Time-resolved spectral imaging of LIBS plasma at low pressures for the exploration of Solar System bodies

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Abstract

Laser-induced breakdown spectroscopy (LIBS) is an increasingly important technique for the robotic exploration of Solar System bodies. We investigate the spatial distribution of species inside the plasma plume of a LIBS measurement for different atmospheric compositions and pressures. The results can help with the interpretation of Martian LIBS data (ChemCam, SuperCam) and from other planetary exploration missions using LIBS.

1. Introduction

LIBS is a type of atomic emission spectroscopy that is very well-suited for the robotic exploration of planetary bodies [1]. The technique has been successfully employed on Mars with the ChemCam instrument on board of NASA’s Mars Science Laboratory [2]. SuperCam, the successor of the ChemCam instrument on NASA’s Mars2020 mission, will use LIBS again in combination with Raman and fluorescence spectroscopy [3]. India’s Chandrayaan-2 mission will also feature a lunar rover with an on-board LIBS instrument [4]. Additionally, concepts for LIBS instruments that could be used on other planetary bodies in the Solar System have been proposed [e.g. 5, 6].

The spectra obtained with LIBS are highly dependent on atmospheric conditions, especially the ambient pressure [7]. The technique relies on the creation of a plasma plume from material that has been ablated from the sample surface by a laser pulse. A spectrum of the light emitted by the plasma contains information about the elemental composition of the sample. At high atmospheric pressure, the plasma plume is confined to a small volume above the sample surface. Due to this confinement, it has a relatively long lifetime, but it is also optically dense and shields the sample surface from further ablation [8]. At low atmospheric pressure, the plasma expands and cools quickly, but its low optical density allows for more material ablation. The tradeoff between both effects yields maximum signal intensities at around 10 mbar, close to Martian atmospheric pressure [1, 9].

In this study, we investigate the effect of atmospheric pressure in more detail. We measure the spatial distributions of the species inside the plasma and the spatial variation of the plasma temperature at pressures between 1 µbar and 1 bar. The results will support the understanding of plasma formation, which in turn can help with the interpretation of LIBS data from Mars and other planetary exploration missions.

2. Experimental setup

A custom-made time-resolved plasma imaging setup with a low-pressure simulation chamber is used for the measurements. The simulation chamber can be filled with Mars-analog atmosphere, air, or other gases. It can be evacuated to a pressure as low as 1 µbar. For a measurement, a pulsed high-energy laser ($\lambda = 1064$ nm, 8 ns pulse FWHM, up to 30 mJ/pulse) is focused onto the sample surface through a window above the sample, generating a plasma plume. A slice of the plasma plume that is perpendicular to its propagation axis is then projected onto the slit of an imaging monochromator with a time-gated ICCD through a sideward window of the simulation chamber. By adjusting the height of the objective lens, slices of the plume at different heights can be measured. Various metals as well as salts and simulants that are relevant to planetary exploration are analyzed. Samples are pressed into pellets of 1 g and 1.4 cm in diameter.

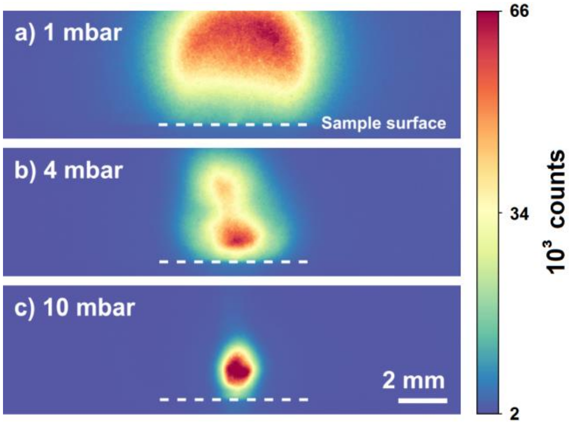

Figure 1: Plasma plume of a steel sample at different pressures (350 ns delay, 100 ns integration time).

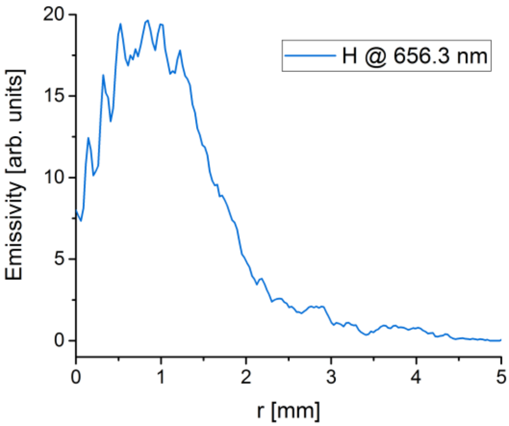

Figure 2: Radial emissivity of hydrogen at 656.3 nm, with the axis of the plasma at r = 0 mm. (NaCl sample measured at 1 mbar, 1 mm above the sample surface, with no delay and 100 ns integration time.)

3. Results

Figure 1 shows monochromatic images (color-coded by intensity) of the plasma plume of a steel sample in air at 1 mbar, 4 mbar, and 10 mbar. The delay time between plasma initiation and measurement was 350 ns. The integration time was 100 ns. The plasma plume is notably smaller at higher pressures, and a slight asymmetry can be observed at 4 mbar. Figure 2 shows an example of the emissivity of hydrogen after performing an Abel inversion on the data. The highest emissivity is not at the center, so that electron densities calculated from the hydrogen line will not describe the inner plasma correctly. This result is in contrast to previous studies at 1 bar [10].

4. Summary and Conclusions

The atmospheric composition and pressure cannot be ignored in the analysis of LIBS data. The spatial and temporal distributions of emitting species inside the plasma plume change with ambient pressure, which can have significant impact on the calculation of plasma parameters and calibration curves. The influence of atmospheric conditions is especially important for LIBS used in planetary exploration, as many planetary bodies of interest have low-pressure atmospheres.

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