Scattering of Sunlight in Lunar Exosphere Caused by Gravitational Microclusters of Lunar Dust

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In this article it is showed how sub-micron dust is able to reach the lunar exosphere and produce the "horizon glow" and "streamers" observed at lunar horizon by astronauts in orbit and surface landers, during the Apollo era of exploration.

Key words: Quantum Gravity, Lunar Exosphere, Dusty Plasma, Sunlight Scattering.

1. Introduction

While orbiting the Moon, the crews of Apollo 8, 10, 12, and 17 have observed "horizon glow" and "streamers" at the lunar horizon, during sunrise and sunset. This was observed from the dark side of the Moon [1,2] (e.g., Fig. 1). NASA's Surveyor spacecraft also photographed "horizon glows," much like what the astronauts saw [3]. These observations were quite unexpected, since it was thought that the Moon had a negligible atmosphere.

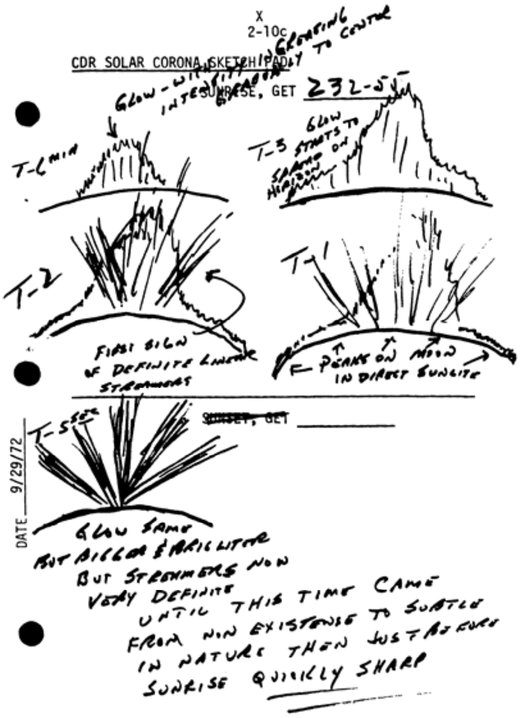

Fig.1 – At sunrise and sunset many Apollo crews saw glows and light rays. This Apollo 17 sketch depicts the mysterious twilight rays.

Now a new mission of NASA, called: "The Lunar Atmosphere and Dust Environment Explorer (LADEE)", was sent to study the Moon's thin exosphere and the lunar dust environment [4]. One of the motivations for this mission is to determine the cause of the *diffuse emission seen at lunar horizon by astronauts in orbit and surface landers.*

Here, we explain how sub-micron dust is able to reach the lunar exosphere and cause the diffuse emission at the lunar horizon.

2. Theory

It is known that the lunar dust results of mechanical disintegration of basaltic and anorthositic rock, caused by continuous meteoric impact and bombardment by interstellar charged atomic particles over billions of years [5]. Dust grains are continuously lifted above the lunar surface by these impacts and dust clouds are formed. They are *dusty plasma* clouds[*] because atoms from the dust grains are ionized by the UV radiation and X-rays from the solar radiation that incides continuously on the lunar surface [6].

The *gravitational interaction* between these *dusty plasma* clouds and the Moon only can be described in the framework of Quantum Gravity.

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[*] A *dusty plasma* is a plasma containing millimeter (10^{-3}) to nanometer (10^{-9}) sized particles suspended in it. Dust particles are charged and the plasma and particles behave as a plasma [7,8].

The quantization of gravity shows that the *gravitational mass* m_g and the *inertial mass* m_i are correlated by means of the following factor [9]:

$$\chi = \frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \left(\frac{\Delta p}{m_{i0}c}\right)^2} - 1\right]\right\} \qquad (1)$$

where m_{i0} is the *rest* inertial mass of the particle and Δp is the variation in the particle's *kinetic momentum*; c is the speed of light.

In general, the *momentum* variation Δp is expressed by $\Delta p = F\Delta t$ where F is the applied force during a time interval Δt. Note that there is no restriction concerning the *nature* of the force F, i.e., it can be mechanical, electromagnetic, etc.

For example, we can look on the *momentum* variation Δp as due to absorption or emission of *electromagnetic energy*. In this case, it was shown previously that the expression of χ, in the particular case of *incident radiation on a heterogeneous matter*(powder, dust, clouds, etc), can be expressed by the following expression [10]:

$$\frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \left[\left(\frac{n^3 S_f^2 S_m^2 \phi_m^2 D}{\rho\, S_\alpha c^2 f}\right) n_r\right]^2} - 1\right]\right\} \qquad (2)$$

where f and D are respectively the frequency and the power density of the incident radiation; n is the number of molecules per unit of volume; S_f is the *total surface area* of the dust grains, which can be obtained by multiplying the *specific surface area* (SSA) *of the grain* (which is given by $SSA = S_{gr}/\rho_{gr}V_{gr} = 3/\rho_{gr}r_{gr}$) *by the total mass* of the grains ($M_{i0(total)} = \rho_{gr}V_{gr}N_{gr}$); $S_\alpha = \pi r_{gr}^2$ is the area of the cross-section of the grain; ϕ_m is the average "diameter" of the molecules of the grain, $S_m = \frac{1}{4}\pi\phi_m^2$ is the cross section area, and n_r is the *index of refraction* of the heterogeneous body.

In the case of dust grain, n is given by the following expression

$$n = \frac{N_0 \rho_{gr}}{A}$$

where $N_0 = 6.02 \times 10^{26}\, molecules/kmole$ is the Avogadro's number; ρ_{gr} is the matter density of the dust grain (in $kg.m^{-3}$) and A is the molar mass of the molecules (in $kg.kmol^{-1}$). Then, Eq. (2), in the case of a *dust cloud*, can be rewritten in the following form

$$\frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + 256\left(\frac{N_0}{A}\right)^6 \frac{\left(\rho_{gr}^4 S_\alpha^2 N_{gr}^4\right) S_m^4 \phi_m^4 n_r^2 D^2}{c^4 f^2}} - 1\right]\right\} \qquad (3)$$

where,

$$\rho_{gr}^4 S_\alpha^2 N_{gr}^4 = \left(\frac{m_{gr}}{V_{gr}}\right)^4 S_\alpha^2 N_{gr}^4 = \frac{M_{i0(total)}^4 S_\alpha^2}{V_{gr}^4} =$$

$$= \frac{M_{i0(total)}^4 \left(\pi r_{gr}^2\right)^2}{\left(\frac{4}{3}\pi r_{gr}^3\right)^4} = \frac{81 M_{i0(total)}^4}{256\pi^2 r_{gr}^8}$$

and, $M_{i0(total)} = \rho_{gr}V_{gr}N_{gr} = \rho_{cloud}V_{cloud}$. Thus, we can write that

$$\rho_{gr}^4 S_{gr}^2 N_{gr}^4 = \frac{81\left(\rho_{cloud}V_{cloud}\right)^4}{256\pi^2 r_{gr}^8}$$

Substitution of this expression into Eq. (3) gives

$$\frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \left(\frac{N_0}{A}\right)^6 \left(\frac{81\left(\rho_{cloud}V_{cloud}\right)^4}{\pi^2 r_{gr}^8}\right) \frac{S_m^4 \phi_m^4 n_r^2 D^2}{c^4 f^2}} - 1\right]\right\} \qquad (4)$$

The analysis of the lunar rocks collected by Apollo and Luna missions shows the following average composition (principal components) of the lunar soil [11]: SiO_2 (44.6%), Al_2O_3 (16.5%), FeO (13.5%), CaO (11.9%). Considering the following data: SiO_2 ($n_r = 1.45$, $A = 60.07 kg.kmol^{-1}$ and $\phi_m = 5.6 \times 10^{-10} m$), Al_2O_3 ($n_r = 1.7$, $A = 101.96 kg.kmol^{-1}$ and $\phi_m = 7.8 \times 10^{-10} m$), FeO ($n_r = 2.23$, $A = 71.84 kg.kmol^{-1}$ and $\phi_m = 5.3 \times 10^{-10} m$), CaO ($n_r = 1.83$, $A = 56.08 kg.kmol^{-1}$ and $\phi_m = 5.9 \times 10^{-10} m$)†, we can calculate the value of the factor

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† The values of ϕ_m were calculated starting from the unit cell volume, i.e., 92.92 Å^3, 253.54 Å^3, 80.41 Å^3, 110.38Å^3, respectively [12].

$S_m^4\phi_m^4 n_r^2/A^6$ (Eq. (4)), for these components of the lunar soil. The result is: 1.62×10^{-122}, 4.96×10^{-122}, 0.673×10^{-122}, 7.29×10^{-122}, respectively. Then, considering the respective percentages, we can calculate the average value for the factor $S_m^4\phi_m^4 n_r^2/A^6$, i.e.,

$$\left[S_m^4\phi_m^4 n_r^2/A^6\right] = 0.446\left(1.62\times10^{-122}\right)+ 0.165\left(4.96\times10^{-122}\right)+0.135\left(0.673\times10^{-122}\right)+ +0.119\left(7.29\times10^{-122}\right) = 2.5\times10^{-122}$$

Substitution of this value into Eq. (4) gives

$$\frac{m_g}{m_{i0}} = \left\{1-2\left[\sqrt{1+1.2\times10^{6}\frac{(\rho_{cloud}V_{cloud})^4}{r_{gr}^8}\frac{D^2}{f^2}}-1\right]\right\} \quad (5)$$

Note that the value of m_g/m_{i0} becomes highly relevant in the case of *sub-micron* particles $(r_{gr}\sim 0.01\mu m)$.

By applying Eq. (5) for the particular case of *lunar* clouds of *dusty plasma* composed by *sub-micro dust*, we get

$$\frac{m_g}{m_{i0}} = \left\{1-2\left[\sqrt{1+1.2\times10^{70}(\rho_{cloud}V_{cloud})^4\frac{D^2}{f^2}}-1\right]\right\} \quad (6)$$

The factor D/f can be expressed by the *Planck's radiation law* i.e.,

$$\frac{D}{f} = \frac{2hf^3}{c^2\left(e^{hf/kT}-1\right)}$$

where $k = 1.38\times10^{-23}\,j/K$ is the Boltzmann's constant; f is given by the Wien's law $\left(\lambda = 2.886\times10^{-3}/T\right)$, i.e., $f/T = c/2.886\times10^{-3}$; T is the *dusty plasma temperature*. Thus, the Equation above can be rewritten as follows:

$$\frac{D^2}{f^2} = 1.27\times10^{-38}T^6 \quad (7)$$

Substitution of Eq. (7) into Eq. (6) yields

$$\frac{m_g}{m_{i0}} = \left\{1-2\left[\sqrt{1+1.52\times10^{32}(\rho_{cloud}V_{cloud})^4T^6}-1\right]\right\} \quad (8)$$

Near the Moon's surface, the density of the lunar atmosphere is about $10^{-12}\,kg.m^{-3}$ [13]. Thus, we can assume that this is the density of *dusty plasma* clouds near the Moon's surface. The temperature of sub-micron dusty plasma can be evaluated by means of the following expression: $\left[\frac{1}{2}m_\mu v_\mu^2\right] = eV = e\left(e/4\pi\varepsilon_0 l_\mu\right) \cong 2\times10^{-22} = \frac{3}{2}kT$ whence, we get $T\cong 10K$. Thus, Eq. (8) gives

$$\chi = \frac{m_{g(cloud)}}{m_{i0(cloud)}} = \left\{1-2\left[\sqrt{1+\sim10^{-10}V_{cloud}^4}-1\right]\right\} \quad (9)$$

Note that, for $V_{cloud} > 334.37m^3$ the factor χ becomes *negative*. Under these conditions, the gravitational interaction between the Moon and the cloud becomes *repulsive*, i.e.,

$$F = -G\frac{M_{g(moon)}m_{g(cloud)}}{r^2} = \cong -\chi\,G\frac{M_{i0(moon)}m_{i0(cloud)}}{r^2} \quad (10)$$

In this way, sub-micron dusty plasma can reach the lunar exosphere.

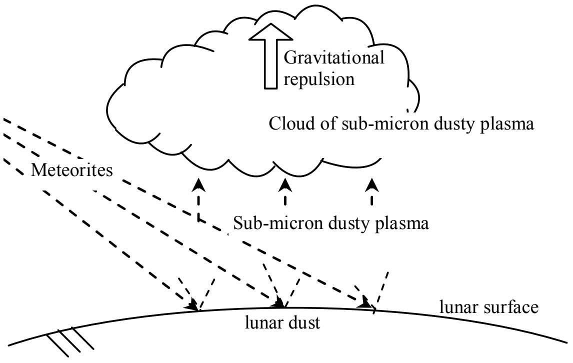

Fig.2 - How sub-micron dusty plasma can reach the lunar exosphere.

In the case of *large clouds* of sub-micron dusty plasma $V_{cloud} > 10^9\,m^3$, Eq. (9) shows that

$$\chi^2 > 10^{26}$$

Thus, the gravitational attraction between two sub-micron particles inside the cloud will be given by

$$F_g = -G\frac{m_{g\mu}^2}{r^2} = -\chi^2 G\frac{m_{i0\mu}^2}{r^2} > 10^{26}G\frac{(\rho_\mu V_\mu)^2}{r^2} \cong \cong 10^{26}G\frac{(3300)^2\left(5.2\times10^{-25}m^3\right)^2}{r^2} \cong \frac{10^{-26}}{r^2} \quad (11)$$

Note that this force is *much greater than the electric force*

$$F_e = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} \cong \frac{10^{-28}}{r^2}$$

This means that, inside the clouds, thousands of *sub-micron* particles will be strongly attracted among them (See Fig.3), forming thousands of large particles with radius in the range $10 - 1000\mu m$ or more.

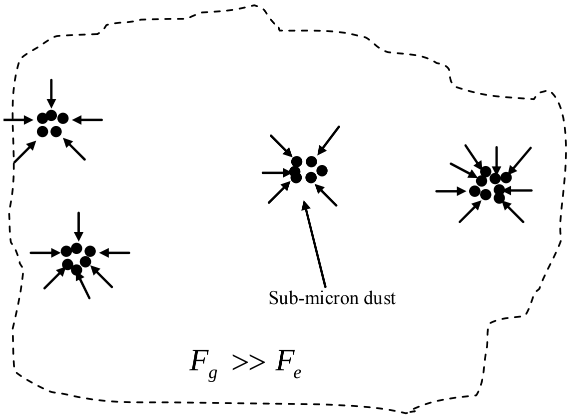

Fig.3 –Strong *gravitational attraction* between sub-micron dust, producing microclusters of dust that will cause strong scattering of the sunlight in the lunar exosphere

Thus, when a cloud of this type arrives to lunar exosphere it increases the number of these particles (*gravitational microclusters of lunar dust*) inside the lunar exosphere. Under these circumstances, it density becomes equal to the density of the lunar exosphere $\left(\sim 10^{-18}\,kg.m^{-3}\right)$[14]. The amount of Rayleigh scattering that occurs for a beam of light depends upon *the size of the particles* and the wavelength of the light. Specifically, the *intensity of the scattered light varies as the sixth power of the particle size*, and varies inversely with the fourth power of the wavelength.

Thus, the lunar exosphere is fundamentally a very large cloud of *sub-millimeter dust plasma*. Consequently, in order to calculate the factor χ for the lunar exosphere, we can use the Eq. (5), assuming that most of the particles has $r_{gr} \cong 100\mu m$ and that $\rho_{cloud} \approx 10^{-18}\,kg.m^{-3}$. The result is

$$\chi = \frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \sim 10^{-66} V^4_{exosphere}} - 1\right]\right\} \qquad (12)$$

Considering that the Moon's radius is 1738km and that, evidences observed during the Apollo missions, indicate the existence of solar light scattering from a significant population of lunar particles, which exist in *a little thick region* (~1km) starting from 100km above the lunar surface [15], we can write that

$$\begin{aligned} V_{exosphere} &= \tfrac{4}{3}\pi\left(r^3_{outer} - r^3_{inner}\right) \cong \\ &\cong \tfrac{4}{3}\pi\left[\left(1.838\times10^6\right)^3 - \left(1.837\times10^6\right)^3\right] \cong \\ &\cong 4\times10^{16}\,m^3 \end{aligned}$$

Substitution of this value into Eq. (12) yields

$$\chi \approx -1 \qquad (13)$$

Alternatively, we may put Eq.(2) as a function of the radiation *power density* $, D$ [9], i.e.,

$$\chi = \frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \left(\frac{n_r^2 D}{\rho c^3}\right)^2} - 1\right]\right\} \qquad (14)$$

From Electrodynamics we know that when an electromagnetic wave with frequency f and velocity c incides on a material with relative permittivity ε_r, relative magnetic permeability μ_r and electrical conductivity σ, its *velocity is reduced* to $v = c/n_r$ where n_r is the index of refraction of the material, given by [16]

$$n_r = \frac{c}{v} = \sqrt{\frac{\varepsilon_r\mu_r}{2}\left(\sqrt{1 + (\sigma/\omega\varepsilon)^2} + 1\right)} \qquad (15)$$

If $\sigma >> \omega\varepsilon$, $\omega = 2\pi f$, Eq. (15) reduces to

$$n_r = \sqrt{\frac{\mu_r\sigma}{4\pi\varepsilon_0 f}} \qquad (16)$$

Due to the lunar exosphere be a plasma its electrical conductivity, σ, must be high. Thus, we can consider that its n_r can be expressed by Eq. (16). Substitution of Eq. (16) into Eq. (14) gives

$$\chi = \frac{m_g}{m_{i0}} = \left\{1 - 2\left[\sqrt{1 + \left(\frac{\mu_r \sigma}{4\pi\varepsilon_0 \rho c^3}\right)^2 \frac{D^2}{f^2}} - 1\right]\right\} \qquad (17)$$

By substituting Eq. (7) into Eq. (17) we obtain the following expression of χ for the lunar exosphere:

$$\chi = \left\{1 - 2\left[\sqrt{1 + 1.27\times10^{-38} T^6 \left(\frac{\mu_r \sigma}{4\pi\varepsilon_0 \rho c^3}\right)^2} - 1\right]\right\} =$$

$$= \left\{1 - 2\left[\sqrt{1 + 1.4\times10^{-33} T^6 (\mu_r \sigma)^2} - 1\right]\right\} \qquad (18)$$

By comparing Eq. (18) with Eq. (13) we can conclude that in the lunar exosphere:

$$T^3 \mu_r \sigma \approx 10^{16} K^3 . S / m \qquad (19)$$

Since the temperature T of the dusty plasma near the Moon's surface, giving by $\left[\frac{1}{2} m_\mu v_\mu^2\right] = \frac{3}{2} kT$, is $T \cong 10K$. Then, considering that in the exosphere the particles are dust clusters with larger masses $\overline{m}_\mu$ (radii ~1,000 times larger), and also with larger velocities $\bar{v}_\mu$ (due to the low density of the exosphere), we can conclude that $T > 1{,}000K$. The temperature of dust in a plasma is typically 1-1,000K [17, 18]. However, it can reach up to 1,000,000K [19].

In a previous paper, we have shown that the explanation of the *Allais effect* requires $\chi = -1.1$ for the lunar exosphere [9, Appendix A]. This is in agreement with the value here obtained (Eq.13). However, in the mentioned paper, we consider *erroneously* that the effect was produced by the incidence of sunlight on the exosphere. Here, we can see the exact description of the phenomenon starting from the same equation (Eq. (14)) used in the above-cited paper.

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