



Article Morphology of Meteorite Surfaces Ablated by High-Power Lasers: Review and Applications

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Abstract: Under controlled laboratory conditions, lasers represent a source of energy with well-defined parameters suitable for mimicking phenomena such as ablation, disintegration, and plasma formation processes that take place during the hypervelocity atmospheric entry of meteoroids. Furthermore, lasers have also been proposed for employment in future space exploration and planetary defense in a wide range of potential applications. This highlights the importance of an experimental investigation of lasers' interaction with real samples of interplanetary matter: meteorite specimens. We summarize the results of numerous meteorite laser ablation experiments performed by several laser sources—a femtosecond Ti:Sapphire laser, the multislab ceramic Yb:YAG Bivoj laser, and the iodine laser known as PALS (Prague Asterix Laser System). The differences in the ablation spots' morphology and their dependence on the laser parameters are examined via optical microscopy, scanning electron microscopy, and profilometry in the context of the meteorite properties and the physical characteristics of laser-induced plasma.

Keywords: meteorites; high-power laser; laser ablation; laser-matter interaction; laser-induced plasma



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1. Introduction

Finding high-power sources with precisely defined parameters that are able to deliver a high amount of energy to an isolated experimental system is a challenging problem for laboratory astrophysics. These experiments involve high-energy states of matter in supernovae explosion shocks [1]), lightning discharges [2–7], interacting explosions, plasma jets [8], accretion processes [9], inertial fusion [10], the generation of extremely hard radiation [11], asteroid impacts and their consequences to the chemistry of early planets [12–15], meteor plasmas, and meteor spectra [16–20].

Laser interaction experiments with meteorites offer a unique opportunity to explore the spectra and the properties of laser-induced plasma (LIP), suitable for the simulation of the physics and chemistry of meteor plasma. The classical application of such studies performed with tabletop (up to J-class lasers) as well as high-power (up to kJ-class lasers) laser sources involves the exploration of hypervelocity atmospheric entry, the effects of asteroid impact, space weathering, and bulk elemental analysis. This idea was originally proposed by William J. Rae and Abe Hertzberg from the US Cornell Aeronautical Laboratory in in 1964 [21]. In the early 1970s, Hapke et al. [22] employed laser ablation in the first simulation of impact evaporation, and Pirri et al. [23] pioneered the first fundamental description of laser light interaction with targets. Subsequent studies explored the formation of ions and dust particles [24], impact physics [25], hypervelocity damage on spacecraft materials [26], impact melting and the recrystallization of asteroid surfaces [27], space weathering by micrometeorite impacts [28–34], the weathering of the lunar surface [35,36], impact ejecta redeposition [37], impact shock wave propagation in materials [38], distribution, mineralogy, and the composition of ejecta produced by the high-velocity collisions of planetary bodies [39,40], the surface structures and reflectance properties of regoliths produced by space weathering [41], the crater-like structures formed after the laser shot [42], or the transformation of carbonates in terrestrial impact craters [43].

The chemical consequences of an impact event were explored in 1989 by a group led by William J. Borucki and Christopher P. McKay [44]. Using laboratory lasers with energy up to 1 J, they estimated the yields of molecules formed by impact-induced atmosphere transformation [45]. Managadze et al. [46] explored the synthesis of more complex organic substances, Nna-Mvondo et al. [47,48] demonstrated impact-induced chemical synthesis on icy bodies, and Navarro-Gonzáles et al. [49] explored the impact-assisted synthesis of nitrates on early Mars. Our current study focuses on the morphology of meteorite ablated surfaces. However, the same kJ-TW-class high-power PALS laser [50] was employed for the first time in research focused on asteroid impact chemical consequences almost 20 years ago. Simulations by PALS demonstrated the impact synthesis of amino acids [51], canonical nucleobases [13,14,52–54], and sugars [55]. They also helped to explore the transformation of simple molecules occurring on early terrestrial planets [56], such as formamide [57], isocyanic acid [58], hydrogen cyanide [15], acetylene [59], methane [60], or carbon monoxide [56,61].

In addition to laboratory astrophysics, lasers are or will be applied in many space technologies (reviewed in [62] and references therein) for the in situ exploration and prospection of asteroids, comets, space debris mitigation, propelling space vehicles, or for the deflection of potentially dangerous near-Earth objects [63–67].

For their development, laboratory interaction experiments are crucial because the ablation process is significantly influenced by physical/chemical matrix effects. The ablation behavior of minerals common on asteroids has already been the subject of several scientific studies [68–70]. However, the behavior of the individual components does not have to reflect the behavior of the whole complex sample. These factors complicate, mainly, the scaling of parameters that are crucial for particular technological designs. Such a complex matrices are also well represented by meteorites. Therefore, interaction experiments with real meteorite specimens that directly represent interplanetary matter can be particularly valuable for evaluating the potential of these possible future high-power laser applications. In this paper, we aim to provide a systematic comparison of the meteorite surface interaction with three selected high-power lasers: (1) a Ti:Sapphire femtosecond laser, (2) the Bivoj laser of the infrastructure HiLASE, and (3) the Prague Asterix Laser System (PALS). Our study is aimed mainly at the ablation morphology with respect to the properties of meteorites, and at the physical characteristics of LIP. Our results appeal to, but are not limited to, the advantages and possible applications of comparable experiments for mimicking meteor spectra, interplanetary matter weathering, micrometeorite impact, or asteroid collisions. Moreover, we discuss the extrapolation of experimental parameters to those suitable for the application of lasers in future space technologies.

2. Materials and Methods

Interaction experiments were conducted for the first time with unique high-power laser systems: a Ti:Sapphire laser with a power of 0.02 TW, the iodine high-power PALS laser with a power of 1.7 TW, and the cryogenically cooled multislab ceramic Yb:YAG Bivoj laser with a power of 0.01 TW. Key experiments were focused on a basic comparison of the physical interaction between the iodine PALS laser, providing relatively long subnanosecond laser pulses (350 ps), and the Ti:Sapphire laser, with very short femtosecond pulses (50 fs), and meteorite samples in vacuum at a pressure of 10^{-2} – 10^{-3} mbar. In the case of these two laser sources, emission spectroscopy was employed in order to provide additionally a physical interaction between the PALS and Ti:Sapphire laser and a third high-power Bivoj laser. Two interaction experiment options were explored for the Bivoj laser—at ambient air pressure and with continuous water flow over the sample surface to simulate the enhanced stress factors occurring during the hypervelocity atmospheric entry.

In addition to a spectral characterization of the plasma and ablation spot mapping via scanning electron microscopy, optical microscopy, and 3D profilometry, we also employed a high-speed camera for recording the laser plume expansion on the PALS infrastructure.

The interaction experiments were performed on meteorite specimens summarized in Table 1.

Meteorite Specimens	Classification			
Dho 1709	Ordinary chondrite	LL4		
JaH 815	Carbonaceous chondrite	CO3		
NWA 3118	Carbonaceous chondrite	CV3		
NWA 8212	Ordinary chondrite	H-melt rock		
SaU 567	Ordinary chondrite	H3		
SaU 571	Ordinary chondrite	L3		
Dho 1763	Carbonaceous chondrite	CM2		
JaH 809	Achondrite	Ureilite		
JaH 267	Mesosiderite			
NWA 4561	Enstatite chondrite	EL-melt rock		
NWA 11273	Lunar meteorite	Feldsp. breccia		
Sikhote-Alin	Iron meteorite	IIAB		
NWA 12269	Martian meteorite	Shergottite		
Košice	Ordinary chondrite	H5		
Seymchan	Pallasite	PMG		

Table 1. List of meteorites used for the interaction experiments.

2.1. Experimental Setup of Interaction Experiments

To accomplish the subsequent analysis of laser spots, the polished sides of meteorite samples were ablated. The set parameters of all three lasers, employed together with laser-induced plasma temperatures and electron densities obtained via optical emission spectroscopy, are given in Table 2.

	PALS	Ti:Sapphire	Bivoj	
Wavelength	1315 nm	nm 810 nm		
Pulse duration	350 ps	50 fs	10 ns	
Repetition rate	1 shot per 30 min	1 kHz	10 Hz	
Energy	120–650 J	1 mJ	5 J	
Spot size	10–1 mm (diameter)	100 μm (diameter)	$3.1 imes 3.1 ext{ mm}$	
Fluence	600–83,000 J/cm ²	13 J/cm^2	50 J/cm ²	
Irradiance	$2-240 \text{ TW}/\text{cm}^2$	250 TW/cm^2	$5 \mathrm{GW/cm^2}$	
Pressure	${\sim}10^{-2}$ mbar	6×10^{-2} – 6×10^{-3} mbar	atm	
Excitation temperature	4500–6000 K	8000–12,000 K	7000 K	
Ionization temperature	8000–13,000 K	5000–12,000 K	13,000 K	
Thermodynamic temperature	13,000–37,000 K	17,000–30,000 K	>10,000 K	
Electron density	10^{15} – 10^{16} cm ⁻³	$10^{16} - 10^{17} \text{ cm}^{-3}$	$10^{16} \mathrm{cm}^{-3}$	

Table 2. Set experimental parameters and mean values of plasma temperatures and electron densities for the three lasers used in this study ¹.

¹ The uncertainty of spectroscopy-based data was estimated to be <3%.

2.1.1. High-Power Terawatt-Class Iodine Asterix Laser

The core of the Prague Asterix Laser System (PALS) is an iodine gas laser capable of delivering energy of up to 650 J in a single shot (pulse duration 350 ps, wavelength 1315 nm) [50]. The repetition rate of the PALS laser is \sim 30 min.

During the PALS experimental campaign, meteorite specimens were placed in the vacuum chamber and slightly out of the focus of the laser beam provided by a plano-convex CaF₂ lens (f/2; f = 60 cm). Depending on their specific positions, the laser spot ranged from 1 to 10 mm in diameter on the polished sample surface. The energy of the laser pulses ranged from 120 to 650 J. For further ablation plasma diagnostics, the radiation emitted by the plasma plume was collected by a collimator directly connected to a high-resolution Echelle spectrograph (ESA 4000, LLA Instruments GmbH, Berlin, Germany), and positioned in the direction of the laser spot at a 20 cm distance from the ablated specimen. A schematic drawing of the experimental instrumentation is depicted in Figure 1. During the experiments with the PALS laser, the longitudinal expansion velocity of the plasma plume was also measured using a high-speed camera.

2.1.2. Ti:Sapphire Laser

The solid-state Ti:Sapphire laser (Ti:Al₂O₃ laser), generating ultra-short pulses in the range from 650 to 1100 nm, was set to the wavelength of 810 nm with a pulse duration of 50 fs, energy of 1 mJ, and repetition rate of 1 kHz. The laser beam was focused using a coated sapphire lens (f/100, f = 1 m).

In the case of the Ti:Sapphire laser, the meteorite specimens were placed in the vacuum chamber and attached to a linear stage. The speed of the linear shift was 200 μ m/s. A high-resolution spectrograph for plasma diagnostics was also employed during these experiments. The experimental ablation setup for the Ti:Sapphire laser is similar to the one used for the PALS (Figure 1).

2.1.3. Bivoj Laser

The diode-pumped solid-state laser (DPSSL) called "Bivoj", with a laser wavelength of 1030 nm, is capable of delivering 10 ns pulses with an energy of more than 100 J at a 10 Hz repetition rate, and is classified as the most powerful laser in its class. For the interaction experiments, the energy output was set to \sim 5 J, the repetition rate to 1 Hz, and the laser beam was focused into a square spot with an edge length of 3.1 mm to reach an intensity of about 5 GW/cm² and, thus, to achieve the desired ablation.



Figure 1. Schematic drawing of the experimental instrumentation for the PALS and the Ti:Sapphire lasers (**panel A**). Experimental setup for the Bivoj laser (**panel B**).

First of all, the meteorite samples were ablated in air by 10 laser pulses, each with an energy of 5 J, accumulated in one spot. Second, the parameters were kept and the surface of the sample was exposed to a continuously flowing water stream. The plasma formed under water increased the pressure to 1–5 GPa. Considering the meteorite fragility, only one shot was focused on the meteorite specimen's surface. In this particular case, emission spectra were not recorded and the typical laser plasma temperature estimated from previous experiments was adopted for comparison with the other lasers used in this study, as summarized in Table 2.

2.1.4. Scanning Electron Microscopy

For the visualization of the ablation spots, a JEOL 6380LV electron microscope equipped with an Oxford Instruments EDS chemical analysis system was employed. To reveal both chemical and topographical information, the backscattered topography-composition imaging mode was used. All measurements were performed in a low-vacuum mode (i.e., \sim 30 Pa) with an electron beam size of about 1 µm. The acceleration voltage was 20 kV, and the beam current was kept at the range of a few nA.

2.1.5. Wide-Area 3D Measurement System

The ablation spots on the surface of meteorites were also investigated with the VR-5000 microscope profilometer (KEYENCE Int.). The information about the depth, size, and shape of a particular relief was obtained by scanning the sample surface with structured light beams, and was based on the deformation of light bands and triangulation of the shadows detected on the surface structures.

2.2. Physical Characterization of LIP and Plasma Longitudinal Expansion

In order to investigate the physical parameters of laser-induced plasma, such as electron density and excitation temperature, emission spectra were recorded during interaction experiments with the PALS and Ti:Sapphire lasers, and subsequently examined through a numerical fitting process, described in more detail in the following section. For the PALS laser, the plasma plume longitudinal expansion velocity was also investigated using a high-speed camera.

2.2.1. Plasma Temperature and Electron Density

Plasma temperature and electron density were calculated using an iterative fitting procedure designed for the analysis of high-resolved UV-ViS LIBS spectra. The emission line intensity profile functions intended for the optimization are summarized in our previous paper [16]. Both electron and heavy particle number densities, together with plasma temperature, were fitted onto the function $I_{ij} = I_{ij}(N_S, N_e, T)$ of a particular transition intensity I_{ij} governed by individual species abundances N_S . Each particular line was modeled by a pseudo-Voigt profile function with a Lorentzian line width directly proportional to the total number density of free electrons. Moreover, we assumed the Boltzmann energy distribution to hold in local thermodynamic equilibrium (LTE) plasma and exploited the particular distribution functions in their nonlinearized form. A fully synthetic spectrum was consequently depicted as a sum of individual line profile functions and fundamental plasma physics parameters (T, N_S, N_e), optimized onto a fitted experimental record.

The physical justification for such a model is dealt with in detail elsewhere; see [16,18] and references therein. The nonlinear optimization procedures were adopted to prevent possible spectral data corruption, which may arise in such warm, dense ablation plasma governed by nontrivial charge transfer phenomena.

2.2.2. Plasma Expansion

The laser-induced plasma behavior is strongly influenced by several parameters—the characteristics of the ambient medium (pressure, chemical composition), the physical and chemical properties of the target, and the laser source features (energy density, wavelength, pulse duration). For the plasma formation, a breakdown threshold must be reached by focusing the laser beam with a lens into gas or onto the surface of a solid or liquid.

The absorption of the laser pulse energy and the resulting ablation of solid samples are achieved through several interaction processes. These initial processes differ depending on the pulse duration and the material properties, as described, for example, in [71]. At the focus spot, rapid material heating and the release of electrons, ions, atoms, molecules, and dust particles from the sample surface is induced. The plasma plume created above the sample surface and containing the ablated matter expands with supersonic velocity, which results in the propagation of a shock wave compressing, heating, and further ionizing the ambient gas in all directions. After the termination of the laser pulse, the plasma gradually dies away through recombination and the diffusion of electrons and ions.

The expansion velocity of plasma is a rapidly changing parameter over time. It depends on several experimental parameters, such as the laser characteristics (energy, pulse duration), focus spot size, ambient pressure, and target material. Experimental observations ([72,73], and references therein) have shown that for ultra-short laser pulses (fs-ps), an early-stage plasma with longitudinal extent is formed ahead of the material vapor plume and above the sample surface. This plasma is characterized by a high electron number density, which originates from the ambient air breakdown assisted by electrons emitted from the target. During the duration of the laser pulse, the propagation of the plasma ionization front can reach velocities of up to 10^9 cm/s, but decreases rapidly after the pulse termination. The later-appearing hemispherical vapor plume consisting of the ablated matter expands with velocities of lower than several orders.

The presence of an ambient gas plays a significant role in the expansion process of the laser-induced plasma. Compared to plasma in vacuum, plasma in an ambient gas is

spatially contracted, thanks to the confinement effects, which results in a smaller size of the plume and a higher density and collision frequency between ablated and ambient gas species, and the expansion is slowed down [71].

2.2.3. Measurement of Laser Plume Longitudinal Expansion Velocity

A streak camera was used for the laser plasma expansion velocity measurement. The experimental set up is depicted in Figure 2. The laser beam was focused by the lens₁ (f = 0.6 m) on the target surface, thereby creating the ablation plasma. The plasma light coming out of the chamber through an optical window was collected by the lens₂ (f = 0.5 m), and projected via an aluminum mirror on the entrance slit of the streak camera with magnification M = 1. There were two filters positioned in front of the camera—a neutral ND filter for the optimization of the light intensity level, and a cutoff filter for the laser beam radiation. The position and angle of the mirror were precisely set so that the central region of the plasma plume (yellow line in Figure 2) was projected on the entrance slit (50 µm) of the streak camera.



Figure 2. Experimental setup for the measurement of the laser plume longitudinal expansion velocity.

The temporal evolution of the plasma radiation passing through the entrance slit along the *z*-axis (representing the distance from the target) is shown in Figure 3, panel A. The main direction of the plasma plume longitudinal expansion is depicted by a red vector in Figure 3, panel B, and the longitudinal expansion velocity is then calculated as the ratio of the corresponding values of Δz and Δt . After the maximum value in time is reached, the signal gradually fades because of the plasma plume expansion in the transverse direction. However, this expansion could not be measured with the selected experimental setup.



Figure 3. Spatial-temporal evolution of the plasma radiation obtained via streak camera (**panel A**), together with the depiction of the main longitudinal expansion direction (red vector, **panel B**).

3. Results and Discussion

3.1. PALS

Due to its high energy, the PALS laser, even with the sample being placed out of the beam focus, is capable of ablating a relatively large volume (mm³) of the chondritic meteorite in one single shot of about 500 J, creating, thus, a crater with a diameter of roughly 10 mm and an average depth of about 100 μ m. A sectional view of this ablation crater is shown in Figure 4, panel A, and pictures obtained via optical and electron microscopy and profilometry are depicted in Figure 5. The profilometry also indicates that the ablation craters became significantly deeper with the decreasing size of the beam focus (up to 250 μ m for 1 mm focus and about 500 J for chondritic meteorites). The iron parts of the pallasite Seymchan evinced greater resistance during ablation, and the depth of the craters is, therefore, around 70 μ m for a laser pulse with an energy of about 650 J and a diameter of 1 mm. These ablation craters also show very distinct hillock formations in the center (Figure 4, panel C). So far, the same phenomenon has not been recorded for meteorites, but it has been observed for zinc [74] or silicon [75]. The origin of this effect could be attributed the non-uniform energy deposition (see intensity profile in Figure 4, panel B), the elastic rebound of the lattice, melt flows, or the recoil pressure [75,76].

For the interaction experiments, the mean values of the ablation plasma excitation and ionization, and the thermodynamic temperature for PALS, were estimated through an examination of the emission spectra at 5100 K, 12,100 K, and 20,000 K, respectively. The electron density of the laser-induced plasma reached the order of 10^{15} – 10^{16} cm⁻³. These physical parameters are also summarized in Table 2.



Figure 4. Profile of the PALS ablation crater on the chondritic meteorite NWA 8212 created by a single shot of about 500 J. The beam focal spot was approximately 10 mm in diameter (**panel A**). The intensity profile of the PALS laser beam (**panel B**) [77] and a hillock formation in the ablation spot center on an iron part of the Seymchan pallasite (**panel C**).



Figure 5. Ablation site for the PALS laser (single shot, 500 J) on the chondritic meteorite NWA 8212, examined by optical microscopy (**panel A**), scanning electron microscopy (**panel B**), and optical profilometry (**panel C**). The diameter of the spot was about 10 mm.

The longitudinal expansion velocities of the ablation plasma within 5 ns after the laser pulse were studied using a streak camera. The measured values are very strongly affected by the set parameters of the streak camera—the streak range, the sweep rate, and the time resolution, which must be set in accordance with the expected expansion velocity. The velocities obtained during the PALS laser experiments are listed in Table 3, along with the camera settings.

The obtained results range from approximately 400 km/s to 1000 km/s. These values are in accordance with findings of other experimental observations [72,73], and represent the expansion of an early-stage plasma constituted predominantly by electrons. Given the fact that the experiments were conducted under vacuum ($\sim 10^{-2}$ mbar), the electrons originated primarily from the target material.

By comparing the values across all samples, no clear dependence of the velocities on the laser fluence was discovered. Within individual samples, similar expansion velocities for comparable fluences can be found (e.g., NWA 12269 experiments nr. 49–52). However, there are also relatively significant differences among the obtained values for individual meteorites. Nonetheless, considering the nonhomogenous structure of the meteorite samples and their non-ideal polished surfaces containing micro cracks and holes, such an outcome is to be expected, and further supports the assumption of the strong dependence of the velocity on the aforementioned experimental factors. For each ablated specimen, every shot was focused on a different place of the meteorite sample, which, given the grainy mineralogical structure of meteorites, resulted in differences in the overall chemical composition and surface characteristics of the ablated material.

Experiment	Focus (mm ²)	Energy (J)	Fluence (J/mm ²)	Plasma Expansion ³ (km/s)	Streak Range (ns)	Time Resolution (ns)	Sweep Rate (ns/pxl)
SAU_571_37	0.785	473	602	390	500	1.9	0.539
SAU_571_38	0.785	650	828	570	500	1.9	0.539
SAU_571_39	0.785	397	505	530	500	1.9	0.539
SAU_571_41	0.785	202	257	490	500	1.9	0.539
SAU_571_42	0.785	133	169	850	500	1.9	0.539
NWA_11273_43	0.785	277	353	580	500	1.9	0.539
NWA_11273_48	0.785	284	362	760	500	1.9	0.539
NWA_12269_49	0.785	412	525	490	500	1.9	0.539
NWA_12269_50	0.785	409	521	500	500	1.9	0.539
NWA_12269_51	0.785	403	513	530	500	1.9	0.539
NWA_12269_52	0.785	400	509	520	500	1.9	0.539
NWA_12269_53	0.785	390	497	930	200	0.8	0.213
NWA_12269_55	0.785	392	499	970	200	0.8	0.213
SAU_567_60	0.785	415	528	680	200	0.8	0.213
SAU_567_61	0.785	218	278	700	200	0.8	0.213
SAU_567_63	0.785	221	281	640	200	0.8	0.213
SAU_567_62	0.785	219	279	680	100	0.4	0.103
SAU_567_64	0.785	215	274	540	100	0.4	0.103
SAU_567_65	0.785	218	277	600	100	0.4	0.103

Table 3. Plasma plume longitudinal expansion velocities for four different meteorite samples, together with the laser's experimental parameters and the streak camera settings ^{1,2}.

¹ Colors represent individual meteorite samples. ² Red lines mark a change in streak camera parameters. ³ The uncertainty of the results obtained with streak camera is <10%.

3.2. Ti:Sapphire

The Ti:Sapphire femtosecond laser created deep incisions with roughly Gaussian profiles (Figure 6). The Gaussian profile is a de facto imprint of the intensity profile of the laser beam [78,79]. Pictures of the laser spots are depicted in Figure 7. The mean values of the depth and the width of the laser incisions for chondritic meteorites are about 60 μ m and 90 μ m, respectively. In the case of the Sikhote–Alin iron meteorite, the incisions are shallower (only about 20 μ m). The mean excitation temperature for Ti:Sapphire was estimated at 9700 K. The value for ionization temperature was slightly lower, i.e., 9500 K, while the mean thermodynamic temperature was calculated at 23,000 K, similar to the PALS laser. The electron density reached the order of 10^{16} – 10^{17} cm⁻³.



Figure 6. Gaussian profile of the Ti:Sapphire femtosecond laser ablation spot on the chondritic meteorite Dho 1709 (**panel A**). Intensity profile of the femtosecond laser employed (**panel B**). Sectional view of the ablation incision on the chondritic meteorite Dho 1709, obtained via profilometry (**panel C**).



Figure 7. Ablation site for the Ti:Sapphire laser (linear shift) on the chodnritic meteorite SaU 567, examined by optical microscopy (**panel A**), scanning electron microscopy (**panel B**), and optical profilometry (**panel C**).

3.3. Bivoj

During the irradiation in air (after 10 shots, each with an energy of 5 J), the beam of the Bivoj laser with a square profile was able to create shallow craters with a depth of roughly 10 μ m (Figure 8, panel A and Figure 9, panel A–C). It can be expected that the depth of the craters would become more prominent (to a certain level) with a smaller focus of the laser beam, as was observed in the case of the PALS. An examination via optical microscopy (see panel A of Figure 9) also showed relatively large, singed areas around the laser spots.

In the case of ablation under a continuous flow of water (Figure 8, panel B and Figure 9, panel D–F), the optical profilometry did not detect any altitude differences. This finding suggests that, despite the apparent melting damage observed by electron microscopy (Figure 10), no ablation occured due to the presence of the water barrier.



Figure 8. Profile of the ablation crater created in air by 10 shots of about 5 J, made by the Bivoj laser, on the chondritic meteorite Dho 1709 (**panel A**). Profile of the spot on the same chondritic meteorite Dho 1709, irradiated under a continuous flow of water, where no altitude differences were detected (**panel B**). Intensity profile of the Bivoj laser (**panel C**).



Figure 9. Cont.



Figure 9. Ablation site for the Bivoj laser (ablation of the chondritic meteorite SaU 567 in air, 10 shots accumulated in one spot) examined by optical microscopy (**panel A**, white dashed square defines the singed areas around the spot), scanning electron microscopy (**panel B**), and optical profilometry (**panel C**). Ablation site for the Bivoj laser (ablation of the chondritic meteorite SaU 567 under water, 1 shot) examined by optical microscopy (**panel D**), scanning electron microscopy (**panel E**), and optical profilometry (**panel F**). The length of the spot's edge is about 3.1 mm.



Figure 10. Ablation site for the Bivoj laser on the chondritic meteorite Dho 1709, created under a flow of water without any evidence of altitude differences (**panel A**). Detailed image of the spot rim, showing the clear boarder of the irradiated area (**panel B**). Detailed structure of the sample surface inside the laser spot, indicating the significant melting of the meteorite (**panel C**).

3.4. Comparison of Physical Interaction

The analysis of the ablation spots and their near surroundings by electron microscopy and optical profilometry proved the crucial importance of the laser parameters (e.g., fluence, pulse duration) and experimental conditions held during ablation for the interaction experiments. In the case of the femtosecond Ti:Sapphire laser, the pulse duration (50 fs) was too short for the thermal effects (e.g., melting) to take place to a larger extent. In the place of the beam focus, the solid meteorite sample was, therefore, transformed directly into gaseous plasma. Because of the absence of thermal effects, the femtosecond laser created craters with clearly defined edges and without any significant amount of molten and deposited material around.

In the vicinity of the ablation spots from lasers with a longer pulse duration, where thermal effects are more significant, a considerable amount of molten meteoritic material was observed. In the case of the high-power PALS laser, relatively large droplets of ejected molten material could be found even at greater distances from the ablation crater, which was caused by the high energy of the laser pulse. A visual comparison of the ablation site surroundings recorded via scanning electron microscopy for the femtosecond Ti:Sapphire laser and the picosecond PALS laser is shown in Figure 11.

The melting effect was most evident inside the craters created by the Bivoj laser under the flow of water (see Figure 10). The presence of water impeded the evaporation of the meteoritic material, and only melting processes occurred.



Figure 11. Clearly defined edges of the ablation spot from the Ti:Sapphire femtosecond laser on the chondritic meteorite JaH 815 (**panel A**), in comparison with a detailed picture of ejected molten Fe–Ni droplets in the vicinity of the PALS ablation crater on the chondritic meteorite NWA 8212 (**panel B**).

In the case of the laser interaction with stony meteorite samples and the large olivine grains in the Seymchan pallasite, material chipping, dusting off, and crumbling were observed due to the mechanical stress caused by a laser pulse-induced shock. In the case of the Seymchan pallasite, no ablation spots with any signs of the olivine chipping were discovered. A visual comparison of the non-ablation effects of the PALS laser on the olivine phase and the Fe–Ni matrix is depicted in Figure 12, panel A. An example of the olivine grain damaged by the PALS laser is shown in Figure 12, panel B.

In several cases, meteorite specimens with a thickness of about 1 mm and a diameter of about 4 cm did not withstand even the shock of a single PALS laser pulse, and were crushed into small pieces ranging in sizes from 1 cm to a few mm. Some meteorites were also broken because of the high pressure (1–5 GPa) acting on the samples while being irradiated under a continuous flow of water by the Bivoj laser.



Figure 12. PALS ablation crater morphology, indicating different resistances of metal and chondritic material of the Seymchan pallasite (**panel A**, dashed white circle). **Panel B** introduces an example of the olivine mineral chipped in the Seymchan pallasite by the PALS laser.

3.5. Evaporated Volume and Crater Depth

In terms of material removed per single shot, the high-power PALS laser appears to be the most efficient source. It is capable of ablating up to $\sim 1.7 \text{ mm}^3$ of chondritic material in one pulse, with a 1 mm focus and an energy of 650 J, which corresponds to a fluence of about 83,000 J/cm² and an irradiance of 240 TW/cm². For comparison, the Bivoj laser, reaching a fluence of 50 J/cm² and an irradiance of 5 GW/cm², was able to remove approximately 0.08 mm³ of chondritic material in 10 pulses. If we consider a linear increase [80,81] in the depth of the crater ablated by the Bivoj laser, approximately 200 pulses would be sufficient to reach the same ablated volume as for the PALS laser, but the total cumulative energy delivered per unit area would be eight-times lower (\sim 10,000 J/cm²). This limited ablation efficiency, even at high fluences, for lasers with longer pulse durations (ps–ns) is primarily attributed to the plasma shielding, resulting in a reduction in the laser energy able to reach the surface [80,82,83].

An investigation of the evaporated volume dependence on the PALS laser's radiation fluence, summarized in Figure 13, showed its apparent dependence on the type of the ablated material. Fe–Ni alloy areas on the Seymchan pallasite surface evinced greater resistance against ablation. Moreover, melting dominanates over ablation itself. Chondritic material poor in iron (SaU 571–L chondrites) is ablated significantly easier and, therefore, shows a much steeper trend. This can be attributed to material properties such as reflectivity, strength, surface structure, morphology, and thermal conductivity.



Figure 13. Dependence of the evaporated volume of several meteorite samples on the laser fluence for the PALS laser.

Furthermore, the bottom surface profilometry of the Ti:Sapphire ablation incisions (see Figure 14) indicates significant ablation non-uniformity. This rugged relief is due to the grainy inhomogeneous structure of meteorites and the different resistances of the individual mineralogical components comprising the meteorite sample.



Figure 14. The bottom surface profilometry of the Ti:Sapphire ablation incision for the mesosiderite JaH 267.

3.6. Laser Applications in Future Space Technologies

Experiments focusing on the interaction of lasers with real samples of interplanetary matter are also of major importance for the future space applications of laser technologies. Their technological level has witnessed a series of innovations and improvements in recent years, and, therefore, novel potential applications of laser technologies are considered. First of all, high-power lasers have been suggested for the deflection of hazardous asteroids, comets, and other near-Earth objects (NEOs), and for de-orbiting space debris [84]. One of the most significant advantages of this technology compared to other approaches [85–87] is the remote control of the NEO or debris trajectory over a long period of time without requiring complicated landing maneuvers.

The trajectory alteration is achieved via the irradiation of the asteroid or debris surface with a high-intensity light source. Within the focus area, the energy absorption causes the sublimation of the exposed solid material into a gas. The expanding ablation plume then provides a continuous low thrust, acting on the ablated object and pushing it gradually from its original trajectory. This thrust method is considered to be an analog of standard rocket propulsion [88]. The material ejected from the ablated surface could then be collected by a spacecraft flying through the ablation plume and, together with the in situ analysis of the plasma plume emission spectra, could help even further with the exploration of the composition, formation, and evolution of the bodies of the Solar System [89].

For such space technologies, it will be essential to correctly determine the laser parameters in order to find a balance between the technological requirements (e.g., power consumption, size, weight) and the conditions that need to be met for achieving efficient ablation. Our results show that even a high-power laser capable of reaching significant fluence, of the order of tens of thousands of J/cm², is capable of ablating only a few cubic millimeters of chondritic meteorite material (SaU 571, see Figure 13) in a single shot. However, the same outcome can be achieved with a much less powerful laser by accumulating a relatively small number of pulses to a single spot, as discussed in the previous section. This result, therefore, indicates that a higher fluence does not necessarily result in more efficient ablation, and on an experimental level, it further supports that high-repetition or CW (continuous-wave) lasers are rightfully the focus of most laser deflection studies (e.g., [64,65,69,90]).

It is also very crucial to understand the ablation behavior of the material that constitutes potentially dangerous interplanetary matter. Figures 13 and 14 clearly show that there are differences among individual types of meteorites, and that the ablation is nonhomogenous even across one sample. Moreover, due to the fragility of the meteorite samples, which was highlighted in Section 3.4, ablation is not the only process responsible for the material's removal. Spallation, spattering, chipping, and dusting off are of crucial importance and, therefore, they should not be neglected in laser ablation models [68]. Although the different resistances of minerals typical for interplanetary matter are known, there is a lack of studies directly focused on more complex samples, such as meteorites, that would provide information about the overall behavior of interplanetary matter during laser irradiation, and not just its individual components.

4. Conclusions

The article summarizes the results of our recent research on the interaction of laser radiation with meteorites and highlights the potential of this kind of experiment for studies focused on meteor plasma simulation, hypervelocity atmospheric entries, and future space applications of laser sources, such as deflecting NEOs and de-orbiting space debris.

A series of interaction experiments was conducted for various meteorite samples and three laser sources, varying in their parameters—a femtosecond Ti:Sapphire laser and the high-power Bivoj and PALS lasers. The investigation showed that the PALS laser was capable of creating, in one single shot of about 500 J, a crater with a diameter of approximately 10 mm and an average depth of 100 μ m in chondritic material. The Fe–Ni parts of the Seymchan pallasite proved to be very resistant to PALS laser ablation, resulting in shallower craters with depths of about 70 μ m at an energy of 650 J, but with a 10-times narrower focus spot (of 1 mm) than that used for experiments with the chondrite meteorite. Very distinct hillock formations, visually similar to the shape of the central uplift in real impact craters, were also observed in the central region of the ablation sites. The average depth and width of the deep incisions created by the femtosecond Ti:Sapphire laser in chodnritic material were 60 μ m and 90 μ m, respectively. The depth was, again, smaller for the iron meteoritic material—roughly 20 μ m. The Bivoj laser with a square beam profile (3.1 × 3.1 mm) barely ablated the surface of the samples. The depth of the craters was only about 10 μ m in the case of the irradiation in air. Moreover, the Bivoj water spots showed no altitude differences, and only distinct melting damage was observed.

The physical characteristics of the laser-induced plasma for the Ti:Sapphire laser and the PALS laser were determined using optical emission spectroscopy. The plasma electron density was comparable for both lasers and ranged from 10^{15} to 10^{17} cm⁻³. The estimated mean values of excitation and thermodynamic temperature were slightly higher in the case of the Ti:Sapphire laser—9700 K and 23,000 K, respectively. For the PALS laser, these calculated temperatures were 5100 K and 20,000 K. On the other hand, the mean ionization temperature turned out to be higher for the PALS laser (12,100 K). The value for the Ti:Sapphire laser was calculated to reach 9500 K.

For the experiments held on the PALS laser, a high-speed streak camera was employed to measure the plasma plume longitudinal expansion velocities within 5 ns after the laser pulse. The measured values ranged between approximately 400 km/s and 1000 km/s; however, no evident dependence on the laser fluence was recognized. The dependence of the evaporated volume on the laser fluence and the sample material was studied and discussed. Even high-power laser pulses with energies of several hundred joules were able to directly vaporize only a limited volume, in the range of a few cubic millimeters, of chondritic meteorite specimens, identified as the least resistant sample in our study. Laser-induced ablation also led to the significant fragmentation of this material. Future research should, therefore, address the limits of high-power laser space technologies in exploring interplanetary matter, as elucidated on the laboratory level in this study, and we should not forget how to deploy them in space without causing international security tensions [91].

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