Investigation of Lunar Pickup-Ion Dynamics

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Progress Report to the National Space Society Center for Lunar Research Summer Internship

Abstract

The National Space Society's Center for Lunar Research funded a summer internship to study the effects of pickup ions on the distribution of solar wind volatiles on the lunar surface. The investigation was prompted by Lunar Prospector's discovery of increased concentrations of hydrogen in the permanently shadowed craters at the lunar poles. This incited the hypothesis that this concentration could have been caused by interactions between particles previously impacted into the moon by the solar wind which have subsequently diffused out of the lunar regolith and been picked up by the solar wind (pickup ions). The purpose of the internship was to model the trajectories that these particles might take and determine how many, if any, would re-impact the moon.

1. Introduction

The solar wind has deposited potentially valuable hydrogen and helium on the lunar surface. Lunar Prospector observed lunar hydrogen [1, 2], possibly indicating water ice, and researchers have identified potential resources of the rare fusion energy fuel helium-3 [3, 4]. Most of these resources remain trapped in the lunar regolith for an uncertain time—probably less than a million years and certainly much less than the Moon's lifetime [5]. Once the implanted hydrogen atoms diffuse from the regolith into the lunar atmosphere, they transport ballistically along the surface and then, usually, undergo photoionization or ion-impact ionization and are "picked up" by the solar wind's magnetic field. Pickup ions are a well-established phenomenon, including observations of heavy ions (Z>>1) in near-Earth space that are interpreted as being of lunar origin [6, 7].

The pickup ions interact with the interplanetary magnetic field (IMF) through the Lorentz force, $\boldsymbol{F} = q(\boldsymbol{v} \times \boldsymbol{B} + \boldsymbol{E})$, where $\boldsymbol{v}$ is the solar-wind velocity, $\boldsymbol{B}$ is the IMF vector, the electric field $\boldsymbol{E}$ is negligible, and the equation is written in a frame moving with the instantaneous solar wind velocity. The net effect on the pickup ions is that, in the solar-wind frame, they experience circular motion perpendicular to $\boldsymbol{B}$ and parallel motion along $\boldsymbol{B}$, resulting in a helical trajectory. In the Moon's frame of motion, the circular component becomes cycloidal with average velocity equal to the solar-wind's velocity. For typical IMF magnitudes and solar-wind velocities, the radius of the circular motion is 100's of km—a significant fraction of the lunar circumference of ~11,000 km. The analysis is complicated by the fact that both the direction and magnitude of the IMF vary considerably on a relatively short time frame, with components primarily in the ecliptic plane at an angle of about 45° to the Earth-Sun line, but also with significant out-of-plane deviations [8, 9]. The IMF also tends to change sign with a typical timescale of days, thereby reversing the direction of the Lorentz force.

The present research analyzes the dynamics of the process of the pickup of ionized lunar atmosphere by the solar wind magnetic field and its re-implantation at nearly solar-wind velocities. We use lunar-solar-ecliptic coordinates, for which the x axis points from the center of the Moon toward the Sun, the z axis points toward ecliptic North, and the y axis completes a right-handed coordinate system. The methodology for the research was to

1. Solve the equations of motion for a pickup ion in a specified solar-wind magnetic field and velocity.

2. Translate the motion into a trajectory from the birth point of the ion to either loss into space or impact on the lunar surface.

3. Average over the distribution of the lunar atmosphere to get the distribution of impact points on the lunar surface.

4. Infer implications for the location and abundance of lunar volatiles.

2. Pickup-ion dynamics

Implanted solar wind volatiles remain in the lunar regolith for an uncertain time, probably less than one million years, and then diffuse out. After entering the lunar atmosphere, they become ionized relatively quickly by solar-wind impact or photoionization. Once ionized, they experience a Lorentz force caused by the solar wind, which moves past the Moon at approximately 400 km/s and carries a magnetic field of a few nT. These pickup ions follow trajectories given by the standard equations of motion of a charged particle in a magnetic field, shown in Table 1.

Table 1. Pickup Ion Equations of Motion

Lorentz force (in this problem E=0)	$F = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = q\mathbf{v} \times \mathbf{B}$
Velocity parallel to the axis of rotation	$\mathbf{v}_{\parallel} = \mathbf{v} \cdot \frac{\mathbf{B}}{\lvert\mathbf{B}\rvert}$
Velocity perpendicular to the axis of rotation	$\mathbf{v}_{\perp} = \frac{\lvert\mathbf{v} \times \mathbf{B}\rvert}{\mathbf{B}}$
Gyrofrequency	$\Omega = \frac{q\lvert\mathbf{B}\rvert}{m}$
Gyroradius	$\rho_i = \frac{v_{\perp}}{\Omega}$

To begin the pickup-ion dynamics analysis, the calculation is done in the solar wind reference frame. In this frame, the magnetic field ***B*** that is carried by the solar wind is at rest, and the particle is traveling towards the field with velocity ***v*** at an angle to the field, which on average is at ~45° and in the ecliptic plane. In the solar-wind frame, the trajectory becomes a simple helix, with gyroradius ρ_i and parallel velocity $\mathbf{v}_{\parallel}$ as given in Table 1. Mathematically, a helix with the proper parameters is first oriented along the z axis; the equation of motion in Cartesian coordinates is

$$\vec{r}_z(t) = \{\rho_i \cos(\Omega t), \rho_i \sin(\Omega t), v_{\parallel} t\}.$$

This helix is rotated into the direction of the solar-wind magnetic field by solving for the appropriate Euler angles. That is, we solve for the Euler angles in the equation

$$\Re(\alpha, \beta, \gamma) \cdot \hat{z} = \hat{b},$$

where $\Re$ is the Euler rotation matrix, $\{\alpha, \beta, \gamma\}$ are the Euler angles, $\hat{z}$ is a unit vector in the z direction, and $\hat{b}$ is a unit vector in the direction of the magnetic field. Note that orienting the initial helix along the z axis causes α to drop out of the transformation. The result of this step is a vector

$$\vec{r}_B(t) = \Re(\alpha, \beta, \gamma) \cdot \vec{r}_z(t).$$

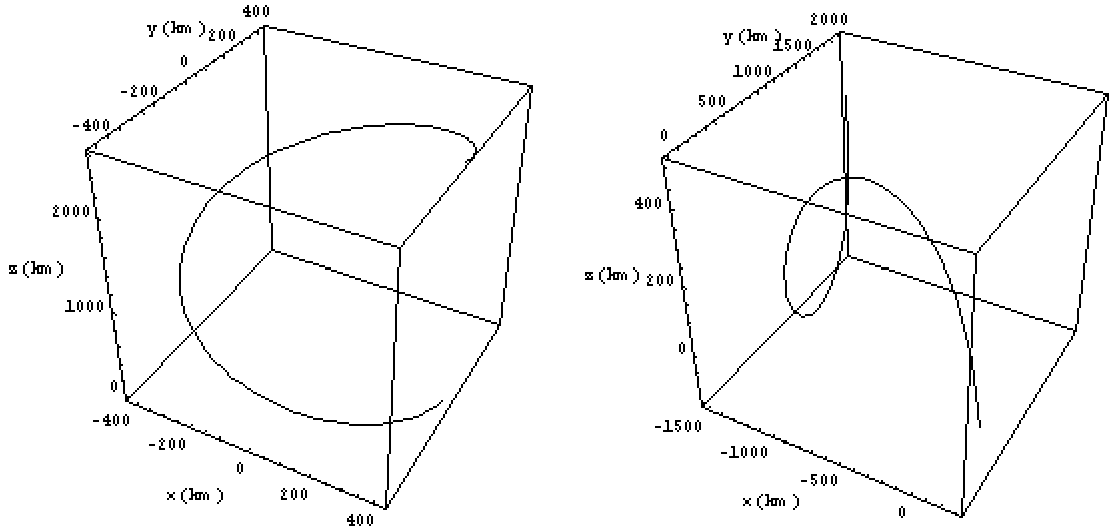

Figure 1. Rotation of the ion trajectory into the solar-wind frame for v_{sw}={400, 0, 0} km/s, B={-5, 5, 1} nT, R(0)=1.5 R_m at sub-Sun point.

A typical case (v_{sw}={400, 0, 0} km/s, B={-5, 5, 1} nT, R(0)=1.5 R_m at sub-Sun point) appears in Figure 1. The final translation of the orbit is to begin the trajectory at a radius r_0 and return to the lunar frame of reference. The governing equation is

$$\vec{r}(t) = \vec{r}_0 + \vec{r}_B(t) - \vec{r}_B(0) + \vec{v}t\,.$$

Because the motion in the solar-wind direction somewhat dominates the gyromotion for typical solar-wind parameters, the resulting trajectory is fairly elongated, as shown in Figure 2 for the same parameters as in Figure 1. To illustrate the trajectory, the ion has been carried through a complete gyroperiod, although the actual trajectory would have intersected the Moon at x = R_m.

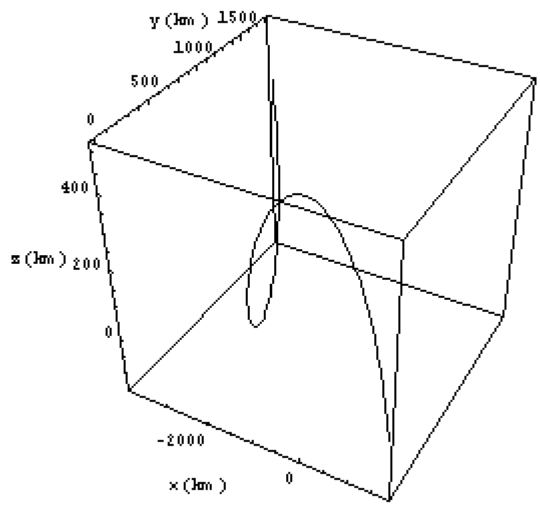

Figure 2. Ion trajectory in the lunar frame for the same parameters as in Figure 1.

3. Pickup-ion source in the lunar atmosphere

Atoms that diffuse out of the regolith enter the lunar atmosphere. They equilibrate in temperature with the regolith and follow ballistic trajectories over the lunar surface. The scale heights (e-folding) for the resulting lunar atmosphere are [10] shown in Table 2.

Table 2. Scale Heights of the Lunar Atmosphere

	Lunar day	Lunar night
H_2	1022 km	256 km
He	511 km	128 km

The atmospheric atoms are ionized by either impact with solar-wind ions or photoionization and are picked up by the solar wind. We assume that only ions created on the lunar dayside hemisphere can subsequently impact the Moon. They then follow the trajectories discussed in Section 2, some of which impact the Moon. Typical trajectories appear in Figure 3.

The problem of the impact of a pickup ion on the Moon starting from an arbitrary point in the lunar atmosphere is nonlinear, as shown in Section 2. It requires solving for the intersection of a helix with a sphere and we are aware of no general analytic solution. Therefore, a Monte Carlo approach would be a suitable technique for numerical solution of the problem. Work on implementing this approach is in progress.

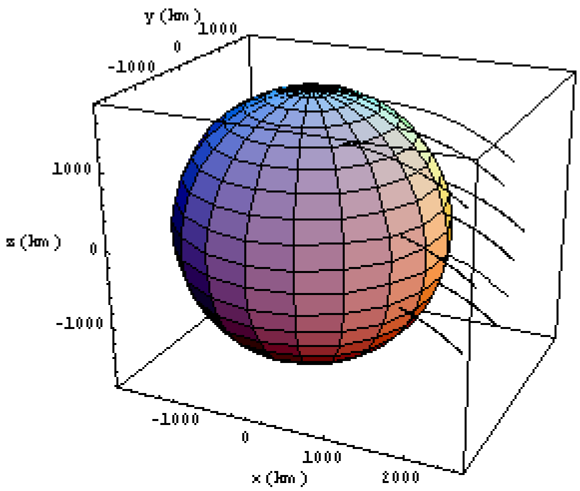

Figure 3. Typical trajectories for pickup ions created at 1.5 times the lunar radius at points centered on the sub-Sun point and separated by 20^o in each direction.

4. Future work

In order to decide automatically whether a pickup ion re-impacts the Moon, an algorithm to discard situations where there is no impact must be developed and implemented in the Mathematica notebook used for the calculations.

The pickup-ion phenomenon redistributes solar-wind volatiles over the lunar surface. Due to the helical nature of their trajectories, the polar regions are more accessible to pickup ions than to ions carried by the solar wind, which follow nearly radial trajectories from the Sun. Quantification of this question requires averaging the trajectories over an initial distribution of the lunar atmosphere, as discussed in Section 3.

5. Conclusions

Pickup ions are an important phenomenon to be included when considering the distribution of volatiles across the surface of the Moon, particularly for the contents of permanently shadowed craters. The work done so far is insufficient to draw definite conclusions as to whether Lunar Prospector did in fact find water ice in those craters. Nevertheless, it indicates that pickup ions provide a potentially important mechanism for redistributing lunar volatiles, including destinations near the poles.

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