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ORIGINAL TITLE:

AN INVESTIGATION OF RADIATIVE DYNAMICAL COUPLING IN THE JOVIAN ATMOSPHERE.

NEW TITLE:

INVESTIGATING ATMOSPHERIC EFFECTS ON IMPACT EJECTA MORPHOLOGY: POSSIBLE TOOL FOR DETERMINING PAST CLIMATE CONDITIONS ON MARS?

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Progress Report

The combined use of impact crater morphology and mechanics provides important information on the physical conditions of both planetary atmospheres and planetary and asteroid surfaces present during crater formation, while an understanding of the rate of crater production on the surface of asteroids provides information of their surface and spin rate evolution. The research performed with support from this project improves our understanding of (1) the mechanics of impact cratering in order to gain insights on the evolution of these physical surface conditions on planets with atmospheres and asteroids, and (2) how impact flux across an asteroid surface may vary due to anisotropic distribution of impactors in the solar system. As part of this project, we have undertaken three studies. In the first study, we investigate atmospheric effects on the morphology of ejecta excavated during a cratering event in order to determine the atmospheric and target conditions from observed crater morphologies. In the second study, we use the physical and morphological consequences of oblique impacts on an asteroid to understand how the asteroid Mathilde (recently imaged by the Near Earth Asteroid Rendezvous - NEAR- spacecraft) could have survived the formation of five giant craters. In a third study, we use a Monte Carlo method to calculate the impact flux on an asteroid given a distribution of impactors on elliptical orbits. In the following section, we present the result obtained from all three studies.

Atmospheric effects on ejecta emplacement

Important advances in understanding atmospheric effects on ejecta entrainment and emplacement have been obtained by observing and developing theory at laboratory scales of the winds created during impact cratering. Below, we describe the mechanics by which such winds are created, and how instabilities in these winds may explain the origin of distal sinuosity of fluidized ejecta facies seen on Mars and Venus. The strong correlation between the observed sinousity of distal ejecta facies and theory has led to further research on the interactions between an advancing ejecta curtain and an atmosphere. Such work should allow computing the dusty-flow conditions in winds generated during an impact. These dusty flow conditions are necessary to model the ejecta deposition by an atmosphere; an essential step if quantitative information on atmospheric properties (i.e. viscosity and density) present during an impact event are to be determined from observed ejecta morphologies on both Mars and Venus.

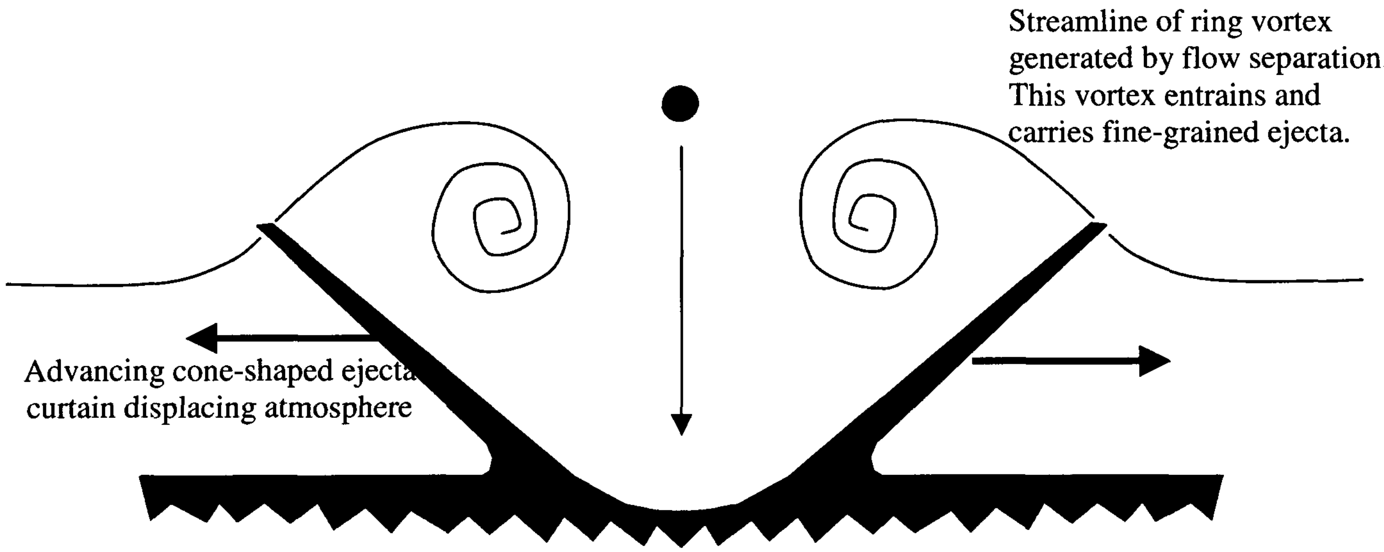

Figure 1: Cross-sectional schematic of winds generated during impact by an advancing ejecta curtain displacing atmosphere around it.

Laboratory experiments performed at the NASA Ames Vertical Gun Range show how an atmosphere affects both the entrainment and emplacement of ejecta excavated during impact cratering [*Schultz and Gault*, 1979; 1982; *Schultz*, 1992a; 1992b; *Barnouin-Jha and Schultz*, 1996]. These excavated ejecta create a continuous curtain that is shaped as an inverted cone. The lower thicker portions of this curtain act as an impermeable barrier that displaces atmosphere around it as it advances radially outwards. Flow separation at the top of the barrier creates a vortex ring analogous to a smoke ring. This vortex ring entrains fine-grained ejecta out of the curtain, which it then transports and deposits after coarser ejecta within the curtain are emplaced ballistically. Previously published work has shown a reliable means to estimate the flow strength or circulation of this curtain-generated ring vortex at laboratory scales [*Barnouin-Jha and Schultz*, 1996]. Preliminary estimates of such flow strengths at planetary scales show that even on Mars (possesses a tenous atmosphere) significant amounts of ejecta should be entrained.

Recent work [see attached *Barnouin-Jha and Schultz*, 1998] indicates that instabilities in the curtain-generated vortex create waves that produce sinuosity in distal ejecta observed in the laboratory. Many studies explain the instability process responsible for forming these waves in smoke rings and vortices shed at the edge of wing tips [*Krutzsch*, 1939; *Maxworthy*, 1972; 1977; *Widnall and Sullivan*, 1973; *Widnall et al.*, 1974; *Moore and Saffman*, 1975; *Tsai and Widnall*, 1976; *Saffman*, 1978]. Sinuosity of ejecta facies observed on Mars and Venus are consistent with an extrapolation of this instability theory to planetary scales. Variations in the sinuosity from the mean expected for a given crater most likely reflect changes in either target properties (including volatile content) or atmospheric properties (density and viscosity). Assuming that target properties do not play a role, the changes in atmospheric properties predicted by the variations in sinousity observed at fresh craters on Lunae Planum, Mars indicate a factor of four change in atmospheric density. Such a change is expected on Mars by orbital forcing [*Kieffer and Zent*, 1992]. Older regions may provide quantitative evidence for a denser atmosphere in Mars' past with possible implications for a warmer wetter climate.

Several studies [see attached *Barnouin-Jha et al.*, 1999a, b] have been undertaken in order to deconvolve atmospheric from target properties that affect the sinuosity of distal ejecta facies. Wind tunnel and numerical experiments have allowed investigating the connection between the strength of the winds that entrain and transport ejecta and the physical nature of the ejecta curtain and atmosphere. The physical nature of the ejecta curtain include for example the mean size of particles comprising it, its width, its velocity and so on. The physical nature of the atmosphere includes its density, its viscosity and its compressibility. The most important result obtained shows that the hydraulic resistance of the curtain determines where along an ejecta curtain flow separation occurs. This hydraulic resistance parameterizes the physical nature of both the atmosphere and curtain and measures the energy loss required for a flow to pass through a porous obstruction. Consequently, atmosphere flows around the curtain when this hydraulic resistance is large, but flows through the curtain when it is small. The position where flow separation occurs controls the strength of the winds generated by the advancing ejecta curtain. This wind strength and its entrainment capacity are critical to determining the effective viscosity and density in the resulting flow. These variables not only control the sinuosity of observed ejecta facies, they also provide inputs to transport and deposition models of ejecta by atmospheric processes. These models should predict ejecta run-out, thereby complementing sinuosity data to estimate atmospheric and/or target conditions present during crater formation.

In final paper [see attached *Barnouin-Jha and Schultz*, 1999], we have shown how the wind tunnel and numerical results can be put into an ejecta curtain model traveling through an atmosphere. These model results duplicate well the behavior of ejecta curtains observed at laboratory scales. When applied to planetary scales, the model results confirm previous preliminary estimates of the size of ejecta entrained on Mars and Venus [*Barnouin-Jha and Schultz*, 1996]. On Venus, the model predicts that the atmosphere completely entrains the ejecta curtain.

Giant craters on Mathilde

The NEAR spacecraft flew by the C-type asteroid [253] Mathilde in June 1997. During the fly-by, NEAR imaged five giant craters on the surface of Mathilde [*Veverka et al.*, 1997]. These giant craters are defined as having diameters that approach the mean radius of the asteroid on which they are found. In a recent study, (see attached manuscript) we have addressed the question: how did Mathilde survive such an onslaught of impacts without being disrupted? This question has important implications for the physical nature and evolution of Mathilde. Below, we (1) outline the observations obtained from NEAR, (2) analyze the angular distribution of impacts on Mathilde, (3) summarize the effects of oblique impacts on Mathilde, and (4) tie our understanding of the impact process to the observations obtained from NEAR.

The geology of Mathilde [*Veverka et al.*, 1997] possesses several important clues that may help explain the survival of this asteroid. First, no obvious ejecta have been observed, although some features could be associated with such ejecta. Second, most small craters are bowl shaped, with average diameter-depth ratios. Shadows prevent easily measuring the depths of the giant craters. Third, NEAR measured a low density for Mathilde at about 1.3±0.2 g cm^{-3}. Comparison of this density with carbaneous condrites suggest a porosity of ~50% for Mathilde.

Analyses of the angular distribution of impacts on Mathilde show that when averaged over the entire body, the most common impact angle occurs at 45°. As a result, oblique impact (impact angle, $\theta < 45°$) represent about 50% of impacts. Experiments show that such impacts are less likely to disrupt a target because peak pressures and compressive strain rate decrease with impact angle (defined by the trajectory of the projectile and the surface tangent plane) [*Schultz and Gault*, 1990]. Oblique impacts also produce less ejecta relative to a normal impact [*Gault and Wedekind*, 1978], and rarely generate elongated craters on curved bodies [*Schultz*, 1997]. In fact, elongated craters form only for impact angles ranging from 35° down to 25°. Furthermore, laboratory experiments indicate that highly oblique impacts (below 25° for curved bodies) can generate large craters without disrupting either projectile or target) [*Schultz and Gault*, 1990].

The giant craters lack of ejecta and bowl-shaped morphology are consistent with an oblique origin for these craters. Because oblique impact angles reduce the chance for disruptions, such an origin for giant craters may be an important contributor in explaining why Mathilde survived. Other contributing factors, such as Mathilde's low density and its volatile content also could have helped prevent Mathilde's disruption. If Mathilde's low density can be explained by micro-scale porosity, then a larger faster projectile is required to create a crater of a given size. However, the shock gets more effectively damped in such a porous target, thereby reducing the chances for catastrophic disruption. Similarly, vaporization of volatiles that are most likely present in this C-type asteroid may reduce the shock strength felt by the asteroid, although more research is required to determine the exact consequences of vaporization on target disruption. Nevertheless, the survival of a large Mathilde should not be a surprise. For a realistic projectile population, Mathilde's chance of surviving the formations of 5 giant craters is approximately 1 in 5 to 1 in 7.

Monte Carlo model investigating impactor fluxes on asteroids

An important result was obtained while researching the survival of Mathilde. As is usually assumed in the literature for an isotopic impactor flux, most impacts occur at 45° when the angular distribution of impacts is averaged over the entire body. We have proven this to be true for any region on any shaped body. However, it is well known that the impactor flux on Earth for example is spatially anisotropic [*Wetherhill*, 1968]. Under such flux conditions, asteroids of different shapes will possess different angular distribution of impact angle over different regions. This has important implications for understanding the link between the impactor and crater population observed on an asteroid, thereby affecting estimated ages for asteroid surfaces. Such regional differences in impact angle distribution may also contribute to our understanding of the evolution of asteroid shape, rotation rate and survivability.

We have developed a new Monte Carlo method to calculate the impact flux on an asteroid given a distribution of impactors on elliptical orbits. The observed distributions of minor planets in semi-major axis, eccentricity, and inclination have been used to calculate the impact flux taking into account not only the orbit of the target but also its size, shape, and rotation. The method traces impacting orbits backward in time from the target area and determines impact probabilities. The variation of impact flux over the surface of the target, the impact angle distributions, and the impact velocity distributions are calculated. The Monte Carlo model confirms that the impact flux is greatest for targets near the center of the asteroid belt; that leading-trailing hemispheric asymmetries arise; and that impact probabilities are greatest at low eccentricity and inclination, consistent with the observed structure of the asteroid belt which is depleted of objects in such orbits. The well-known $\sin 2\theta$ impact angle distribution for a spherical target is reproduced. We predict cratering rates for Ida and Eros in its present orbit using conventional assumptions about the total impactor population, which is extrapolated down to sizes that are not directly observable in the main belt. For Ida, 10% geometric saturation can be achieved within 5 byrs for craters up to 500 m diameter. For Eros in its present orbit, impact fluxes are about 15 times lower than for Ida. For Mathilde, the present model would have difficulty explaining the observed geometric saturation with giant craters. We eventually hope that the above work will allow us to create a Monto-Carlo experiment in which we can see regional changes in impact angle as the shape of body evolves given the anisotropic distributuion of impactors currently visible in the asteroid belt. These experiments shall use our understanding of the above described impact angle effect, known cratering efficiency rules [e.g. *Schmidt and Housen*, 1987] and reasonable scaling of numerical results for asteroid disruption [e.g. *Asphaug et al.*, 1996] to investigate how the shape of the sphere evolves in time. More complicated Monto-Carlo experiments could keep track of the evolution of the rotation rate of these asteroids as well.

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