Effect of planetary rotation on distal tektite deposition on Mars

Kelly E. Wrobel and Peter H. Schultz
Department of Geological Sciences, Brown University, Providence, Rhode Island, USA

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[1] The rapid rotation of Mars creates a significant pseudoforce, known as the Coriolis force, that greatly modifies the flight paths and subsequent deposition of distal ejecta (ejecta with launch velocities of 3 km/s and greater). An accurate depiction of the effects of the Coriolis force requires the integration of the Coriolis terms directly into a series of spherical ballistic equations applied within a rotating reference frame. The resulting landing positions of radially ejected particles tend to form distinct wrapping patterns that are focused to specific areas in the hemisphere opposite from the source crater: around the pole for high-latitude craters (45° in latitude and above) and in an equatorial band for low-latitude craters (below 45° latitude). Consequently, particular locations on the surface receive deposits in stages: direct delivery of ejecta followed by deposits of higher-velocity ejecta. This staged deposition leads to regions of enhanced ejecta accumulations where meters of material collect (millimeters would be predicted in nonrotational radial decay models). Thus high-latitude craters could supply a considerable amount of distal products (tektites and melts) to polar locations, perhaps contributing to the dark circumpolar materials.


1. Introduction

[2] The surface of Mars preserves a history of impact cratering dating from about 4 Ga to the present [Tanaka, 1986]. The lunar impact record is much better preserved due to the absence of an atmosphere. However, high-velocity ejecta are lost from the Moon due to its low escape velocity (2.38 km/s). Such ejecta on Mars are retained because of its higher escape velocity (5.02 km/s) and its tenuous atmosphere, which serves to decelerate and capture fine distal ejecta.

[3] Gravity and the presence of an atmosphere are not the only important differences for cratering between the Moon and Mars. The rapid rotation of Mars creates a significant pseudoforce, known as the Coriolis force, that can greatly modify the ballistic trajectories of ejecta in flight. This force is most influential on the flight paths of ejecta with launch velocities of 3 km/s and greater (distal ejecta). Similar effects of planetary rotation on ejecta trajectories occur on the Earth [see Wrobel and Schultz, 2003b]. Rotational effects on the Earth, however, are more complex due to factors such as the larger planetary radius, greater interactions of ejecta with impact-induced vapor, and the much thicker atmosphere.

[4] The following contribution addresses the effect of the Coriolis force on delivered distal ejecta on Mars. We first review previous approaches to the problem. We then describe a more complete approach including the Coriolis terms in calculations of the flight paths of particles for various ejecta velocities up to the Martian escape velocity. Lastly, the Coriolis effect is incorporated into first-order models of impact ejecta velocity/mass relationships.

2. Background

[5] One strategy of incorporating the effects of planetary rotation on the ballistic flight of ejecta involves simply shifting the ejecta arrival sites on the surface longitudinally according to both the rotation rate of the body and the time of flight of the particle. Such an approach, however, does not fully account for the effects of the Coriolis force and neglects the conservation of the angular momentum of the ejecta.

[6] A rotating planet can be thought of in terms of two different reference frames, a fixed inertial frame at the center of the body and a moving reference frame near the surface. Forces exerted on an object in flight can be expressed in terms of a total effective force, \( \vec{F}_{\text{eff}} \), measured in the moving system:

\[
\vec{F}_{\text{eff}} = \vec{S} + m\vec{g} - 2m(\vec{\omega} \times \vec{v}_{r}).
\]

\( \vec{S} \) represents the vector sum of external forces (e.g., impulse, electromagnetic force, and friction); \( m \) is the mass of the particle in flight; \( \vec{g} \) denotes the gravitational field vector (allows for the consideration of the variation of gravity with altitude as well as centrifugal force effects); \( \vec{\omega} \)
is the angular velocity of the planet; and \( \mathbf{\omega}' \) is the vector velocity of the particle (relative to the rotating axes) [Marion and Thornton, 1995].

[7] The third term in equation (1) corresponds to the Coriolis force. Outside of a rotating reference frame, the Coriolis force is observed as an apparent deflection of the motion of a particle that is in free flight within the rotating coordinate system. The angular velocity vector, \( \mathbf{\omega}' \), is directed toward the north pole of a planet, producing a vertical component, \( \omega_z \), that is directed upward in the northern hemisphere and downward in the southern hemisphere. Consequently, a particle in flight experiences a horizontal component of the Coriolis force with magnitude \( 2m\omega \cdot \mathbf{v}_h \), where \( \mathbf{v}_h \) is the horizontal velocity component of the particle in the rotating frame. This force component deflects the particle’s flight path to the right in the northern hemisphere and to the left in the southern hemisphere [Marion and Thornton, 1995].

[8] Inclusion of the Coriolis terms directly in a series of detailed ballistic equations allows mapping the full consequences of planetary rotation on the trajectories and subsequent deposition of impact ejecta. The model here uses an integrated approach by calculating the force as it is exerted on an ejecta particle at every stage in its flight. Previous studies demonstrated the Coriolis effect on ejecta deposition on an ejecta particle at every stage in its flight. The angular velocity vector, \( \mathbf{\omega}' \), is the horizontal velocity component of the particle in the rotating frame. This force component deflects the particle’s flight path to the right in the northern hemisphere and to the left in the southern hemisphere [Marion and Thornton, 1995].

3. Approach: Model

[9] The velocity, \( \mathbf{v}' \), of a particle launched from a site at an angle \( \theta \) to the vertical and in a direction of azimuth \( \phi \) (measured eastward with respect to local north) can be resolved into eastward, northward, and vertical components:

\[
\begin{align*}
\mathbf{v}_x &= |\mathbf{v}'| \sin \theta \sin \phi, \\
\mathbf{v}_y &= |\mathbf{v}'| \sin \theta \cos \phi, \\
\mathbf{v}_z &= |\mathbf{v}'| \cos \theta,
\end{align*}
\]

respectively, relative to a fixed frame of reference in the rotating planetary body [Dobrovolskis, 1981].

[10] It is simpler to discuss the spherical ballistics of particles in flight above a rotating planet in terms of an inertial reference frame attached to the planet. Transforming a particle velocity into this new frame of reference requires the addition of the term

\[
b = |\mathbf{\omega}'| R \cos \psi
\]

to the eastward component of the velocity, \( \mathbf{v}_x \). This term, \( b \), defines the inertial speed of the surface at the point of impact. \( R \) denotes the radius of the planetary body and \( \psi \) is the latitude of the launch point of the particle, the location of the source crater. The magnitude of the new speed of the particle, \( |\mathbf{v}'_o| \), relative to the rotating system, is

\[
|\mathbf{v}'_o| = \sqrt{|\mathbf{v}'|^2 + b^2 + 2|\mathbf{v}'|b \sin \theta \sin \phi}.
\]

The new launch angle, \( \theta_o \), and azimuth, \( \phi_o \), can be calculated from

\[
\cos \theta_o = \frac{|\mathbf{v}'|}{|\mathbf{v}'_o|} \cos \theta, \\
\cos \phi_o = \tan \theta \cos \phi,
\]

respectively [Dobrovolskis, 1981].

[11] The flight of a particle in a rotating system can be addressed in exactly the same manner as would be an object in a ballistic path above a nonrotating sphere. Through a series of complete ballistic equations, the specific angular momentum of the particle, the distance traveled by that particle, and the time of flight can be calculated. From this information, the latitude and longitude of the final impact can be found (incorporating rotation). The reader is directed to the work of Dobrovolskis [1981] for a detailed description of the ballistic equations.

[12] Once terminal positions on the surface are known, ejecta-scaling models from O’Keefe and Ahrens [1977] and Hounsen et al. [1983] can be used to map the potential thicknesses of deposits from individual craters as well as cumulative deposits from a series of craters. For the moment, the ultimate fate of the ejecta is ignored. The size of most particles launched at velocities that are affected greatest by the rotation of Mars (3–5 km/s) will be rather small, regardless of the size of the source crater, since the peak pressures exerted on these particles will be large. This assumption is consistent with particle size estimates for distal deposits from major terrestrial craters (e.g., Chixculub glasses and tektites distributed across the Texas Gulf Coast). As a result of such small particle sizes, along with the thin Martian atmosphere (compared to Earth), the effects of phenomena such as ablation, dynamic disruption, etc. are expected to be minimal (~100% (~30%) survival rate for 500-μm-diameter (1000-μm-diameter) particles) [Flynn and McKay, 1990; Lorenz, 2000]. Thus only the total mass of ejecta projected to arrive at a given area of the surface is examined.

[13] Gravity-scaling relations give approximations for ejecta volume at different ranges from the crater center. Mass balance between crater excavation and ejecta require the following [Schultz et al., 1981]:

\[
\frac{V_e (v_e)}{V_E} = \left( \frac{x_e}{R_A} \right)^{3/2},
\]

where \( V_e (v_e) \) is the total volume of ejecta with initial launch velocity \( \geq v_{e0} \); \( V_E \) denotes the total ejected volume or total expected volume of ejecta \( V_E \approx 1/2V_T \) [e.g., Stöffler et al., 1975], where \( V_T \) is the total displaced volume of the crater); \( R_A \) is the apparent radius of the crater, \( R_A \approx R_F/1.56 \) [Schultz, 1988; Melosh, 1989], where \( R_F \) is the final radius; and \( x_e \) symbolizes the ejection position of each particle. The value of \( V_T \) is estimated from gravity-scaling relations using the formulas for sand [Schultz and Gaul, 1985].

[14] The ejection position of a particle, \( x_e \), measured radially from the crater center, is obtained from assumptions of gravity-controlled crater growth following Housen et al. [1983]:

\[
v_e \approx 0.47 \sqrt{\left( g R_A \right)} \left( \frac{x_e}{R_A} \right)^{-2.4}.
\]

The new launch angle, \( \theta_o \), and azimuth, \( \phi_o \), can be calculated from

\[
\cos \theta_o = \frac{|\mathbf{v}'|}{|\mathbf{v}'_o|} \cos \theta, \\
\cos \phi_o = \tan \theta \cos \phi,
\]

respectively [Dobrovolskis, 1981].

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\[
v_e \approx 0.47 \sqrt{\left( g R_A \right)} \left( \frac{x_e}{R_A} \right)^{-2.4}.
\]
where $v_e$ is ejection velocity and $g$ is the surface gravity (3.71 m/s$^2$ on Mars). The resulting ratio $x_e/R_F$ ranges from 1.0 (at the crater rim) to 0.0 (at the crater center). Specific values of $x_e/R_F$ will depend on ejecta launch velocities (equation (7)).

Combining equations (6) and (7) thus gives

$$V_c = \frac{v_e}{v_c} = \frac{v_e}{0.47 \sqrt{g} R_0^{0.25}}. \quad (8)$$

Assuming ejection velocities ranging from 0.25 km/s to 5.02 km/s (escape velocity) in increments of 0.01 km/s, deposit thickness (volume/area) values were obtained for ejecta arrival sites using equation (8) by averaging the volume of ejecta emplaced at a site over a 1° × 1° spherical polygon centered on the location of deposition.

4. Results

The Coriolis effect was applied to several different cases. First, the landing positions of ejecta launched with 45° ejection angles from different locations on Mars were mapped in order to assess the overall effect on distal ejecta deposition. Second, the consequences of planetary rotation on particles in flight with much lower (oblique impacts) and higher (plume-driven ejecta) ejection angles were evaluated. Third, the potential rotational effects on ejecta distributions from a selected crater (Lyot) were considered.

4.1. Effects of Latitude

The Coriolis force is strongest at the poles of a rotating body and zero in magnitude at the equator [Marion and Thornton, 1995]. As a result, ejecta launched northward, in the northern hemisphere, are deflected eastward from the path of a great circle. Ejecta launched eastward are more gently diverted southward. Particles launched westward experience the opposite deflection. In the southern hemisphere, all deflections mirror those from the northern hemisphere.

The Coriolis force thus redirects (from the path of a great circle) trajectories of ejecta particles. The symbols in Figures 1–3 display final arrival locations of ejecta. The actual flight paths of these particles are not indicated, just the location of origination, the source crater, and the final arrival sites. A direct consequence of the Coriolis deflection can be observed in these figures: terminal positions of distal ejecta originating from the same location, but from different directions, can ultimately overlap on the surface [Dobrovolskis, 1981].

Figures 1a and 1b are projections of Mars showing arrival sites of ejecta from the large Hesperian-aged Martian crater Lyot (220 km in diameter at 50°N, 30°E). All ejecta arrival sites mapped in these figures (likewise for Figures 2 and 3) are for particles that were launched with increasing velocities (0.01 km/s increments) at ejection angles of 45° in azimuthal intervals of 15°. Only a fraction of all possible landing sites for ejected particles is mapped in these figures. All other potential deposition locations can be interpolated between these mapped sites.

The Coriolis force does not substantially alter ejecta arrivals in the northern hemisphere near Lyot (Figure 1a). Hence ejecta-thickness decay relations for proximal deposits should not be significantly affected (for gravity-controlled
The trajectories of arrival sites (Figure 1b) of more distal (high-velocity) ejecta, however, wrap in a counter-clockwise direction around the south pole due to the cumulative effects of the Coriolis force acting throughout the long ballistic flight time.

For comparison, Figures 2a and 2b reveal the effects of planetary rotation on ejecta from the 190-km-diameter crater Lowell, a high-latitude impact located in the southern hemisphere of Mars (53°S, 82°W). Just as for Lyot, the ejecta arrival sites wrap around the pole opposite from impact, in this case clockwise around the north pole.

The Bakhuysen crater (180 km in diameter), a low-latitude southern hemisphere crater (23°S, 16°E), is shown in Figure 3, accompanied by mapped ejecta arrival sites. The ejecta deposition locations again wrap in the hemisphere opposite from impact (clockwise in the northern hemisphere). This wrapping now occurs, however, as a band just on the opposite side of the equator (rather than around the pole) from the source crater.

An impact directly at a pole of Mars will exhibit similar ejecta distribution patterns as the high-latitude craters with ejecta arrival sites wrapping around the pole in the opposite hemisphere. Impacts very near the equator produce somewhat different results. There, ejecta will be deposited symmetrically with respect to the equator [Dobrovolskis, 1981]. Those particles launched toward the northern (southern) hemisphere will wrap clockwise (counter-clockwise) and form a band of arrival sites similar to that formed from Bakhuysen, except smaller and just north (south) of the equator.

An intuitive (but incomplete) explanation of these results can be made. Particles launched at 45° from a excavation). The trajectories of arrival sites (Figure 1b) of more distal (high-velocity) ejecta, however, wrap in a counter-clockwise direction around the south pole due to the cumulative effects of the Coriolis force acting throughout the long ballistic flight time.

Figure 2. Orthographic projections of Mars centered at (a) (0°, 82°W) and (b) the north pole (center meridian through pole at 82°W/98°E). Black diamonds indicate the landing positions of ejecta launched radially symmetric (ejection angles of 45°) from the Lowell crater (53°S, 82°W) at azimuth intervals of 15°. Rotational effects are manifest in the wrapping of the ejecta landing sites in the northern hemisphere. Stars in Figure 2b denote examples of arrival sites of ejecta with initial launch velocities of 4 km/s.

Figure 3. Orthographic projection of Mars centered at (0°, 16°E). The black diamonds indicate the terminal positions of ejecta launched radially symmetric (ejection angles of 45°) from the Bakhuysen crater (23°S, 16°E) at azimuth intervals of 15°. Rotational effects are observable in the equatorial wrapping of ejecta arrival sites on the surface in the northern hemisphere. Stars indicate examples of landing sites of ejecta that were initially launched at 4 km/s.
spherical body with increasing velocities achieve greater distances to apoapsis without significantly increasing the ballistic range on the surface (from launch to redeposition). Consequently, particles with high ejection velocities remain in flight for progressively longer times while the planet rotates below. Along with this rotational effect, the calculations here also incorporate angular momentum terms and the decrease in gravitational forces with distance from the surface.

As a result of the vastly different travel times among the highest-velocity ejecta, the intersections of particle trajectories with the surface (the ejecta arrival sites) eventually spread out in bands that center around the latitude opposite from the source crater. Such particular ejecta deposition patterns thus actually constrain the location of the source crater.

To summarize, the effects of the rotation of Mars on ejecta emplacement from symmetrical excavation are latitudinally dependent. The landing sites of distal ejecta wrap in the hemisphere opposite from the source crater: poleward for high-latitude craters (45° latitude and above) and equatorially for low-latitude craters (below 45° latitude). Consequently, large impacts (craters >100 km) at high latitudes could contribute a significant amount of distal ejecta (\(v_e \geq 3\) km/s) to near-polar regions.

4.2. Effects of Ejection Angle

Analytical approximations for crater excavation (equations (6)–(8)) provide a useful, first-order assessment of the delivery of distal ejecta across Mars. Computational models would be required to completely address melt fractions and additional complexities created at early times in the cratering process. Nevertheless, the possible effects of such complexities can be generally assessed by examining two distinct ejecta components: low-angle, downrange trajectories (during oblique impacts) [see Schultz and Gault, 1990; Schultz, 1996] and high-angle trajectories (vapor-entrained particles) [see Jones and Kodis, 1982; Schultz, 1996]. The effects of the Coriolis force on these various ejecta components are radically different.

Figures 4a and 4b illustrate arrival sites for ejecta launched over a range of different angles from the crater Hale (136-km-diameter crater at 36°S, 36°W). All ejecta were launched downrange 325° east of north, for this appears to be the most probable direction of the path of the projectile that impacted the surface to form Hale [Schultz and Mustard, 2004].

The Coriolis force does not dramatically alter the arrival positions for ejecta with low ejection velocities (Figure 4a) or high-velocity ejecta with low ejection angles (e.g., 5° in Figure 4b) (trajectories of terminal ejecta positions are not significantly different from the path of a great circle). The minimal Coriolis deflection occurring under this latter set of conditions reflects the fact that ejecta launched at low angles require higher velocities to reach a particular location on the surface, thereby minimizing the time these particles are in flight above the rotating planet. As ejection angles increase, the Coriolis term becomes more significant (Figure 4b).

The initial stages of a hypervelocity impact may generate significant vapor, whether due to high impact velocity or to volatile components in the substrate [e.g., Schultz, 1996; Stewart et al., 2000]. While a forward model is required to incorporate complete details, the effects of
4.3. Ejecta Deposit Thicknesses

vapor expansion on early-time ejecta can be revealed clearly by simply assessing the effects of high ejection angles, as observed in experiments [Schultz, 1996] and theory [Jones and Kodis, 1982]. Arrival sites of ejecta launched at an angle of 80° from the Lyot crater are illustrated in Figure 5. Deposition is severely limited east of the crater but greatly enhanced west of the crater (as well as immediately north, south, and east) as a direct expression of the longer planetary rotation time beneath particles whose flight trajectories obtain greater distances to apoapsis. An application of the O'Keefe and Ahrens [1977] model provides estimates of up to meters of vapor-entrained particles being deposited west of the Lyot crater.

Figure 5. Orthographic projection of Mars centered at (45°N, 15°E). Landing sites for ejecta launched radially symmetric at 80° (from the horizontal) from the Lyot impact site (50°N, 30°E) are shown (black diamonds). Effects of rotation on high-angle ejecta trajectories are evident in the sharp wrapping of terminal positions just east of the crater. Stars denote a few examples of arrival sites of ejecta with initial launch velocities of 4 km/s.

5. Implications and Conclusions

[33] The study of Lorenz [2000] addressed the likelihood of the delivery of microtektites to polar locations on Mars from the crater Lyot and estimated that the south pole could receive millimeter-thick deposits. These approximations, however, appear to be significantly underestimated, perhaps due to an incomplete account of rotational effects in the model. Differences in the thickness equations used by Lorenz (corresponding to equations (6) and (7) here) also could contribute to volume estimates up to 10 times smaller than those presented here. Such inconsistencies, however, cannot solely account for the three-orders-of-magnitude difference in the estimated deposit thicknesses for the south polar region, i.e., millimeters (Lorenz) vs. meters (this study). Regardless, the study by Lorenz does conclude that distal ejecta originating from Lyot could be preserved in layered terrains near the south pole. This conclusion is reinforced by the results of our study.

[34] Another significant result illustrated in Figure 6 is the absence of ejecta deposits projected for the area that is antipodal to the Lyot crater. In a nonrotational model, all directions of launch supply ejecta to the position antipodal to Lyot, 50°S, 150°W. Consequently, a multitude of depositional events occurs over time exactly 180° from the source crater. This results in an enhanced accumulation of deposits at the antipode, as is predicted in standard radial decay models (Figure 7) [Moore et al., 1974].

[35] Incorporating rotational effects, however, reduces the antipodal concentrations since the trajectories of ejecta in flight within a rotating system do not follow the path of a great circle. For some ejection azimuths, the antipode is never reached since the particle velocities exceed the escape velocity of Mars before reaching this distance. Thus antipodal deposits are considerably thinner than predicted in nonrotational models. Specifically, the gravity-scaled excavation model of Housen et al. [1983] would predict an accumulation of ~40 cm antipodal to Lyot for a nonrotating body (depicted by the dashed line in Figure 7). Incorporating rotational effects into this model results in predictions of only ~1 cm of antipodal ejecta deposition.
Figure 6. Map of deposit thicknesses for ejecta from the Lyot crater based on both the terminal positions of ejecta, as mapped in Figure 1, and the mass balance equation (equation (6)). Terminal positions used were limited to those corresponding to particles with ejection velocities >2 km/s. This was done to observe the rotational effects on the deposition of distal ejecta and to assure that this image would not be saturated by kilometer-thick proximal deposits. Purple indicates deposits 500 cm thick or greater, and black denotes a complete lack of deposits (0 cm). The antipode of Lyot is located at 50°S, 150°W.

Figure 7. This graph compares the Housen et al. [1983] gravity-scaled excavation model applied to a nonrotational body to the rotational model used in this study. The dashed line (nonrotational model) depicts a general decay of deposit thickness with increasing range from the source crater (Lyot) accompanied by an antipodal buildup of deposits. The green and red lines (rotational model) delineate predicted ejecta thicknesses for given ranges from Lyot for two particular azimuth directions (red, 225° east of north; green, 135° east of north), illustrating contrasting effects of the Coriolis force for different ejection directions. A symmetric distribution of ejecta does not occur in models incorporating planetary rotation due to Coriolis deflections of ejecta flight paths. Rotational models, also, do not predict an enhanced accumulation of deposits antipodal to Lyot.
low-latitude craters. In general, most distal deposits should consist of primarily high-velocity (but late-arriving) ejecta that should be rich in melt and/or glass, including tektites and microtektites. For example, the Australasian tektite strewn field on Earth is believed to have a source in southeast Asia [e.g., Glass and Pizzuto, 1994], implying the delivery of tektites to locations 1000 km to 5000 km from the crater. If it is assumed that similar ejection velocities reflect similar peak pressures, then tektites and impact melts should comprise most of the ejecta launched over the velocity range considered for Mars in the present study ($v_e \geq 3$ km/s). Thus high-latitude craters the size of Lyot (220 km in diameter and larger) could supply a considerable amount (on the scale of meters) of melt and glass products to the opposite pole, providing an alternative hypothesis for the origin of the dark circumpolar materials (as opposed to unweathered volcanics, pyroclastics, exposed bedrock, etc.) [Wrobel and Schultz, 2003b; Schultz and Mustard, 2004]. More ancient polar deposits should have accumulated increased contributions due to the higher flux rate in the past. Exhumation and lag deposits from such accumulations may have further contributed to the present circumpolar erg fields. The dry, cold conditions of the current polar regions would ensure the survival of such deposits over hundreds of millions, if not billions, of years.

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**References**


P. H. Schultz and K. E. Wrobel, Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912, USA. (kelly_wrobel@brown.edu)