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Spectral probing of impact-generated vapor in laboratory experiments

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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 μs). 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 monochromaters. 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 the 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.

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-laying 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 Heitowit, 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 ($CaMg(CO_3)_2$), produces a peak pressure of ~24 GPa. For oblique impacts, peak pressures decrease as $(\sin\theta)^2$ 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 Monochromaters (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″ thick) acrylic sheet placed along the trajectory and perpendicular to the detector (Fig. 1B). Such a strategy provides a window into the cratering process, such as crater growth (e.g., Piekutowski et al., 1977; Schultz, 2013). Here, quarter-space experiments are used to look inside the evolving vapor plume, both above and below the surface (e.g., Eberhardy and Schultz, 2003, 2004).

Careful positioning of the target allows the projectile to pass by an acrylic sheet within a centimeter or less. First contact by the projectile too close to the sheet fractures and disrupts the window; contact too far, obscures the initial stages. Optimally, the projectile should be within about a projectile radius (3 mm) away from the sheet. After the shock wave propagates away from the sheet, the initial penetration of the projectile creates a gap next to the sheet, thereby coupling little energy to the Plexiglas even at hypervelocities (5–6 km/s). In successful quarter-space experiments, a small zone in the sheet exhibits light scouring. This zone occurs just