SHOCK WAVE EXPANSION, DECOUPLING AND ACOUSTIC SIGNALS IN LIBS MEASUREMENTS UNDER MARTIAN ATMOSPHERIC CONDITIONS.

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Introduction: The Mars2020 Mission's Perseverance rover landed successfully on Mars in February 2021 and began its operations. Among the payloads is the SuperCam instrument suite that includes a system to perform laser-induced breakdown spectroscopy (LIBS) measurements as well as a microphone. The microphone can be operated as a single instrument or in conjunction with the LIBS instrument to acquire supplementary data that can enhance the analysis of the LIBS spectra [1,2].

In a LIBS measurement, a short, intense laser pulse is focused on the sample surface, e.g. a rock or soil, to ablate some of the sample material and induce a transient plasma. The plasma is analyzed spectroscopically to gain insight into the elemental composition of the sample. This method is especially attractive for planetary exploration rovers, since it only requires optical access to the target that can be located several meters away from the instrument [3]. When a LIBS measurement is performed, the high pressure of the plasma plume causes it to expand rapidly into the ambient atmosphere. This leads to the generation of a shock wave that can be recorded to gain insight into the interaction between the ablating laser beam and the sample material, e.g. to find the optimal laser focus or to evaluate the material hardness [4,5]. Furthermore, the acoustic energy was suggested to be a good quantity for normalization of LIBS spectra, since it correlates with the mass ablated during a measurement [6].

Motivation: In this study, we investigate the connection between the generation of a laser-induced plasma and its shockwave, the decoupling of the shock wave from the plasma, and the acoustic signal that is produced after the initially supersonically expanding shock wave degenerates into a sound wave. The generation of a LIBS plasma is a highly complex process that involves interactions between the laser radiation and the material, the plasma and the material as well as interactions between the laser radiation and the plasma. Changes in these interactions also influence the shock wave and the acoustic signal [4,7,8]. The generation and the decoupling of the shock wave from the expanding plasma plume has been investigated to some extent in terrestrial conditions, but is not well-understood for Martian atmospheric conditions. In order to investigate these effects, we have developed a setup for the imaging of the laser-induced shock wave in a simulated Martian atmosphere using the schlieren imaging technique [9]. The setup was integrated into a previously built plasma-imaging setup capable of taking both spectrally and spatially resolved images of the plasma plume [10]. Furthermore, a microphone was installed to acquire data that can be compared directly to data available from measurements on Mars.

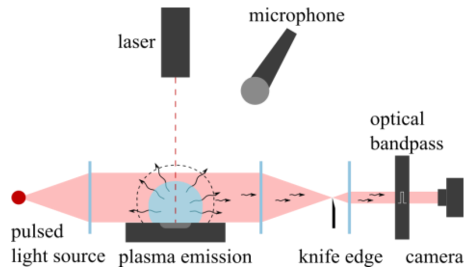

Figure 1: Sketch of the schlieren imaging and microphone setup. The plasma is ignited inside a vacuum chamber not shown here. It also houses the microphone.

Experimental Setup: The system we used to perform the presented measurements consists of three elements: a plasma imaging setup, a schlieren imaging system, and a microphone. Acoustic recordings can be performed simultaneously with either schlieren or plasma imaging measurements. The plasma is induced inside a vacuum chamber that can be flooded with Mars-analogue gas to simulate Martian atmospheric conditions.

Schlieren Imaging System. A sketch of the schlieren imaging system with the integrated microphone can be seen in Figure 1. Schlieren images reveal changes in the refractive index of a medium by partially blocking light rays that were deflected by a refractive index gradient. The gray-value of a given pixel corresponds to the refractive index gradient along a chosen direction at this location in the imaged object and also represents density changes caused by the laser-induced shock wave. Our setup was designed so that refractive index gradients normal to the sample surface are resolved. By using pulsed laser diodes for strobe illumination, we achieve a temporal resolution of 18 ns, which is necessary to resolve the fast dynamics of the shock wave in the early expansion phase. An optical bandpass centered at 900 nm with a full width of 20 nm filters out most of the plasma emission. The system is optimized to achieve high sensitivity at low pressures in order to be able to observe the shock wave even at low Martian atmospheric pressures of around 1 kPa.

Plasma Imaging System. The plasma imaging system is capable of taking both spatially and spectrally

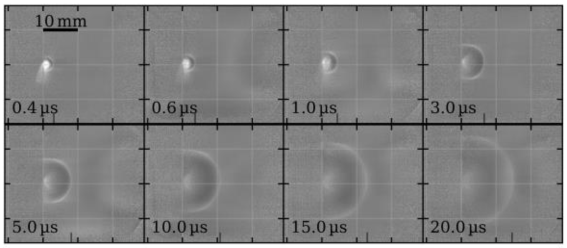

Figure 2: Schlieren images of a shock wave expanding from an iron target after laser ablation.

resolved images of the emitting plasma plume [10]. For the measurements presented here, we were interested in the entire spectrum of the plasma emission, so no spectral filtering was applied, though the system as it was used here is most sensitive between approximately 300 nm and 900 nm. In the presented measurements, we set the ICCD's gating time to 10 ns to investigate the earliest times in the plasma development.

Acoustic Recording System. The microphone (see Fig. 1) used to detect the pressure wave is mounted at a distance of about 7 cm from the sample. We chose the *Multicomp Pro* microphone *ABM-709-RC* with similar characteristics to the one used on the Perseverance rover covering the frequencies from 100 Hz to 10 kHz.

Results: The temporal development of the shock wave can be analyzed using the schlieren imaging setup by delaying the exposure of the system relative to the time of plasma ignition. Figure 2 shows a time series of a shock wave expanding from a laser-induced plasma under Martian atmospheric conditions. All presented measurements were performed on the pristine surface of an iron sample.

Tracking the shock front's movement perpendicular to the sample surface reveals the expansion dynamics of the shock wave that can be described well by the Taylor-Sedov model as previously found for laser-induced plasmas under terrestrial atmospheric pressures [8]. The function fitted to the shock front data in Figure 3 (blue) follows the Taylor-Sedov model until the speed of sound is reached. After that, a linear model with the slope of the speed of sound is fitted. Velocities within the first 2 µs exceed 1 km/s. In the presented measurement, the speed of sound is reached after about 21 µs. The plasma's leading-edge position is shown in green for comparison. Similar to previous studies under terrestrial atmospheric conditions, a drag model is fitted to the position of the expanding plasma that shows reasonable agreement with the data at later times [11]. Early deviations could be explained by plasma radiation that ionizes the adjacent gas layers and the generation of an early shock wave, leading to enhanced laser absorption within the plasma. The decoupling of the shock wave from the plasma can be seen between 400 ns and 500 ns.

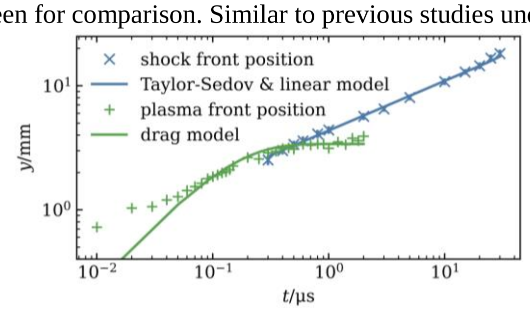

Figure 3: Expansion of the shock front and plasma plume from an iron sample. Crosses are data, lines are fitted models.

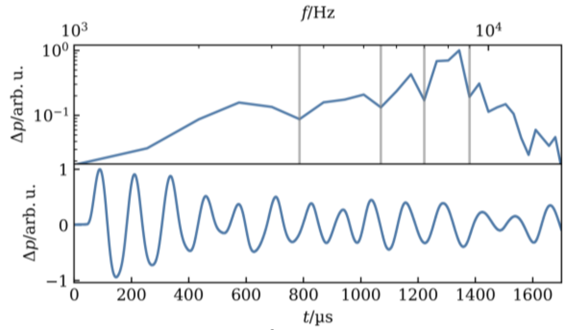

Figure 4: Acoustic signal of the laser-induced shock wave from an iron target and its frequency spectrum.

Figure 4 shows the acoustic signal Δp emitted from a laser-ablation process and the corresponding frequency spectrum. The duration of the first compression phase that can also be seen in the schlieren images is about 40 µs, which corresponds to a width of about 11 mm. The frequency spectrum shows four distinct dips at around 3.5 kHz, 5.5 kHz, 7.0 kHz and 9.0 kHz that are likely the result of interferences inside the simulation chamber.

Conclusion: The investigation of the processes involved in the generation of the acoustic signal in LIBS measurements is important to deepen our understanding on how to make use of this additional source of information. In first studies with a new schlieren setup, we investigated those processes in a simulated Martian environment. We show that the early phase of the shock wave expansion can be described by the Taylor-Sedov model. The shock wave decouples at about 400 ns to 500 ns after plasma ignition. The simultaneously acquired acoustic recordings can provide data that is directly comparable to data available from Mars.

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