
Hypervelocity impacts into volatile-rich targets generate a self-luminous cloud that expands and decelerates in the presence of an atmosphere following theoretical expectations (1, 2). Spectra of such clouds reveal prominent emission lines resulting from vaporized target components and reactions with the impactor (1, 3). Because the degree of vaporization and cloud luminosity is found to vary with impact velocity, angle, and impactor/target combinations, experiments were designed using the NASA Ames Vertical Gun Range to assess the evolving spectral content. Our results establish that a wealth of compositional information can be derived from emission spectra at relatively modest impact velocities (5–6 km/s) for a wide range of carbonate and silicate targets. In contrast with much earlier studies that viewed the phenomena as a nearly instantaneous flash (4, 5), our results document a complex vapor cloud that evolves in both time and space. Consequently, spectroscopy provides a powerful new tool not only for probing the impact process but also for exploiting this information to determine planetary surface compositions that might be difficult to measure or interpret with conventional remote-sensing techniques.

Approach: Three spectrographic systems have been used. The first is a high-resolution (0.2 nm) photographic diffraction spectrograph (PDS) covering the range from 400 nm to 630 nm. The second is a CCD Personal Spectrometer II (PS-II) covering the range from 380 nm to 880 nm at low-resolution (5 nm). These two instruments provide poor time resolution relative to the impact event: essentially open exposures. The motion of the vapor cloud past the field of view, however, resulted in an effective time exposure of less than 1 ms. This approach revealed the integrated spectral content for a variety of targets and impact conditions. The third system is a gated-intensified CCD spectrograph by the Oriel Corporation allowing the spectral range, resolution, and exposure time to be tuned according to need. For these experiments, we chose a relatively narrow spectral range (360 nm to 580 nm) with a spectral resolution of 1 nm. Time gating of the spectrograph allowed measurements over the first 2.3 ms and from 2.3 ms-50 ms after the impact. This higher resolution in both time and wavelength is critical for deriving quantitative information from the spectra. The three systems were not used simultaneously but at different times for different purposes. Collectively they provide an intriguing overview of the complex phenomena and processes that will help to constrain future studies.

The NASA Ames Vertical Gun Range is uniquely suited for this effort. The variable launch angle allows use of unconsolidated and liquid targets. Equally important, the large chamber size permits free expansion of the vapor cloud in a near-vacuum (3 m) without interference from the chamber walls. Moreover, multiple viewing ports allow alternative viewing geometries. The photographic spectograph was positioned at the side port and provided a high-resolution, two-dimensional view of the evolving vapor cloud as it passed by the imaged slit. Targets included dry ice (CO₂) and CaCO₃ powder impacted 5 km/s-5.5 km/s aluminum spheres (0.635 cm) at 15° from the horizontal. The low-resolution PS-II was also positioned at the side port and used a narrow viewing angle (5°) on specific sites within the vapor cloud for different impact angles (15°, 30°, 90°) and impactor types (aluminum and pyrex). These experiments allowed a preliminary assessment of impact angle effects and compositional heterogeneity within the cloud. Lastly, the Oriel system was used to determine composition from observed spectra for three distinct natural target materials (dolomite powder, calcite crystal, and gabbroic [diabase] block). Aluminum projectiles (0.3175 cm spheres) impacted these targets at 15° (from the horizontal).

Results: The high spectral resolution from the PDS reveals clear signatures from both the impactor (aluminum) and dissolved components of carbonate targets (1). The distinctive AlO⁺ molecular bands near 470, 480, and 510 nm indicate rapid chemical reactions between target and impactor. Identified emissions from the target include NaI (589, 590 nm), CaO (554, 604, and 622 nm), Ca2 (423, 527, 560, and 586, 610, and 612 nm) and partly masked CO (561 and 609 nm). Such impact products are consistent with expectations (6, 7).

Impacts into non-volatile silicate powders allow tracing the effect of impact angle on the impactor (AlO⁺) dispersal and Na/K fractionation. Figure 1 shows the decreasing intensities of emissions from Na and K with increasing impact angles of 15°, 30°, and 90° from the horizontal. The Na/K ratio, however, systematically increases with increasing impact angle from 1.2 at 15°, to 1.3 at 30°, and to 1.5 at 90°. These trends may indicate enhanced vaporized mass with lower temperatures at lower impact angles as previously inferred for impacts into carbonate targets (2, 3). Figure 1 also reveals that the intensity of the impactor component decreases as impact angle increases.

Because the observed spectral emissions change with time due to evolving conditions within the vapor cloud (reactions, mixing, cooling, trajectories) and exposure (motion across the detector), the gated Oriel spectrometer is necessary for deriving meaningful elemental abundances. Figure 2 contrasts spectra captured during early (0–2.3 ms) and late (2.3–25 ms) times following 15° impacts (0.318 cm aluminum) into calcite. In contrast with the side-looking views (Fig. 1), Fig. 2 shows data acquired focused from above on a 10 cm-diameter spot positioned 5 cm downrange from the point of impact. It reveals not only the rapid decay in the intensity as the gas cloud moves downrange beyond the viewing area but also the evolving species due to radiative, reactive, and transport processes. While the early-time exposure captures the impactor (AlI, AlO⁺), the late-time exposure reveals more clearly the target components (CO, CaO, Ca2) although considerably reduced in intensity. Additional experiments using calcite, dolomite, and gabbro allowed determining the relative abundances of Mg and Ca from the relative intensities of their emission lines (Fig. 3) that were consistent with their known compositions.
Conclusions and Implications: The experiments to date establish that 1) atomic and molecular emission bands can be easily measured; 2) the spectra exhibit variations in elemental emission lines which are consistent with known target compositions; 3) the emission spectra content and character evolve considerably both in time and space; 4) impact angle has a significant effect on the dispersal of the impactor within the vapor cloud; 5) lower impact angles appear to enhance the peak spectral emissions possibly reflecting increased vapor production at lower temperatures; and 6) impact angle affects the relative intensity of Na and K emissions, most likely reflecting fractionation due to greater peak shock pressures at higher angles.

Impact Flash Spectroscopy (IFS) may provide a new tool for probing planetary surface compositions once the physical processes are better understood. While carbonates, space-weathered silicates (glasses), and hydrated minerals can be difficult to recognize in conventional reflectance spectra, impact-induced emission spectra provide clear signatures of target composition. Future missions using released probes could provide critical and complementary compositional information through IFS.


Figure 1. Comparison of emission spectra created by Al impacts into dolomite at 5.2 km/s. Early (0 - 2.3 ms, solid) and late (2.3 - 25 ms, dotted) exhibit very different spectral content. The late-time spectrum (a.u. = arbitrary units) has been multiplied by 50 for comparison. Oriel CCD Spectrograph.

Figure 2. Time evolution of emission spectra created by Al impacts into dolomite at 5.2 km/s. Early (0 - 2.3 ms, solid) and late (2.3 - 25 ms, dotted) exhibit very different spectral content. The late-time spectrum (a.u. = arbitrary units) has been multiplied by 50 for comparison. Oriel CCD Spectrograph.

Figure 3. Comparison of spectra of the first 2.3 ms created by impacts into calcite (top), dolomite (middle), and gabbro (bottom) by Al spheres at ~5 km/s (offset by ~5 intensity units for comparison).