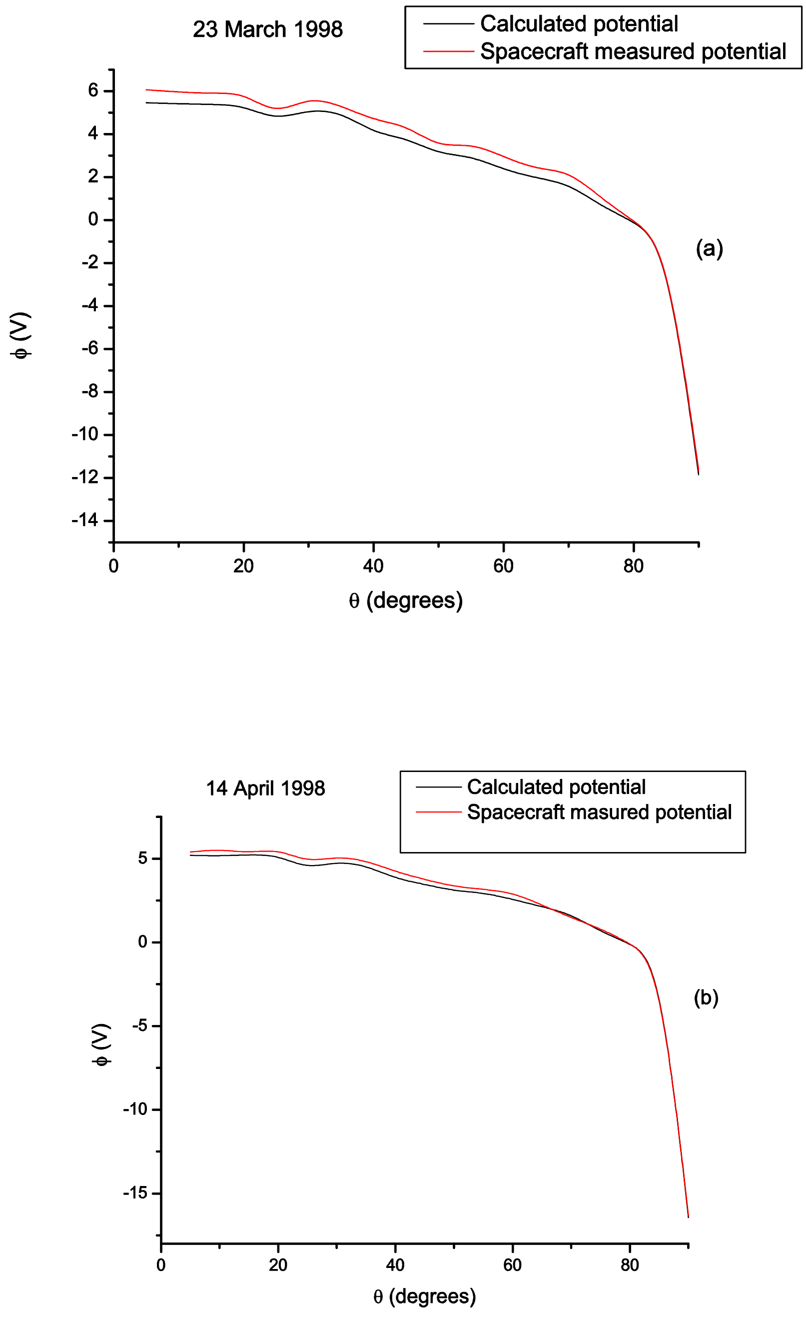

Figure 1.6 Plot of Lunar surface potential versus θ in dayside on 23 March (a) and 14 April 1998 (b).

Using Probe equations and LPER data on 23 March 1998, the variation of charging currents with respect to the lunar surface potential of dayside was studied.

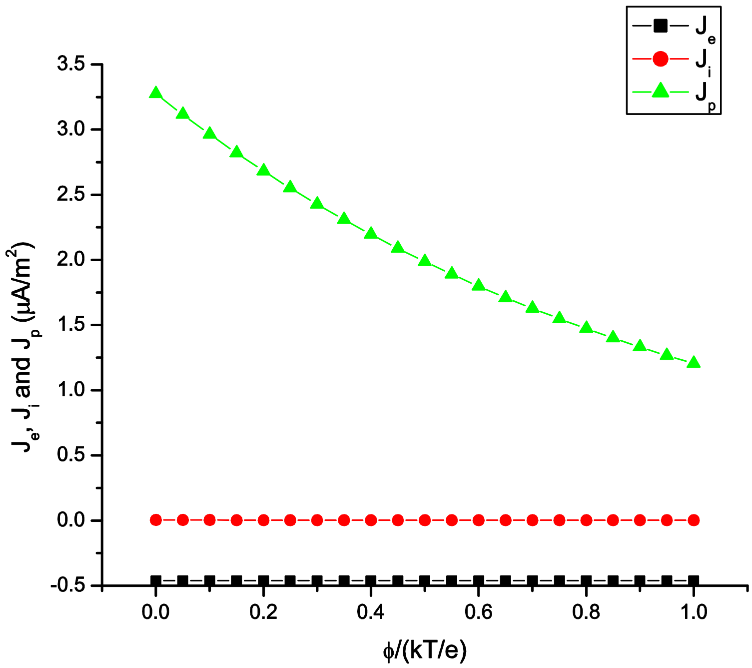

Figure 1.7 Potential – current density characteristics of the dayside region

From the figure it is clear that the photo electron current density due to solar UV photons is dominant in lunar day side. It has a maximum value of 3.3×10^{-6} Am^{-2}, whereas J_e and J_i have values -0.46×10^{-6} Am^{-2} and 0.004×10^{-6} Am^{-2} respectively. As the positive potential in lunar dayside increases, J_P decreases exponentially and J_e remains constant all over the dayside region. Graph clearly suggests that the ion current is very feeble to make its effect in lunar dayside.

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