Spectral probing of impact-generated vapor in laboratory experiments

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**Abstract**

High-speed spectra of hypervelocity impacts at the NASA Ames Vertical Gun Range (AVGR) captured the rapidly evolving conditions of impact-generated vapor as a function of impact angle, viewpoint, and time (within the first 50 ms). Impact speeds possible at the AVGR (<7 km/s) are insufficient to induce significant vaporization in silicates, other than the high-temperature (but low-mass) jetting component created at first contact. Consequently, this study used powdered dolomite as a proxy for surveying the evolution and distribution of chemical constituents within much longer lasting vapor. Seven separate telescopes focused on different portions of the impact vapor plume and were connected through quartz fibers to two 0.35 cm monochrometers. Quarter-space experiments reduced the thermal background and opaque phases due to condensing particles and heated projectile fragments while different exposure times isolated components passing through different fields of view, both above and below the surface within the growing transient cavity. At early times (<5 μs), atomic emission lines dominate the spectra. At later times, molecular emission lines dominate the composition of the vapor plume along a given direction. Layered targets and target mixtures isolated the source and reveal that much of the vaporization comes from the uppermost surface. Collisions by projectile fragments downrange also make significant contributions for impacts below 60° (from the horizontal). Further, impacts into mixtures of silicates with powdered dolomite reveal that frictional heating must play a role in vapor production. Such results have implications for processes controlling vaporization on planetary surfaces including volatile release, atmospheric evolution (formation and erosion), vapor generated by the Deep Impact collision, and the possible consequences of the Chicxulub impact.

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1. Introduction

Hypervelocity impacts generate a sudden and intense flash. Early studies using microscopic projectiles recognized multiple components of the flash (Gehring and Warnica, 1963; Jean and Rollins, 1970; Eicchorn, 1976; Tsemblis et al., 2008). High-speed cameras recording macro-scale (cm) experimental impacts, however, reveal that the flash represents a complexly evolving plume of cooling plasma (Schultz, 1996; Crawford and Schultz, 1999), early plasmas and jetting phases (Kondo and Ahrens, 1983; Ang, 1990; Yang and Ahrens, 1995; Sugita et al., 1998; Sugita and Schultz, 1999), later expanding vapor (Schultz, 1996; Kadono and Fujiwara, 1996; Sugita et al., 1998; Schultz et al., 2006; Bruck Syal et al., 2012; Mihaly et al., 2013), and molten/heated ejecta (Ernst and Schultz, 2004, 2007; Tsemblis et al., 2008; Ernst et al., 2011). More recent studies characterize plasmas generated by impacts into plates using time-resolved spectroscopy at speeds from 8 km/s (e.g., Heunoske et al., 2013) to 25 km/s (Reinhart et al., 2006).

The NASA Ames Vertical Gun Range (AVGR) permits impacts at different angles into flat-lying unconsolidated half-space targets and water. The large size of the impact chamber (2.5 m) allows impact-generated vapor to not only expand freely but also separate into different components without interference. Rather than a radiating point source at the point of first contact, the high-speed imaging reveals that the “flash” from a 0.635 cm diameter projectile is actually a large (10s of cm in scale), self-luminous vapor plume (Schultz, 1996). The transient cavity briefly restrains part of the vapor, just as in early models of vertical impacts (e.g., O’Keefe and Ahrens, 1977), after which the vapor rapidly evolves into a plume expanding spherically above the surface before eventually engulfing the surface. For oblique impacts, however, the plume exhibits a more complex evolution. An early-stage, high-speed jetting phase moves downrange at speeds that are three times the initial impact speed (e.g., Walsh et al., 1953; Jean and Rollins, 1970; Gault and Heitowitz, 1963; Kieffer, 1977; Sugita and Schultz, 1999), followed by a later downrange-moving and expanding vapor plume (Schultz, 1996). Consequently, oblique impacts result in both hot

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and cool phases evolving in different directions (Schultz, 1996; Pierazzo and Melosh, 2000; Schultz et al., 2006).

Hypervelocity impacts generate vapor when material undergoes irreversible heating unloading behind a high-enough shock. As a result, peak shock pressure is commonly used to predict vaporization, both analytically and in numerical models. Equations of state (EoS) are needed in order to determine the amount of vaporization with values that are unique for a given material (e.g., Pierazzo and Melosh, 2000). The EoS describes the thermodynamics of a system over a wide range of pressures, temperatures, and specific volumes. At the high speeds characterizing planetary impacts, the EoS is best understood along the Hugoniot, i.e., the locus of possible end states obtained across a single shock wave from an initial state.

Gupta et al. (2002) determined that complete devolatization of solid carbonate requires a peak pressure of 110 ± 10 GPa. Although consistent with prior measurements by Yang and Ahrens (1996), such high pressures seemed at odds with results of other impact experiments (Schultz, 1996). More recently, Ohno et al. (2008) found that the shock pressure for complete vaporization of solid calcite would need to be only 25 GPa. Porous targets require even lower peak pressures, with the onset speed for vaporization of porous carbonate targets as low as 1–1.5 km/s (Shen et al., 2003). For reference, a 2D model calculates that a 5 km/s (Pyrex) vertical impact into porous (40%) carbonate, such as dolomite (CaMg(CO₃)₂), produces a peak pressure of ~24 GPa. For oblique impacts, peak pressures decrease as (sin θ) for impact angles (θ) referenced to the horizontal (Gault and Wedekind, 1978). A 30° impact angle, therefore, should yield a peak pressure of only 6 GPa, equivalent to a 1.25 km/s vertical impact. Although such pressures may be consistent with onset conditions for vaporization following Shen et al. (2008), the effect of impact angle remains enigmatic. Specifically, an impact at 15° generates more than two orders of magnitude more vapor than does a vertical impact (Schultz, 1996), in contrast with numerical models for silicates at the much higher speed of 20 km/s (Pierazzo and Melosh, 2000). Hence, heating from scouring and frictional shear by the failed projectile impacting downrange must play a role, at least for volatile-rich targets.

Documenting the speciation and distribution of the vapor products (e.g., atomic versus molecular components) provides a better understanding of the impact-vaporization process and chemical processing within the plume. Such an understanding contributes to understanding volatile delivery to the Moon and Mercury, the consequences of the Chicxulub impact on Earth 65 myr ago, and interpretations of the Deep Impact mission results. Because much higher speeds are necessary for impact-generated vapor from silicate targets, the present study uses dolomite as a proxy target in order to assess the evolution of (and composition within) the vapor plume and the underlying processes.

Sugita et al. (1998) previously captured time-resolved spectroscopic observations at the AVGR as viewed from above the impact point. The ratio of spectral emissions with different excitation temperatures established the effect of impact speed and angle on the earliest components for solid dolomite targets. Moreover, the initial stages (first few microseconds) were found to depend on the vertical component of velocity, consistent with expectations for peak pressures. Derived temperatures ranged from near 6000 K (vertical impacts) to 4000 K (30° impact) for speeds near 5 km/s. Since the jetting phase dominates the earliest spectral emissions (mostly atomic), time-resolved spectroscopy could be used to refine the theory of jetting, including the relative contribution of the projectile and target (Sugita and Schultz, 1999). The total intensity of optical emission over visible wavelengths was found to depend on impact velocity with a power law exponent of 5 with different emission lines exhibiting different power laws depending on the specific emitting species (Sugita et al., 2003). Hence, multiple processes may contribute to the observed vapor.

Considerable spectral content, however, remains well after the jetting phase, especially for porous targets (Schultz et al., 2007). Consequently, the present study surveys the evolution of spectral emission lines from different viewpoints for impacts into porous targets. The specific objectives are to: (a) assess the evolving spectral content as a function of time and location; (b) place first-order constraints on the source (depth) of vaporization; (c) examine some of the controlling processes at the impact velocities available; and (d) consider the implications for Solar System exploration. Our results serve as a guide for follow-on quantitative studies (e.g., temperatures and abundances) and benchmarked numerical models for freely expanding impacts into half-space targets.

2. Laboratory experiments

The NASA Ames Vertical Gun Range (AVGR) is designed for a wide range of projectiles and targets with impact speeds up to 7 km/s at different impact angles into gravity-affected targets (sands, water, etc.). View windows from seven different directions allow documentation of the evolving impact-generated vapor with high-speed imaging and spectrometers. The following study uses targets composed of target materials previously observed to vaporize experimentally, such as carbonates (e.g., powdered dolomite), dry ice, or polycarbonates.

For the present study, four separate telescopes were connected to one of two McPherson Model 2035 Monochromators (Czerny-Turner type, 0.35 m focal length with 300 lines/mm or 600 lines/mm gratings) through quartz fibers connected to each of two Oriel InstaSpecV-ICCD detectors (Model 77193-5). Consequently, a total of seven spectral observations were possible. In general, the spectral range covered typically 440–600 nm (in some cases to 640 nm). Four narrow-field telescopes (~2.5 cm field of view, FOV) linked to each monochromater simultaneously captured spectra in multiple regions of the expanding vapor plume (Fig. 1A). Exposure times varied, depending on the intensity of the source region and experimental objectives. Intensity calibrations were made using both a filament light source (Tungsten halogen lamp, Oriel Corporation, Model 63355) and an extended light source (Labsphere, Model USS-600), following the procedures and measurement errors described in Sugita et al. (2003). As noted there, relative intensity within the same spectrum has an error of only 3%. For some experiments, a Princeton Instruments PI-MAX: 512-HQ thermal camera (512 × 512) simultaneously captured short exposure (50 ns) exposures at certain times with sensitivity from the visible to near infrared (flat response over from 540 nm to ~850 nm).

Full-space experiments refer to energy release below the surface within a semi-infinite target, whereas half-space experiments refer to a target with a free surface, e.g., by an impacting projectile. A quarter-space experiment, then, splits the target in half again by using a transparent sheet: specifically a thick (3/4 cm) acrylic.
below the surface with a depth (depending on impact angle) and corresponds to the zone of maximum energy transfer, i.e., the “effective depth of burst.” Here we compare spectra from the same series of experiments in order to minimize effects of variations in experimental setup and pointing. All experiments were done under near-vacuum conditions (pressure less than 0.7 mmHg). Any residual atmosphere has little to no effect on either heating the vapor or slowing expansion because of the amount of vapor produced. This can be demonstrated by observations of the jetting phase and later vapor that are not decelerated, as well as the absence of any spectral signature from the atmosphere (e.g., Schultz, 1996).

Sugita et al. (1998) provides a review of the basics of spectral observations as applied to impact-generated vapor plumes. Very briefly, atomic emission lines are generated by electronic transitions from an excited state back to a ground or less-excited state. The energy level, Einstein-A coefficient, and number of atoms in the excited state control the intensity and wavelength of a specific emission line. The spectral range chosen for the study here covers the visible range, generally between 390 nm and 620 nm. This choice of both spectral range and resolution is based on the sensitivity of the available ICCD cameras, the desired exposure times, and available spectral transparency of the view ports. Ongoing and future studies (e.g., Heunoske et al., 2013; Bruck Syal and Schultz, 2014) will quantify conditions (temperature, abundances, plasma components) within the vapor plume using greater resolutions and shorter wavelengths allowed by the next-generation ICCD cameras.

The following survey results from 33 different impact experiments. First, we contrast the evolution of the vapor plume as determined from viewpoints above and below in order to place the spectral observations in context. Next, a general comparison is made for different target types in images taken from above and below at different times in order to place later spectral observations in context. These results illustrate the need for looking inside the vapor plume by the use of quarter-space experiments (above and within the transient crater at different times and for different impact angles). We then explore the process and source of vaporization by examining the effect of surface layers and mixtures on the vaporization process. We finally consider possible implications, including the release of carbon dioxide from carbonate targets.

3. Vapor plume evolution viewed from above (half space)

Different portions of the moving and expanding plume pass through the fields of view of each spectrometer during different exposures. Consequently, it is important to understand what is actually being recorded in the resulting spectra. Fig. 2 illustrates the evolution of vapor phases viewed from above (1/2 space, 30° impact, Fig. 2A) and from the side (1/4 space, 60° impact, Fig. 2B) as captured in short exposures (5 ns) by a thermal imaging camera at different times. Views from above reveal the rapid downrange motion of the expanding vapor with a well-defined serrated front, likely the result of Kelvin-Helmholtz instabilities created at first contact by the spherical projectile. Laterally, the front initially expands at very high speeds (>10 km/s) but slows after approximately 5 μs to a value representing the initial non-isentropic gas expansion speed. Downrange, the front travels at a speed corresponding to this expansion rate added to the horizontal velocity component of the impactor (Schultz et al., 2007). The leading edge shown here does not represent the jetting phase, which continues downrange at speeds three times the initial impact speed until hitting the witness plate attached to the wall of the chamber. This component composed of hot vapor is captured in other imaging systems (e.g., Schultz, 1996) but not detected in the thermal imaging system.

For oblique impacts, sheared off portions of the projectile (decapitation fragments) decouple from the impact the soon after first contact but strike the surface downrange. As a result, the brightest (hottest) regions occur downrange from the impact soon after first contact (Fig. 2A). In views from above, an opaque component partly obscures the region just downrange, likely the result of the disrupted projectile along with early-time ejecta debris. Side views using the 1/4-space configuration (Fig. 2B), however, allow looking inside the vapor plume at different locations and reduce thermal contributions from hot debris. In this case, the subsurface is blocked-off from view in order to reduce scattered light from within the cavity. The vapor plume expands not from the center of the final crater but from a point offset downrange from the impact point.

Previous experiments used copper projectiles impacting solid dolomite in order to increase the peak pressures and optimize atomic emission spectra (e.g., Sugita et al., 1998). Here we concentrate instead on vapor generated from impacts into porous (powdered) dolomite targets, which results in a plume smaller than that from a solid target (over the first 5 μs after impact, Fig. 3). In both cases, the expanding plume exhibits a serrated leading
edge along with a strong thermal source (bright in these thermal images) downrange. Although at about the same distance from the impact point, these “hot” zones differ downrange: the impact into the solid dolomite has a narrow linear zone perpendicular to the trajectory while the impact into the powdered dolomite results in two bright spots. These zones result from impacts by the decapitated projectile impacting at low angles downrange (see Schultz, 1996). The opaque stringers downrange from the impact point likely indicate cooler fragments sheared (and spalled) off the top of the projectile in the foreground (Schultz and Gault, 1990). The leading edge of the vapor from the solid dolomite outpaced that from the powdered dolomite (at 5 µs) due to the contrast in both coupling time at first contact and containment of the vapor before free expansion.

Target porosity affects not only the evolution of the expanding vapor plume but also the spectral content. Over the first 50 µs, impacts into the dolomite block (Fig. 4, image B) and dolomite powder (Fig. 4, image C) both exhibit a strong thermal background (increasing intensity toward the red). They differ in that atomic and molecular emission lines characterize the impact into the solid dolomite, in contrast with the weaker atomic emissions but stronger molecular emission lines from the powdered dolomite targets. The molecular components (e.g., CO, CaO, MgO, and C2) represent either products of thermal decomposition at lower temperatures (e.g., from later stages of coupling) or back reactions (i.e., atomic and molecular species recombining within the plume). In the latter case, formula balancing requires the presence of emission lines of Ca and Mg in the plume as well. Consequently, the latter case should have detected these atomic emissions. Their absence may indicate an optically thick plume of both gas and dust in the foreground.

Covering the dolomite with a layer of sugar with a thickness equal to a projectile radius significantly suppressed the emergence
of atomic and molecular emissions from the dolomite below and resulted in a very weak blackbody component (Fig. 4, spectrum D). Sprinkling graphite on top of this layer of sugar, however, generated atomic and molecular emissions (Ca, Mg) superimposed on a much stronger blackbody background (Fig. 4, spectrum A). The contrast in spectral content between spectra A and D can be attributed to contributions from hot, condensed carbon particles in A. The oblique impact into the thin graphite layer on top of the sugar (spectrum A) generated carbon condensates within 5 μs (time of the accompanied exposed image) but then mixed with the sugar and dolomite below during penetration. The impact into just the layer of sugar (spectrum D), however, fully vaporized the sugar. Much later imaging for the same experimental set up revealed a delayed emergence of the strong blackbody farther downrange, out of the view captured here (see Schultz et al., 2007). This sequence indicates delayed condensation of carbon droplets out of the plume of vaporized sugar since such delay only occurs when sugar is added to the target material. In all cases, the spectral “noise” is not due to poor signal to noise ratio but to Mie scattering from condensed droplets of different sizes.

The composition of impact-generated vapor evolves with time, as documented in views from above. One strategy for capturing this evolution is to observe the plume passing by two different fields of view radial from the impact point (Fig. 5A); another is to sample the passage of the plume at the same location at different times (Fig. 5B). In Fig. 5A, the change in composition along a radial from the impact point corresponds to temporal changes during a 50 μs exposure from the moment of impact. Close to the impact, atomic emission lines are strong (Mg, Ca); farther away, atomic emissions fade while molecular lines increase. The one exception is the 423 nm Ca line, which remains strong in both locations due to its low excitation energy level (see Sugita et al., 1998). Since both fields of view captured the same parcel of vapor (both hot and cool) passing by during the 50 μs exposure, we conclude that the vapor plume chemistry must be rapidly evolving with back reactions, i.e., the recombination of Ca, Mg, CO in the plume that lead to MgO and CO.

Another strategy captures the passage of the plume at the same location at two different times directly downrange from the impact (Fig. 5B). In this case, however, the target is a 1:1 mix (by weight)
of sand and dolomite. The long exposure (0–50 μs) samples the earliest and hottest part of the vapor as well as the later cooler components. Delaying the exposure by 12 μs, however, eliminates contributions from the hottest portion of the vapor. For example, the jetting component would have traveled 18 cm by this time, well beyond the FOV for this viewpoint. The composition of this later arriving vapor resembles the component captured in the slightly more distant FOV (0–50 μs) in Fig. 5A but differs in the blackbody component. The delayed exposure (12–50 μs, Fig. 5B) captures a cooler background (lower slope of the blackbody background) directly downrange, perhaps because of the lesser amount of condensed species from dolomite (due to the sand mixture).

All spectra viewed from above (excepting Case D from a layer of sugar in Fig. 4) exhibit a significant thermal component. Fig. 5C contrasts a view from above (1/2 space) with a view from the side (1/4 space) exposed over the first 50 μs. Surprisingly, the side view results in very little contribution from a thermal component, along with a much cleaner spectrum due to reduced scattering from condensed droplets. While spectra taken from above contain spectral lines from both molecular and atomic emissions, the 1/4-space experiment exhibits no contributions from molecular species.

Fig. 6. (A) Quarter-space experiments comparing the evolution of the vapor plume from a vertical (left, 90°) at 5.78 km/s with the plume from an oblique impact (at right, 60°) at 5.69 km/s into dolomite powder, both 5 μs after impact. Images have been logarithmically stretched and contrast enhanced to bring out detail. Bar-scale corresponds to 1 cm. Note plume with a bright, serrated edge that leads the brighter central portion. (B) Locations and fields of view (FOV) for different spectra for a series of 60° impacts in dolomite superimposed on the thermal image in (A) (providing reference for illustrations to follow). Numbers indicate specific telescope FOV (about 2.5 cm in diameter in grey) linked to the spectrometer by quartz fibers to two different spectrographs: 1 and 5 (25° above the surface from the impact point); 2 and 4 (45°); 3 and 6 (60°); 7 (90°). Image is the same as shown in Fig. 2B, showing a side view of an oblique impact into dolomite at 5.69 km/s (exposed from 0 to 5 μs after impact).

Fig. 7. Comparison of spectral content within vapor plume in different FOV’s uprange (colored dots, Fig. 6) during the first 5 μs from an impact by a Pyrex sphere (0.635 cm) impact at 5.45 km/s (60°) downrange (top, (A)) and uprange (below, (B)). Note that the spectral content in the plume is non-uniform. The strongest atomic emissions come from FOV’s directed downrange, even for this relatively high angle impact (FOV-4 and -5). Nevertheless, emission lines viewed above the impact point (FOV-6 and -7) are weaker than those observed uprange (FOV-1 and -2). The projectile (Pyrex) contributes to the sodium line, which can be seen uprange (FOV-1, -2). The absence of spectra beyond 575 nm in (A) is due to a different center point for the monochromator.

Fig. 8. Comparison between early and late stages below the impact point for a 60° impact into dolomite powder (filled circle in inset). Vaporized dolomite products fill the cavity and produce strong atomic emission lines with evolving compositions. A thermal component (hot debris) raises the overall level. Sodium line results from vaporization of portions of the projectile and appears to reduce in strength as it escapes the transient cavity. Later, molecular species from the target become more important. The 0–2 μs exposure captured emissions from a 5.68 km/s, 0.635 cm Pyrex sphere, whereas emission lines from the 2 to 20 μs exposure resulted from a 5.73 km/s, 0.635 cm, Pyrex sphere.

Consequently, the view from above appears to be capturing emissions from multiple phases with contrasting temperatures passing through the field of view during the exposure.
Consequently, Figs. 4 and 5 demonstrate the need to: (a) isolate different components; (b) reduce the contribution from the thermal component; and (c) use different exposure times in order to understand the evolving vapor plume. In addition, it appears that the source of the vapor component comes from the uppermost surface. These three issues are considered next.

4. Vapor plume evolution viewed from side (quarter space)

In half-space experiments, views from above capture multi-phase components (projectile fragments, melt, and different-temperature vapor components) passing through the field of view during long exposures (Fig. 5C). Views from the side, on the other hand, are dominated by contributions from the leading edge expanding in the foreground. The quarter-space arrangement, however, eliminates contributions from foreground while different exposures at different times isolate contributions from various elements of the plume passing through the FOV.

Before comparing spectra, we first contrast the evolution of expanding impact-generated vapor from a vertical impact and an oblique impact (Fig. 6A). This difference illustrates the degree of temporary containment within the transient crater before freely expanding above the surface. In vertical impacts, the transient crater temporarily restricts and redirects expanding gas. Oblique impacts, however, result in a vapor plume that expands upward as it moves rapidly downrange, thereby exposing different stages of the process more clearly.

4.1. Above and below the impact

Each light-gathering telescope focused on different regions capture different portions of the vapor plume (Fig. 6B). The positioning close to the impact was necessary in order to use short exposure times for some spectra. The strongest spectral emission (greatest amount of vapor and/or highest temperature) occurs 2.5 cm downrange, only about 1 cm above the surface at FOV-5 (Low Downrange = Low-DR, Fig. 7A). Even for impact angles as high as 60°, asymmetry in the spectral content is evident here, with the least signal in the direction of the incoming projectile (no. 6, Fig. 7B).

Directly uprange (FOV-1, UR-Low), the inferred vapor mass (based on the overall spectral intensity) exceeds that directly above the impact point (no. 7, above). Note that the sodium line likely comes from the Pyrex projectile (2.8% by weight) since dolomite has less (<0.3%). This component is not caught in the thermal imaging camera but can be identified in high-speed imaging.

Impact vapor also fills the transient crater directly below the impact point during the first 2 μs (Fig. 8). For these experiments, a mask placed in front of the acrylic sheet blocks out scattering from sources above the impact point. The observed vapor could not be related to jetting, which is created at the surface between the projectile and target (see Sugita and Schultz, 1999), although it is possible that this component is redirected below the surface during penetration and mixed turbulently in porous targets. Note that the sodium-D couplet (589.29 nm) is strongest during the earliest exposure due to vaporization of the projectile at first contact.

Later (between 2 μs and 20 μs, Fig. 8), vapor continues to fill the growing cavity, but strong CaO and CO emission lines replace disassociation products (Ca, C2, and Mg) after 2 μs. As before (e.g., Fig. 5A), the increased abundance of molecular bands reflects either back reactions within the cavity or lower temperature byproducts. In addition, the reduced intensity of atomic emissions is accompanied by a slight increase in the blackbody (thermal component). This means that either heated particulates (projectile and target) are emerging from the cavity or that the vapor phases are condensing.

Above the point of first contact, spectral emission lines remain much stronger than emission below the surface, whether during the initial 2 μs (Fig. 9A) or later (Fig. 9B). During the first 2 μs, the continuum is relatively flat from 400 nm to 600 nm with weak molecular bands (CaO, MgO, CO) but very strong lines of Ca, Mg, and C2, both above and below the impact point. In addition, the Na line (from the projectile) appears strongest above the surface in an absolute sense, but not relative to other lines below the surface. Later (2–20 μs), the molecular bands of CaO, MgO, and CaO dominate the spectrum above the impact. Also note the reduced change in the contribution from Mg (near 519 nm) relative to Ca (528 nm).

The greater intensity of the Ca line near 430 nm (characterized by higher excitation temperature) compared to the line near 445 nm confirms expectations for the higher temperature at earlier times, yet the stronger 422.7 nm line above the impact point at late time seems inconsistent with this interpretation. This inconsistency results from self-absorption at 422.7 nm due to its lower excitation temperature, which decreases its intensity under strong emission. Greater spectral resolution can establish actual vapor phase temperatures through the Boltzmann equation (following Sugita et al., 1998; Bruck Syal and Schultz, 2014), but this is not the focus of this general survey.

Melted ejecta and condensates entering the FOV contribute a stronger blackbody above the surface between 2 μs and 20 μs (Fig. 9B). There, different components of the vapor plume (e.g., jetting, shock heated ejecta, and thermal disassociation products)

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**Fig. 9.** Comparison of the evolving vapor plume as viewed above and below the target surface. Elemental emission lines dominate early-time spectra from a 5.68 km/s impact. (A) Molecular emissions dominate later from a 5.73 km/s impact. (B) Vapor fills the transient cavity, even later (2–20 μs). Above the impact point, the reversal in relative intensities of 424 nm and 432 nm calcium lines at different times indicate decreasing temperature of the gas phase. These emission lines are superimposed on a background continuum. Sodium line from the projectile (0.635 cm Pyrex sphere) is strong above the impact but weak within the cavity after 2 μs.
freely expand and move rapidly downrange as they pass through the FOV. Higher temperature components observed earlier near the point of first contact superimpose other contributions. The transient cavity still retains some of vapor beneath the surface at this time.

Longer exposures (~50 μs) capture vapor emerging just uprange from the point of impact with emission lines much weaker than those from within the transient cavity (Fig. 10). The upper states of electronic transitions labeled in Fig. 10 (from Sugita et al., 1998) reveal that the relative intensity of Ca lines near 445 nm and 430 nm is a sensitive indicator of temperature in the vapor plume. At 3000 K, the 430 nm line is weaker than the 445 nm line, but the relative intensities reverse at 6000 K. This reversal in strength reflects different energy levels of the upper states of electronic transitions (divided by the Boltzmann constant): ~5430 K for the 445 nm line, versus 5540 K for the 430 nm line. As expected, the relative strength of these two lines indicates that the earlier exposure captures higher temperature vapor. The intensity of the emission line near 616 nm, however, is extremely strong (as shown below, this line is not superposed on a molecular band). Because the other Ca lines are consistently weak, the 616 nm line with its low excitation temperature indicates a much lower temperature in the vapor component directed uprange.

Shorter exposures at different times reveal a vapor composition that evolves within the transient crater (Fig. 11). Strong emission lines occur below the impact point (uprange inside the transient crater, Fig. 11A) within the first 2.5 μs. Away from the sub-impact point (DR Below, Fig. 11A), emission line intensities (and the background) decrease. The intensity of the 445 nm emission line relative to the 430 nm line again provides a qualitative comparison of temperature based on electronic transitions. Directly below the impact point, the 445 nm emission line is stronger than the 430 nm line. Farther away (DR Below), the reverse is true. Hence, vapor filling the cavity during the first 2.5 μs below the surface is hotter farther from the impact than the vapor just below it. This indicates that the vapor moves downrange within the transient cavity, just as it does above the surface.

The FOV's beneath the impact point captures both hot and cooler vapor components that rapidly escape the cavity in different directions. A higher temperature component expands and fills the growing cavity below (DR Below, Fig. 11A), while a cooler component dominates above (Fig. 10). Later (2.5–20 μs), the 430–445 nm line intensity ratio above the surface (Fig. 11B) resembles the ratio observed earlier, below-impact spectrum (Fig. 11A), consistent with a lower temperature gas escaping the cavity and expanding above. Within the transient cavity farther away (DR-Below, Fig. 11A), a cooler component now remains (DR-Below, Fig. 11B). Overall, line strengths for Ca and Mg lines (above the continuum) are reduced by at least half at later time (Fig. 11B), in spite of a sevenfold increase in exposure for all three spectra. The high-temperature component has disappeared while much stronger MgO, CO, and CaO bands indicate the added contributions from lower temperature vapor still residing within the cavity after 2.5 μs.

4.2. Effect of impact angle

Impact angle affects spectral content and temperature, both above and below the impact point (Fig. 12). All experiments for this series took place during the same run at the AVGR with the identical configuration and exposure (0–50 μs) in order to minimize issues related to calibration or pointing. In a vertical impact, nearly the entire spectral content occurs above the impact point and has the richest and strongest emission lines of all the impact angles, with only a weak signal coming from within the transient crater (Fig. 12A). In addition, the vertical impact generated vapor having

Fig. 10. Comparison of above and below the target surface for an exposure from 0.25 μs to 50 μs after impact by a Pyrex sphere (0.635 cm diameter) at 5.72 km/s. Values in parentheses indicate the energy levels of upper states of electronic transitions (divided by the Boltzmann constant) in 1000K (see Sugita et al., 1998). Lower values (<50 indicated in blue) represent transitions occurring at lower temperatures; higher values (>60 in red) transition at higher temperatures, with intermediate values in black. The absence of data for the subsurface FOV is due to a different wavelength center for this monochromater.

Fig. 11. Evolution of spectral content in different locations within the transient crater at two different times (60° impact, 5.61 km/s). (A) Immediately after impact (2.5 μs), the transient cavity is filled with high-temperature vapor, which is dominated by atomic emission lines from disassociation products of dolomite (Ca, C2, and Mg). Strongest emission lines occur below the impact point. (B) Molecular species (CaO, MgO) dominate spectral content later (2.5–20 μs). This figure reveals that the vapor is not uniform within the transient cavity: the highest temperature vapor phases occur directly below the impact point but fill the cavity in every direction before escaping. Different spectral limits between (A) and (B) reflect different ICCD cameras with different band centers in the monochromater. The insets in the upper right are two superimposed images (50 ns exposure, 5 μs after impact) of a 60° impact (quarter space) isolating the vapor plume expanding above and filling the transient crater below the surface.
the highest temperatures, based on the 430 nm-to-445 nm line ratio and the emergence of lines with high excitation temperatures (e.g., near 535 nm, 487 nm, 459 nm, and 510 nm lines). The presence of strong 555 nm and 610 nm CaO bands could indicate additional contributions from a cooler component emerging later over the long exposure (0–50 μs). Note that very little blackbody
emission exists over the sampled wavelength, in spite of the long exposures (compare with spectrum C in Fig. 4).

For the 60° impact, the strongest emission lines also occur directly above the impact point (Fig. 12B). In contrast with the vertical impact, other regions contain spectral content as well. The “downrange-low” FOV captured strong molecular emissions from CaO and CaO, while atomic emissions below the surface indicate a high-temperature vapor filling the transient crater. The Ca emission line near 616 nm (indicative of a lower temperature vapor) exhibits the highest peak intensity (above or below the cavity) but occurs above the surface in the uprange FOV, as noted above (e.g., Fig. 10).

The 45° impact appears to generate a spectrum with the greatest overall intensity (DR-low FOV), but this impression is largely due to a greater contribution from blackbody emission (Fig. 12C). The relative intensities of Ca and Mg emission lines (above the continuum) from a 45° impact are not that different from lines from a 60° impact, but both are weaker than those generated from the vertical impact. The very strong molecular lines from CaO, CO, and MgO at 45° represent cooler vapor presumably trailing behind the fast-moving gas downrange during the 50 μs exposure.

Condensates and hot projectile fragments (see Figs. 4–6) contribute to a significant blackbody in the DR-low FOV at 45° (Fig. 12C), but to lesser levels in the adjacent FOV above (DR-high), which exhibits obvious molecular (CaO and CO) lines but weak atomic emission. Hot, high-speed vapor escapes from the transient crater and rapidly moves downrange (DR-low). The second strongest atomic Ca emission lines, however, occur directly above the impact. High-speed imaging reveals that this component likely comes from vapor rapidly emerging directly above the initial transient cavity (Schultz et al., 2007; Schultz, 2009). As observed for the 60° impact, the weakest spectral content occurs uprange, excepting the 616 nm line indicative of cooler vapor. While still strong, it is weaker than the emission from the 60° impact.

For the 30° impact, Na emission from the projectile and molecular emission lines (CaO and CO) dominate close to the surface downrange (DR-low FOV, Fig. 12D). Above (DR-high FOV), molecular emissions (primarily CaO) are much reduced but still present. The strongest Ca and Mg emission lines, however, occur above the impact point while very little emission occurs below the target. Only the 616 nm Ca line persists uprange.

Most of the vapor from the 30° impact expands freely above the surface while moving downrange. This plume must hug the surface downrange since it is not captured as well in the DR-High FOV. Another component (dominated by atomic species) expands above the impact point and the transient cavity. Nevertheless, a cooler vapor component (strong 616 nm Ca line) again emerges uprange. This component does not contain the sodium line from the projectile, which is strongest downrange. In contrast to the 45° impact, the thermal background is very low, even though projectile fragments should be in the field of view. The most likely explanation is that the lower impact angle resulted in reduced heating of the decapitated projectile fragments (e.g., see Schultz and Gault, 1990) that decoupled and impacted farther downrange, beyond the fields of view covered here.

5. Source regions and vaporization process

5.1. Source regions

Layered targets allow isolating the source depth for impact-generated vaporization. Even a thin layer of sugar or graphite on top of particulate target dramatically alters the spectral content and masks contributions from below (see Fig. 4). Here we consider this process further, first with the effect of thin layers on top of solid blocks (Fig. 13), then with layers placed at the point of first contact or downrange.

Prior studies presented evidence that frictional shear heating must play an important role in impact vaporization of carbonates and that multiple impacts downrange by the failed projectile contribute to this process (Schultz, 1996; Schultz et al., 2006). This can be demonstrated by isolating contributions from first contact by the projectile and impacts by projectile fragments (Fig. 14). In one case, the projectile makes first contact with a thin layer (100 μm) of dolomite (Fig. 14A, above), called Case A here. In the other, the projectile makes first contact with the copper such that the only contribution from the projectile comes from impacting projectile fragments downrange (Fig. 14A, below), called Case B. Here, telescopes cover four different fields of view downrange from the impact point in order to isolate the different vapor components (Fig. 14B).

In Fig. 15A, the FOV just downrange from the impact point misses the signal from the thin layer since the exposure was delayed 2.8 μs after impact. The only spectral line comes from sodium in absorption (rather than emission) as a result of vapor expanding in front of a blackbody source (from the heated target). Farther downrange (Fig. 15B), projectile fragments impacting the dolomite layer downrange (Case B, Fig. 14) generate emission lines that are actually stronger than lines from vapor generated by the projectile making first contact (Case A, Fig. 14). The Ca line strengths, however, appear nearly identical. The exposure time and distance from the impact point samples vapor traveling downrange at a speed of at least 1.8 km/s, including the jetting phase. Consequently, both processes contribute atomic emission lines from jetting, but the isolated fragments impacting downrange generate greater amounts of CaO and CO.

Still farther downrange (FOV-C), the vapor component captured by the spectrometer requires speeds greater than 4.9 km/s.

Fig. 14. Experiments designed to isolate the source of vaporization and vapor components. Different fields of view combined with different exposure and delay times serve to isolate contributions to the vaporization by an impact (angle of 30°). (A) shows the isolation of vaporization resulting from first contact (above) with a 100 μm layer of dolomite on one half of a milled copper block. Another experiment isolates vapor due to the downrange hypervelocity projectile fragments impacting a 100 μm layer of dolomite. (B) shows the fields of view (2 cm diameter) at different locations downrange from the impact. Modified from Schultz et al. (2006).
Here, isolated fragments impacting at very low angles downrange (Case B) generate vapor with CO, C2, and Na emission lines that are stronger than those from the first contact (Case A) but with the same CaO. Again, the strong Na line comes from the Pyrex projectile. The emission lines from the target (Ca) indicate higher temperatures (e.g., see Fig. 9A) resulting from the fragments impacting carbonate downrange (Case B), rather than at first contact. Impacts by a large number of isolated downrange fragments at very low angles would increase the number of contact surfaces, thereby generating a stronger Na emission than that from the intact projectile (isolated first contact).

Farther downrange (FOV-D), the solid projectile making first contact with the carbonate layer (Case A) generates much stronger CaO and Ca emissions than did the isolated fragments (Fig. 15D). The reversal in intensities most likely indicates contrasting speeds of the downrange vapor plume for the two cases. Isolated downrange impacts by numerous projectile fragments (Case B) result in significant interactions and instabilities, thereby slowing the downrange component relative to the vapor generated at first contact. Multiple impacts by these fragments also generate a much stronger sodium line.

Consequently, Fig. 15 demonstrates that both the first contact by the projectile and second contact by decapitated fragments downrange contribute to the spectral content in an oblique impact.

These fragments impact downrange at lower angles than the initial trajectory of 30° (Schultz and Gault, 1990). Because peak shock pressures depend on the vertical component of velocity, the low-angle downrange fragments must generate high-temperature frictional shear heating that contributes to vaporization even at pressures much lower than those generated at first contact.

The same processes must occur for impacts into particulate targets. As a first example, dolomite powder was sieved lightly on top of a target of powdered pumice to a level where the pumice could not be seen (less than a millimeter thick). The thermal imaging camera reveals that this thin layer resulted in a plume resembling that of dolomite powder alone but with slower expansion (Fig. 16).

Consequently, upper surface layers may contribute a significant amount of the spectral content for oblique impacts into both solid and particulate substrates.

5.2. The vaporization process

Frictional shear heating between grains appears to contribute to vaporization. Such a process can be illustrated by examining the effects of mixing the volatile component (dolomite) with a non-volatile component (no. 20-30 sieved sand). This experiment (Fig. 17) resulted in an increased thermal background (and enhanced CaO and CO bands) due to the added contribution of...
heated sand grains for comparable impact speeds (5.8–5.93 km/s at 60°C). As shown in Figs. 13 and 14, upper surface layers contribute most (if not all) of the spectral content. Introducing a non-volatile surface layer, therefore, should suppress emission lines from the substrate (Fig. 4, spectrum A). Fig. 18, however, reveals that a thin (<2 mm) layer of sand over dolomite produces the same, if not stronger, emission lines (above the thermal background) for nearly identical impact speeds (e.g., CO and MgO). The one exception is the 425 nm emission line, which is affected by self-absorption. Consequently, interactions with the heated sand grains as they are driven downward into the dolomite must contribute to vaporization from thermal decomposition, rather than shock.

6. Discussion

Spectral probing of impact-generated vapor generated from porous targets reveals a complex evolution, separate and well after the early-time jetting phase. Above-impact views can become difficult to interpret because multiple components contribute to the spectra, including mixed phases (e.g., solid ejecta, melt droplets, and vapor from both target and projectile) passing through the fields of view. Quarter-space experiments, however, partly isolate conditions inside the plume (as well as the transient cavity). Such a strategy helps to minimize contributions from not only condensation droplets but also fragmented projectile debris, both producing a strong thermal component (except for views directly downrange from an oblique impact). Beneath the surface, this perspective reveals that the hot vapor from oblique impacts initially fills the transient crater for at least 20–50 s after impact. Ironically, vertical impacts result in vapor phases rapidly escaping (within first 2 s) with little signal detected below the surface. Different components pass by the field of view at different times. At early times, atomic emission lines (Ca, Mg, and C2) dominate and indicate high-temperature disassociation products, as inferred from the relative intensity of key emission lines with different excitation levels. Molecular species (CaO, MgO, and CO) develop later as a result of both thermal disassociation at lower temperatures (farther from the source) and recombination (back reactions within the plume). At later times, the blackbody background increases due to condensation of small carbon droplets. Powdered dolomite targets contain small amounts of graphite on the crater floor, consistent with carbon calabashes generated from impacts into solid dolomite targets (Rietmeijer et al., 2003). Uprange, a lower temperature component also emerges from oblique impacts, especially for a 60° impact angle. Because the shock wave in an oblique impact is directed downrange (Schultz and...
Anderson, 1996; Dahl and Schultz, 1998, 2001; Pierazzo and Melosh, 2000), shock pressures should be less uprange and released vapor should be cooler. As the projectile continues to penetrate the target, a gap is created between the less-shocked uprange transient crater wall and the downrange-moving projectile. This gap allows vapor to escape uprange without further interactions.

Experimental design further reveals that most of the vaporization (at these impact speeds) comes from the uppermost surface layer, whether for solid or particulate targets. In oblique impacts, the failed projectile fragments impact the target downrange and contribute a significant additional vapor component. The large amount of vaporized mass observed for oblique impacts, then, also must require vapor generated from an extended area downrange related to impacts by projectile fragments (Schultz, 1996). Because these fragments impact at very low angles, shock levels are reduced; consequently, waste heat behind the shock front does not appear to play a major role. Instead, the source of vaporization must come from thermal decomposition at low pressures due to the high temperatures generated by frictional shear heating from multiple sources.

The combination of non-volatile silicate sand (no. 20-30 sieve) with dolomite powder provides further insight. If intimately mixed, the thermal blackbody increases due to particle–particle interactions behind the shock and within the flow field. Typically a thin, non-volatile layer over a solid volatile target acts as a flak jacket, reducing the amount of vapor generated by the impact, consistent with experiments investigating the effect on peak pressures (Stickle and Schultz, 2011). From the results here, spectral observations indicate that the shock–shear-heated sand grains in the surface layer generate secondary thermal release of volatiles from dolomite powder below.

A revised shock Hugoniot for carbonates indicates that hypervelocity impacts should not vaporize easily (Ivanov and Deutsch, 2002). Spectral data seem to indicate otherwise. This contradiction can be reconciled by considering the increased contribution of frictional shear heating that result in high temperatures (5000 K) but low pressures (less than 0.1 GPa), along with free expansion. Consequently, estimates for vaporization based on peak pressure alone likely underestimate the amount of vaporization and melting, especially for both lower impact speeds (<10 km/s) and oblique impacts, which generate reduced peak pressures.

Numerical models indicate that oblique impacts do not result in increased vaporization at lower impact angles (Pierazzo and Melosh, 2000), in contrast with experimental results (Schultz, 1996). Moreover, some models may not accurately capture the range of temperatures within the vapor plume, especially for lower speeds (Quintana et al., 2013) and impact angles. Such differences between experiments and models indicate that numerical models should be benchmarked with spectral observations of the plume under different impact angles and conditions (e.g., mixtures) and should be designed to isolate various contributions to the vaporization process, including granular interactions, source depth, frictional shear heating, and projectile fragments impacting downrange.

7. Summary and implications

7.1. Summary

Hypervelocity impact experiments into volatile-rich particulate targets reveal that the generated vapor exhibits considerable variability in its distribution, composition, and temperature in both time and space. Several specific conclusions are reached (with reference to relevant figures illustrating each point):

1. Half-space experiments viewed from above capture multiple components passing through the field of view at the same time (e.g., condensation droplets, heated/melted projectile fragments, and contrasting plume conditions), which can complicate interpretations of conditions. Figs. 4 and 5A, B.
2. Quarter-space experiments of particulate targets viewed from the side allow probing within the vapor plume not only above the surface but also inside the transient crater. This strategy minimizes contributions from multiple components when viewed from above. Figs. 5C and 7.
3. Both the projectile at first contact and downrange impacts by projectile fragments contribute to the vaporization process for oblique impacts less than 45°. Figs. 4 (insets A and D) and 15.
4. Impact-generated vapor fills the transient cavity and evolves in composition as it expands above. Figs. 5 and 8–13.
5. The composition of vapor phases within the transient crater (below the surface) evolves from atomic to molecular emissions. The molecular emissions are due to less heated thermal decomposition products emerging later, as well as recombination products. Figs. 8 and 9.
6. In oblique impacts, a low-temperature vapor component emerges uprange, for angles as high as 60°. Figs. 7 and 12.
7. The source of vaporization generally comes from the uppermost layers for solid targets (at these speeds), even for high-angle impacts (e.g., 60°). Figs. 4 and 13–15. Conversely, even a thin refractory layer over a solid target can suppress or mask vaporization. Fig. 4.
8. Vaporization is not just due to peak pressures at first-contact; it also depends on the temperature generated by frictional shear heating, i.e., high temperatures under low pressures. Figs. 13–18.
9. Both direct (i.e., at contact) and indirect (interactions with heated projectile fragments or heated particulates in the target) contribute to vaporization, especially for oblique impacts (<45°). Fig. 18.

7.2. Implications

Examples of three implications from this study include: (a) the amount of vapor generated by the Chicxulub impact; (b) the delivery of volatiles to planetary surfaces; (c) spectra of the Deep Impact collision.

First, the amount of vaporization from oblique impacts may be underestimated if based on peak pressure alone or the peak-pressure footprint, i.e., an ellipse dependent on the angle. For example, an oblique trajectory for the Chicxulub asteroid impacting into the thick carbonate platform on the present-day Yucatan could have released much more CO₂ than some prior estimates based only on pressure (e.g., Ivanov et al., 1996; Pierazzo et al., 1998). If the Chicxulub impact had occurred at an impact angle of 30° with a velocity of 25 km/s, then ~26 projectile masses could have been vaporized, based on extrapolations of experimental results from 6 km/s to 23 km/s (Schultz, 1996). With the assumption that only 25% of the vaporized sediment cover had been composed of carbonate, then 164,000 GT would have been vaporized, thereby yielding 57,000 GT of CO₂. From the results presented here, significant vaporization comes from frictional shear created by the failed/melted projectile after first contact and is derived from surface materials less than a projectile radius in depth and covering a fan-shaped area with a width and length equal to the cotangent of the projectile diameter (see Schultz, 1996). So, another strategy considers the amount of vapor liberated from a downrange fan-shaped zone about 15 km wide and 15 km with a 3 km thick sedimentary cover, again with the assumption that carbonates comprise 25% of the sediment layer above basement and only 35% of this mass could actually yield CO₂. In this case, about
74,000 GT of CO₂ would have been released. Such estimates are consistent with the highest amounts from early studies (O’Keefe and Ahrens, 1989) but well exceed later determinations (Takate and Ahrens, 1994). These values dwarf the abundance of CO₂ thought to have been present (9000 GT) in the late Cretaceous atmosphere (Berner, 1994), even if much of this vaporized mass escaped the Earth or the CO₂ recombined into other forms. Such estimates serve only to emphasize the need for (and implications of) more complete modeling of oblique impact processes.

Second, the experiments demonstrate that a component of impact-generated vapor fills the transient cavity. This result has two implications. First, vaporized products from both the projectile and target can condense out on regolith grains within the crater cavity, thereby contributing to space weathering (Noble et al., 2001). Impact experiments using iron-bearing minerals already have demonstrated vaporization of iron at speeds achievable in the AVGR (Adams et al., 1997; Bruck Syal and Schultz, 2014). Second, cometary particles contribute a significant fraction of the flux on the Moon for sizes less about 10 cm (Nesvorný et al., 2010). Vaporized portions from small objects should be injected into the regolith and/or plated out on grains, especially during the cold lunar (or mercurian) night. Thermal recycling during a lunation could then release volatile components later with speeds much lower than those during the impact itself. This process would provide a daily supply of volatiles to cold traps at the poles (e.g., Stern, 1999; Schultz, 2011). Moreover, not all impact-generated vapor phases emerge at high temperatures: low-temperature vapor also escapes uprange in oblique impacts. Such vapor has lower expansion speeds, which would increase the likelihood of contributing volatiles to polar cold traps. Future studies at higher resolution spectra along matched by hydrocode models should establish new constraints on vapor temperatures and chemistries for more realistic planetary target materials.

Third, the Deep Impact (DI) collision resulted in multiple stages of ejection visible for more than 14 min (e.g., A’Hearn et al., 2005). The laboratory experiments here, however, only capture the earliest stages including: the rapidly moving (but evolving) downrange plume; an uprange-directed plume (followed by a high-angle plume); and the hemispherical plume above the crater. Results indicate that spectra of the initial high-speed (distal) components from the DI impact came from the uppermost surface materials but included other contributions depending on the field of view (direction of observation). Downrange, the high-speed (10 km/s), highest temperature plume (>6000 K) passed through the slit at 10 km/s within about 10–20 ms. While imaging captured this component, the relatively long exposure time for the IR spectrometer (>700 ms) recorded multiple components passing by, including hydrocarbons, H₂O, and CO₂ at lower temperatures (1000–2000 K), as previously described (A’Hearn et al., 2005). Further analyses concluded that this mix evolved after ~2 s into multiple components: first, a downrange zone composed of water ice; second, lateral ejecta of dust and ice (Sunshine et al., 2007). Impacts into layered targets (e.g., Fig. 4, inset D) demonstrate that a surface layer significantly suppresses contributions from below. Consequently, the Deep Impact IR spectra captured either a trailing plume downrange derived from just below a more refractory surface layer or a high-angle plume in the foreground from deeper below. Finally, the vapor filling the transient crater in laboratory experiments (Figs. 11 and 12D) establishes a process for initiating both the reverse and high-angle plumes of snowy particulates from depth (Schultz, 2009).

Although these experiments use impactor speeds and sizes well below those at larger scales (e.g., Chicxulub), they nevertheless reveal fundamental processes that should occur even at large scales. For example, models not including the constitutive and failure models at sufficient resolution will not capture contributions by the failed impactor impacting downrange (e.g., Stickle and Schultz, 2012) nor the contributions of frictional shear heating (Quintana et al., 2013; Crawford and Schultz, 2013). Additionally, models indicate that silicates should not vaporize at speeds of only 6 km/s, yet spectral observations document dissociation products, such as iron and magnesium emission lines (e.g., Adams et al., 1997; Bruck Syal and Schultz, 2014). Finally, surface expressions of impactor failure on the Moon and Mars demonstrate that the role of impactor failure observed in laboratory experiments also occurs at much larger scales (e.g., Schultz and Lutz-Garihan, 1982; Schultz and Stickle, 2011; Schultz et al., 2012; Schultz and Crawford, 2014). The initial peak pressures experienced by the Chicxulub asteroid impacting at a 20° angle should be reduced by 75%, making a 23 km/s collision equivalent to a 7.9 km/s vertical impact, comparable to laboratory impact speeds where the projectiles is observed to survive (Daly and Schultz, 2013). If numerical models cannot match processes actually observed in the laboratory experiments, then they may not fully capture the vaporization processes on the planets and asteroids.

8. Concluding remarks

High-speed spectroscopy reveals unexpected processes that could focus hydrocode modeling and not just be a technique for benchmarking. Future experiments will detail conditions (temperature) within the late-stage vapor at higher spectral and temporal resolution, use more realistic planetary materials or proxies (e.g., hydrous silicates), explore the effect of a greater range of target porosities, and reverse the roles of target and projectile for volatile-bearing materials.

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