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Simulating asteroid impacts and meteor events by high-power lasers: from the laboratory to spaceborne missions

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Meteor plasmas and impact events are complex, dynamic natural phenomena. Simulating these processes in the laboratory is, however, a challenge. The technique of laser induced dielectric breakdown was first used for this purpose almost 50 years ago. Since then, laser-based experiments have helped to simulate high energy processes in the Tunguska and Chicxulub impact events, heavy bombardment on the early Earth, prebiotic chemical evolution, space weathering of celestial bodies and meteor plasma. This review summarizes the current level of knowledge and outlines possible paths of future development.

KEYWORDS

astrochemistry, laser, ablation, origin of life, exoplanet

1 Introduction

Currently, there are two main approaches to studying meteors and impacts—laboratory experiments, and *in silico* theoretical calculations. Both require understanding of the structure, dynamics, chemistry and spectroscopy of the meteor plasma, and disintegration of meteoroids after atmospheric entry (Madiedo et al., 2014; Kuwahara and Sugita, 2015; Oppenheim and Dimant, 2015; Vojacek et al., 2015; Borovička and Berezhnoy, 2016; Rotelli et al., 2016; Berezhnoy et al., 2018; Ferus et al., 2018; Silber et al., 2018; Bizzarri et al., 2020; Ferus et al., 2020; Zahnle et al., 2020; Ferus et al., 2021; Popov et al., 2021; Kubelík et al., 2022; Zakuskin et al., 2023). Meteor science is also important for future cosmic and engineering applications, such as the mitigation of potential catastrophic impacts (Collins et al., 2005), asteroid mining (Sonter, 1997; Elvis, 2012; Mueller and Van Susante, 2012), future spaceborne observation of meteors (Jenniskens et al., 2000; Carbary et al., 2003; Ishimaru et al., 2014; Rambaux et al., 2014; Petri et al., 2019; Chen et al., 2020; Czech Ministry of Transportation, 2021), or the detection of impacts on (exo)planets by space telescopes (PLATO, Ariel, JWST (Rimmer et al., 2019).

In the first part, this review summarizes contemporary experimental approaches to studying meteor and impact plasma physics and chemistry. The second part of this paper focuses on recent developments in the application of high power lasers to spaceborne observations of meteors in the Earth's atmosphere (Ferus et al., 2019; Czech Ministry of Transportation, 2021), detection of impacts and atmospheric reprocessing on exoplanets (Ferus et al., 2019; Navarro-González et al., 2019; Navarro et al., 2020; Ferus et al., 2021), space weathering and meteoroid ablative disintegration during atmospheric entry (Kaluna et al., 2017; Křivková et al., 2022).

2 State of the art experimental approaches

A large number of computational and observational studies on meteor science has been published (Ceplecha et al., 1998; Rogers et al., 2005; Johnston et al., 2018; Silber et al., 2018) and references therein for details). On the other hand, experimental investigations are relatively sparse, particularly because of the complexity of this phenomena. There exist four main experimental approaches: (a) hypervelocity gun experiments, (b) shock tube experiments, (c) air plasma flows and (d) high power lasers.

2.1 Hypervelocity gun experiments

Hypervelocity gun target experiments are a known tool in impact physics (Libourel et al., 2019). However, the typical speed of such projectiles reaches 3–7 km s^{-1} (Hibbert et al., 2017), which is a major drawback for simulating meteor plasma during atmospheric entry, where the meteoroids reach significantly higher velocities. This projectile velocity is also less than the minimum velocity of a meteoroid, which is ~11.2 km s^{-1} given by the gravity of the Earth (Ceplecha et al., 1998). Furthermore, meteor ablation begins during atmospheric entry at altitudes typically near 120 ± 10 km (depending on the meteoroid mechanical strength and composition (Adolfsson and Gustafson, 1994; Ceplecha et al., 1998). During hypervelocity gun experiments, the plasma forms only after collision with the target. The projectiles are made of synthetic materials, such as steel, or hard natural materials, such as basalt or dunite. The composition of these materials is naturally not representative of chondritic materials. Chondritic materials, on the other hand, cannot be used as projectiles, because they cannot survive the compression of the gun (Libourel et al., 2019).

However, gun experiments remain an important tool for understanding, e.g., impact-induced formation of biologically relevant materials (Blank et al., 2001; Blank et al., 2001; Furukawa et al., 2009; Martins et al., 2013), observed, e.g., in sterilized stainless steel containers (Martins et al., 2013). Several other studies have performed impact shock synthesis of organic molecules important for the origin of life (Blank et al., 2001; Blank et al., 2001; Furukawa et al., 2009). Some of those were supported by *ab initio* molecular dynamical simulations (Goldman et al., 2010).

2.2 Shock tube experiments

Shock tube experiments are of great importance to impact plasma chemistry (Dremin, 1989; Roy et al., 2022). These experiments are useful for the assessment of the survival potential, decomposition lifetime, and *de novo* synthesis of molecules in a cometary (Rubin et al., 2019) or asteroid impact event (Singh et al., 2022). Recently, piston driven shock tube experiments were used to heat Ar and N_2 gas mixture (Jayaram et al., 2013) to significant temperatures approaching conditions of impacts (9,100–12 300 K) with reflected shock pressure of about 59–70 bar for about 2–4 ms. Shock tube experiments remain an important source of data for impact plasma simulation, especially regarding its chemical consequences.

2.3 Air plasma flows

Another approach to simulating meteor plasmas is by exposing meteorite samples to powerful heat sources such as high-enthalpy subsonic air plasma flows in a wind tunnel (Loehle et al., 2017a; Agrawal et al., 2018; Drouard et al., 2018) or (Helber et al., 2019; Loehle et al., 2022). These experiments are useful for simulating the atmospheric entry of, e.g., spacecraft materials. They have been used for simple spectral line identification from emission spectra of chondrites, achondrites, and iron meteorites (Drouard et al., 2018).

One drawback of these experiments is that the simulated meteor plasma in wind tunnels can attain temperatures up to 2,400 K (Loehle et al., 2017a). Real meteor plasmas exhibit a complicated structure with high temperature regions as hot as 4,000–100,000 K (Silber et al., 2018). Another disadvantage is that the high-enthalpy experiments involve plasma treatment of the specimen material performed in large chambers, which are not fully vacuum sealed, chemically clean and filled with different gas mixtures.

2.4 High power lasers

A fourth possible approach is to use high power lasers. The laser radiation can be well characterized, and they are versatile enough to allow experimental simulation of the chemistry and physics of supernovae explosion shocks, the interiors of gas giants, explosions and plasma jets (Villagrán-Muniz et al., 2003), accretion processes, nuclear fusion, hypervelocity atmospheric entries, impacts and meteors (Ferus et al., 2014b; Ferus et al., 2017b; Rimmer et al., 2019), and lightning discharges (Wooding, 1972; Borucki, 1985; Borucki and McKay, 1987; Borucki et al., 1988; Sobral et al., 2000; Navarro-González et al., 2001a; Sobral et al., 2002; Villagrán-Muniz et al., 2003).

Lasers have multiple advantages for studying consequential chemistry of meteor plasma events: chemical contamination from an electrode material is excluded (Borucki et al., 1988; Sobral et al., 2000), gas volumes are small, the system is generally chemically clean, isolated and well-defined (Sobral et al., 2000), and they can be applied in the meso-to microscale on mineral surfaces to allow experimentation on single phases. The properties of laser induced dielectric breakdown are characterized by pulse duration, energy density, laser wavelength, photon fluency, the chemical nature of the irradiated material or gas density, and chemical composition of the surrounding atmosphere (McKay and Borucki, 1997; Villagrán-Muniz et al., 2003; Saeidfirozeh et al., 2022; Zakuskin et al., 2023). This creates a noticeable range of parameters which are adjustable on demand and based on the required properties suitable for the simulation of the selected phenomena.

The use of lasers for simulation of impact events was theoretically suggested as early as 1964 by Rae and Hertzberg (Rae and Hertzberg, 1964) and experimentally explored by (Hapke et al., 1975), who simulated impact evaporation processes. A pioneering study on the use of small lasers in the exploration of meteorites and meteors was provided by (Pirri, 1977). In parallel, laser-based experiments were also suggested to serve as a simulation of the ball (Wooding, 1972) or lightning discharges (Borucki, 1985; Borucki and McKay, 1987; Jebens et al., 1992). Since then, lasers are used by experimentalists for both simulations of impacts and lightning ever since, as for instance in the case of laser-based experiments using very similar experimental set-ups focused on nitrogen oxide synthesis by impact plasma (Navarro-González et al., 2019; Heays et al., 2022), or lightning plasma (Navarro-González et al., 2001b).

The first connection between laser and lightning physics was discussed in (Borucki, 1985; Borucki and McKay, 1987; Jebens et al., 1992) by identifying the similarity in electron density (7×10^{17} to 9×10^{16} cm^{-3}), temperature (over 16,000 K), energy dissipation per unit spark length (10^4 J m^{-1}), and chemical freeze-out temperature. However, the hydrodynamic evolution of laser-induced dielectric breakdown (LIDB) leads to a faster cooling compared to lightning (Stark et al., 1996; Navarro-González et al., 2001a; Sobral et al., 2002). For example, the high power laser facility Prague Asterix Laser System (PALS) is able to deliver energy of up to 600 J creating a plasma fireball with the electron density 1.5×10^{17}–10^{20} cm^{-3} and the temperature decreasing from 10^5 K to 9,300 K (Šmíd et al., 2019) after the pulse. These conditions are consistent with the findings of Sobral for lightning (Sobral et al., 2000), (Sponer et al., 2020).

However, the suitability of laser-based experiments for meteor and impact plasma simulations is also supported by multiple arguments (Pirri, 1977; Ferus et al., 2017a; Rimmer et al., 2019). For example (McKay and Borucki, 1997), found that the expansion of the high temperature gas in LIDB takes between 1 and 2 μs. These values are consistent with the laser breakdown duration of 1.5 μs, as indicated by the combined experimental and theoretical simulations of laser plasma chemistry (Ferus et al., 2014a). These times are shorter than the typical shocks from an atmospheric entry (from 0.5 s for small meteoroids and up to 10 s for large impacts). A real meteor plasma is quite a complex phenomenon. Two temperature components of 4,400 K and 10,000 K have been confirmed by spectral observations (Borovička, 1994). However the meteor plasma consists in fact of envelopes expected to involve not only plasmas exhibiting relatively low temperatures ranging from 2,900 K to 5,500 K (Jenniskens et al., 2004; Jenniskens and Stenbaek-Nielsen, 2004), but also deeper bow shock regions, as hot as 95, 000 K (Silber et al., 2018). The laser plasma reaches a peak temperature up to 100, 000 K. Then, the plasma cools down quickly to temperatures below 10,000 K as the gas expands from the initial dielectric breakdown location. Spectroscopic examination of the plasma generated by high-power lasers, such as PALS, shows a decrease in temperatures from 100,000 K to 9,300 K (Šmíd et al., 2019; Křivková et al., 2021). Recent development in high repetition high power lasers (Haefner et al., 2017; Mason et al., 2017; Röcker et al., 2020) allows to study phenomena that are connected not only with plasma creation, but also repetitive processes connected with heating of the target, its ablation, etc. Such processes can be experienced by meteoroids during atmospheric entry. The lasers offer peak power from hundreds of megawatts and nanosecond pulses, through tens of gigawatts and picosecond pulses to petawatts and femtosecond pulses, all with hundreds of watts to kilowatt average power.

The major weakness of laser experiments is a mismatch in electron densities between observed meteors and the experiments (Křivková et al., 2021). Spectroscopic (Borovička and Betlem, 1997; Kasuga et al., 2005; Jenniskens, 2007; Ferus et al., 2018; Kubelík et al., 2022) and radar data attest to electron densities 10^{11}–10^{15} cm^{-3}, while laser induced plasma usually reaches electron densities $\approx 10^{16}$–10^{20} cm^{-3}, which fulfils the McWhirter equilibrium criterion (De Giacomo, 2011; Ferus et al., 2018; Ferus et al., 2019; Ferus et al., 2020; Křivková et al., 2021).

Suitability of laser-based experiments for estimation of chemical yields is also of great importance, especially for evaluation of environmental changes triggered by large impacts. Impact events deliver sufficient energy able to chemically transform an atmosphere or a surface and produce new chemicals and aerosols, or enrich the surface of a meteoroid with heavy elements providing environment supporting chemical catalysis (Ferus et al., 2021). This is especially important for early planets exposed to early and late heavy bombardment (Koeberl, 2006; Reimold and Gibson, 2006; Ferus et al., 2021).

Studies using lasers for the simulation of meteor and impact plasma include for instance the synthesis of silicon oligomers and simple hydrocarbons (Managadze et al., 2003), hydrogen cyanide and acetylene formation (Scattergood et al., 1989; McKay and Borucki, 1997), or origin of nitrates on early Mars (Navarro-González et al., 2019). During the last two decades, our team has also conducted several experiments on the PALS laser facility focusing mostly on the prebiotic synthesis and the impact transformation of planetary atmospheres. Subsequent studies successfully demonstrated the crucial role of impact plasma in the origin of canonical nucleobases and amino acids (Ferus et al., 2014a; Ferus et al., 2014b; Ferus et al., 2017b), sugars (Civis et al., 2016). Studies with this and other lasers also showed the transformation of simple molecules in early terrestrial planet environments, such as hydrogen cyanide (Ferus et al., 2017a), acetylene, methane (Civiš et al., 2017), carbon monoxide (Civiš et al., 2008) and aromatic compounds (Petera et al., 2023).

Moreover, laser plasma has been used to perform ablation experiments (Ferus et al., 2018; Ferus et al., 2019; Ferus et al., 2020; Křivková et al., 2021). For instance, in the first comprehensive work published by (Hawkes et al., 2008), it has been proposed that laboratory-based laser ablation techniques can be used to study the size of the luminous region, predict spectral features in meteors, estimate the luminous efficiency factor, and assess the role of chemically differentiated thermal ablation of meteoroids. Then (Milley et al., 2007), simulated the meteor luminosity through laser ablation of meteorites and later (Ebert et al., 2017) studied the virtually instantaneous melting of target rocks during meteorite impacts. They discovered that the entropy changes when laser-melting sandstone and iron meteorites corresponds to a minimum impact velocity which is approximately 6 km s^{-1}, inducing peak shock pressures at around 100 GPa on the target (Zakharov, 2003) also concluded that laser experiments can reproduce several phenomena such as barium release in Earth's magnetosphere, collision less deceleration of supernova remnants and related shockwave generation in the interstellar medium or near-Earth asteroid laser defense system.

Alongside the above-mentioned studies, space weathering simulations and asteroid deflection by lasers remain the most studied research topics connected with the application of lasers. Space weathering is a common process affecting the surfaces of airless bodies across our Solar System. It is caused by a combination of the solar wind, micrometeorite bombardment, and galactic radiation, and it alters the physical, chemical, and crystallographic properties of surface materials (Hapke, 2001; Bennett et al., 2013; Domingue et al., 2014; Pieters and Noble, 2016). The micrometeorite bombardment component caused by high-velocity sub-millimeter dust grains is often simulated by pulse laser irradiation. The idea behind use of laser pulse is that its short duration and small footprint rather realistically mimics the kinetic energy deposition of an impacting dust particle and its conversion to thermal energy causing localized melting and vaporization with subsequent melt sputtering, and vapor redeposition. First attempts (Moroz et al., 1996) used rather long ~ 1 μs pulse durations which was about 1,000 times longer than expected timescale of micrometeorite impact (Sasaki et al., 2001). Thus shorter, nanosecond, or later femtosecond laser pulses were later applied and reproduced well the space weathering morphology of natural microimpacts (Fulvio et al., 2021) including microstructure of amorphous rims often with reduced nanophase iron (Sasaki et al., 2001; Kurahashi et al., 2002; Sasaki et al., 2002; Sasaki et al., 2003; Worms, 2003; Brunetto et al., 2006; Lazzarin et al., 2006; Markley et al., 2013), and redeposition of impact ejecta on mineral surfaces (Loeffler et al., 2008). The laser-irradiated reflectance spectrum of minerals and meteorites match these of asteroids or the Moon (Yamada et al., 1999; Sasaki et al., 2001; Sasaki et al., 2002; Jiang et al., 2019; Matsuoka et al., 2020). While nanosecond laser pulse causes mainly heating and melting with subsonic and sonic evaporation from the surface (Gusarov and Smurov, 2005) the femtosecond laser pulse with high peak irradiance allows the propagation of a shock wave of several tens of GPa and confined melting (Boustie et al., 2008; Berthe et al., 2011) being better proxy to shock processes associated with natural impacts and prevents undesired interaction of the laser with the generated plasma plume as can happen in nanosecond laser pulse. Ablation of the material proceeds through spallation, fragmentation, homogeneous nucleation, and vaporization (Perez and Lewis, 2003), resulting in structure of the microcraters that is remarkably similar not only to natural microimpact craters, but also to that of large craters on the Moon or asteroid (25,143) Itokawa (Fazio et al., 2018).

3 Future applications of high-power lasers

Laboratory-based astrochemistry and astrophysics, directly connected to the upcoming space missions, will determine the field of high-power laser applications in the future. We are currently in an era of unprecedented opportunities for proposing a flight of a spacecrafts exploring nearly any object in the Solar System. At the same time, space telescopes such as CoRoT, Kepler/K2 and TES along with ground-based observatories confirmed over 5,300 exoplanets. The known sample of confirmed exoplanets has shown an astonishing diversity in properties and orbital parameters. In the upcoming decade the space mission PLATO is expected to observe a sample of about a million bright stars for planetary transits. The first detection of exo-atmospheres is dated back to 2002 (Charbonneau et al., 2002). We possess now more details about exo-atmospheres of gas planets (Redfield et al., 2008; Wyttenbach et al., 2015; Kabáth et al., 2019; Kabáth et al., 2019). Characterization of exo-atmospheres is still a rapidly developing discipline. The telescopes such as JWST or Ariel and beyond (Tinetti et al., 2018) will fill this gap mainly by observation of atmospheric spectral imprints (Guilluy et al., 2022). In spite of the wealth of information to be returned by these spacecrafts, ground based experimental support will be needed in order to create a spectral and chemical knowledge for supporting the characterization of exoplanets as well as to learn more about geochemistry of interplanetary space, more details about primordial highly dynamic nebular accretion processes, planetary evolution, origin of life and its evolution, and finally the potential of mineral resources for metals and rare elements.

In the following section on future applications, we specifically discuss application potential of laser-based laboratory experiments with regard to upcoming space telescopes (Ferus et al., 2017b), orbiters (Borucki et al., 1996; Ferus et al., 2019), landing probes and rovers (Lasue et al., 2012; Wiens et al., 2012; Wiens et al., 2012; Clegg et al., 2017), for the analysis of propulsion systems (Hudson and Lemmer, 2017), plasma created by natural (Cipriano et al., 2018) or artificial (Lee et al., 2017) kinetic impactors as planned for Moon or asteroid missions (Cheng et al., 2018), or remote sensing from a small flyby or orbiting satellites (Arnold et al., 2019). The specific future perspectives of laser-based regarding all these specific fields is provided below. We also discuss future uses of laser experiments in the analysis of meteor plasmas.

3.1 Spaceborne observation of meteors

Spaceborne spectral survey of meteors or impact events evades many limitations of ground-based observations and therefore, represents very promising future application field for simulating meteors and impacts using laser-based experiments. Observations provided by ground based spectroscopy are limited by the absorption of atmospheric molecules (Kaltenegger et al., 2020), aerosols, molecular scattering (Yan et al., 2015), or by weather conditions (Jenniskens, 2007; Milley et al., 2007; Vojacek et al., 2015; Ferus et al., 2018; Ferus et al., 2019). This situation can be easily demonstrated on a broad band spectral data compilation of the Leonid meteors (Carbary et al., 2003; Ferus et al., 2018; Kubelík et al., 2022), depicted in Figure 1, panel A, with indication of particular regions accessible by the naked eye, ground based video camera, spaceborne optical-UV emission hyperspectral camera on a CubeSat, and space telescopes. Laser-based experiments have been so far used for mapping the spectral features in visible region, as depicted in Figure 1, panel B. Future applications will support to identify and describe meteor spectral features in other regions. The ground-based observations are not limited only by capability to record spectra mostly in ViS range, but also by restricted number of convenient observation places, which must not be located only in accessible places on land, but also in politically stable and cooperating countries with institutions open to international collaboration. Observation of meteors by a spacecraft avoids most of these problems.

So far, extraterrestrial impacts or meteor events have been observed on the Moon (NASA et al., 2022), Mars (Selsis et al., 2005; Christou et al., 2012; Brown et al., 2014), and Jupiter (Levy, 1998). Considering the outer space, occasional asteroids have been explored, such as 'Oumuamua, see (Bannister et al., 2019) and references therein, or sporadic meteors suspected to be having an extrasolar origin (Afanasiev et al., 2007). It has been proposed that spectral surveys of interstellar meteors offer a unique opportunity to probe extrasolar systems. The first and only analyzed spaceborne meteor UV spectrum has been captured by the MSX military satellite (Carbary et al., 2003). The only running instrument is currently on ISS in the WORF facility. That project aims at the detection of major elements (Fe, Ca, Mg, and Na) in the spectral range between 304–700 nm (Kramer, 1994). On the other hand, several satellite mission concepts have been already proposed: A proposal by Nuth et al. (Nuth et al., 2008) suggesting the observation of meteors in the UV range, between 125–300 nm, has been followed by Rambaux et al. (Rambaux et al., 2014), proposing a 3U-Nanosatellite equipped with a UV spectrometer and ViS camera for meteors and space debris that re-enter the terrestrial atmosphere (Chen et al., 2020). Similar CubeSats, such as S-CUBE, have been developed in parallel by Ishimaru et al. (Ishimaru et al., 2014), while recently Petri et al. (Petri et al., 2019) introduced the FACIS mission for stereoscopic meteor observation. A combined orbital spectroscopic-stereoscopic survey of meteors has been recently proposed in the framework of the Czech CubeSat mission SLAVIA (Czech Ministry of Transportation, 2021).

Notably, spectral records of plasma sources emitting radiation in the atmosphere do not include only natural meteors, but also fireball or airglow surrounding artificial objects entering the atmosphere (Loehle et al., 2021), atmospheric electricity (Pérez-Invernón et al., 2022), rocket launches (Qian et al., 2005) or explosions of manmade objects (Zhang et al., 2018) and interplanetary bodies (Svettsov, 1998; Ferus et al., 2019). The application potential of spaceborne spectroscopy of plasma provided by a hyperspectral camera and supported by laboratory laser-based experiments includes:

(a) Detection, identification, classification and triangulation from at least two satellites which simultaneously observe an individual event (Chen et al., 2020; Petri, 2020). This is important for warning systems, hazard mitigation regarding, e.g., distinguishing atmospheric entries of natural objects from spacecraft or space debris (Coradini et al., 1994; Leiser et al., 2022), space debris surveillance and statistics (Loehle et al., 2017b; Leiser et al., 2022), explosions, rocket launchers (Qian et al., 2005; Langford et al., 2007), and to establish a statistical determination of the mass flux and the distribution of interplanetary material reaching out to the Earth (Rambaux et al., 2021).

(b) Measurement and analysis for scientific or engineering studies, which include physical characterization of a plasma surrounding a spacecraft or meteoroids (Martin and Boyd, 2012), exploration of plasma dynamics, or the evaporation and ablation of surfaces during the atmospheric entry (Silber et al., 2018).

3.2 Detection of impacts on exoplanets

Laser experiments will be crucial for the future identification of markers of impacts, such as in the case of the Shoemaker-Levy comet impact on Jupiter (Zahnle et al., 1995), where S_2, CS_2, OCS, NH_3, HCN, H_2O, and CO have been observed (Zahnle et al., 1995). Recent studies are also associated the tentative detection of PH_3 in the atmosphere of Venus (Bains et al., 2021; Schulze-Makuch, 2021; Truong and Lunine, 2021; Bains et al., 2022) to a stochastic atmospheric corrosion of a single giant impactor or to a random elevation in the impact flux (Omran et al., 2021). A possible future milestone in astronomy is to detect very large meteors and impacts in exoplanetary atmospheres. This will be provided by upcoming spectroscopic studies of exoplanets (Schneider, 2018). However, it has been estimated that an impact of the size of the Chicxulub event, which occurred 65 Mya ago, viewed from 10 light-years away would exhibit an absolute magnitude of 20.9 and be barely detectable even assuming 100% emissivity (Paine, 2006). We can expect that regular meteors will be too faint to be observed with the ARIEL or JWST telescopes. On the other hand, we may assume that in other exoplanet systems, large impact events, explosions or collisions can be occasionally observed such as an analogue of large impact event recently created different twins in the Kepler-107 exoplanet system (Bonomo et al., 2019). For young planetary systems, mathematical models (De Niem et al.,

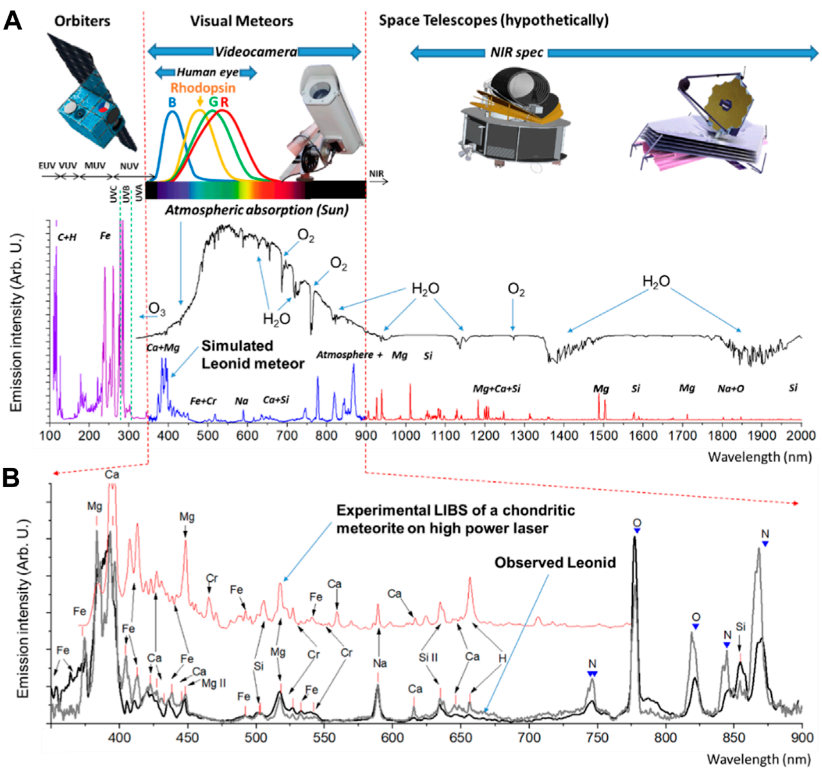

FIGURE 1
Panel **(A)** shows a computer simulation of Leonid meteor emission spectra in the ranges from UV to NIR (violet, blue and red) with indicated regions typically observable by naked eye or ground based video camera. However, these spectral regions are limited by atmospheric transmission embedded in the figure (black). Orbiters allow to overcome this limitation to both UV + visible (likely accessible by a CubeSat, such as the future SLAVIA mission (Czech Ministry of Transportation, 2021), and NIR (operated by space telescopes) regions (Tinetti et al., 2018). Panel **(B)** shows two example spectra of Leonid meteors (grey and black) compared to LIBS spectra of a chondritic meteorite recorded using high power TW-kJ-class laser PALS (red). The data are compiled from the paper (Ferus et al., 2019).

2012) suggest that oligarchic growth, late accretion and early stages of their evolution (i.e., first a few hundred million years) are dominated by giant impacts (Koeberl et al., 2005; Reimold and Gibson, 2006; Quintana et al., 2016). This is supported by looking at the Moon's cratering history (Geiss and Rossi, 2013; Morbidelli et al., 2018), and at the evidence for late veneer on Earth (Brasser et al., 2016). The history of impact mass delivery and size distribution is not entirely resolved, and it is unknown whether other planetary systems would have had the same impact history, because different planet formation models make diverging predictions about the typical early impact frequency (Morbidelli et al., 2018). Such predictions are wedded to planet formation history and planetary system architectures (Genda et al., 2017; Sinclair et al., 2020). Impact history is also relevant to the question of habitability, because the extraplanetary delivery of chemical compounds is important to the evolution of environments that can support life (Todd and Öberg, 2020), the origin of life's building blocks in the impact plasmas, (Ferus et al., 2014b; Ferus et al., 2017b), as well as in the post-impact (Ferus et al., 2021), and origin of feedstock molecules for prebiotic synthesis (Martin et al., 2007) as the result of impact-induced atmospheric and surface chemistry (Quintana et al., 2016).

Experiments with laser treatment of gas mixtures, and solid or liquid targets simulating the chemical effect of an impact plasma on the atmosphere, the surface, or an impactor already indicate the synthesis of species to be connected to the plasma chemistry, such as in the case of C_2H_2 and HCN (Ferus et al., 2017a; Rimmer et al., 2019) (shown in Figure 2), as well as of N_2O (Heays et al., 2022), HNCO and $HCONH_2$. This might be crucial to recognizing impact processes on young planets (Ferus et al., 2021). It should be noted that the results of laser-based experiments in our laboratory lead us to the prediction that the recognition of impacts directly on early Earth-like planets will be a very complicated task due to very complex interplay among the geochemical, the physical and the geological processes, because other possible sources must be ruled out. It is likely that the evidence of elevation in impact frequency might have been provided by the detection of the otherwise unexplainable disequilibria in the mixing ratios of molecular species that are associated with the impact chemistry, or their time variation is associated with their formation and decomposition.

3.3 Simulation of meteoroid disintegration

There is also one relatively new potential application for high-power lasers, especially regarding suitability of high power lasers to create laboratory plasmas characterized by high temperature

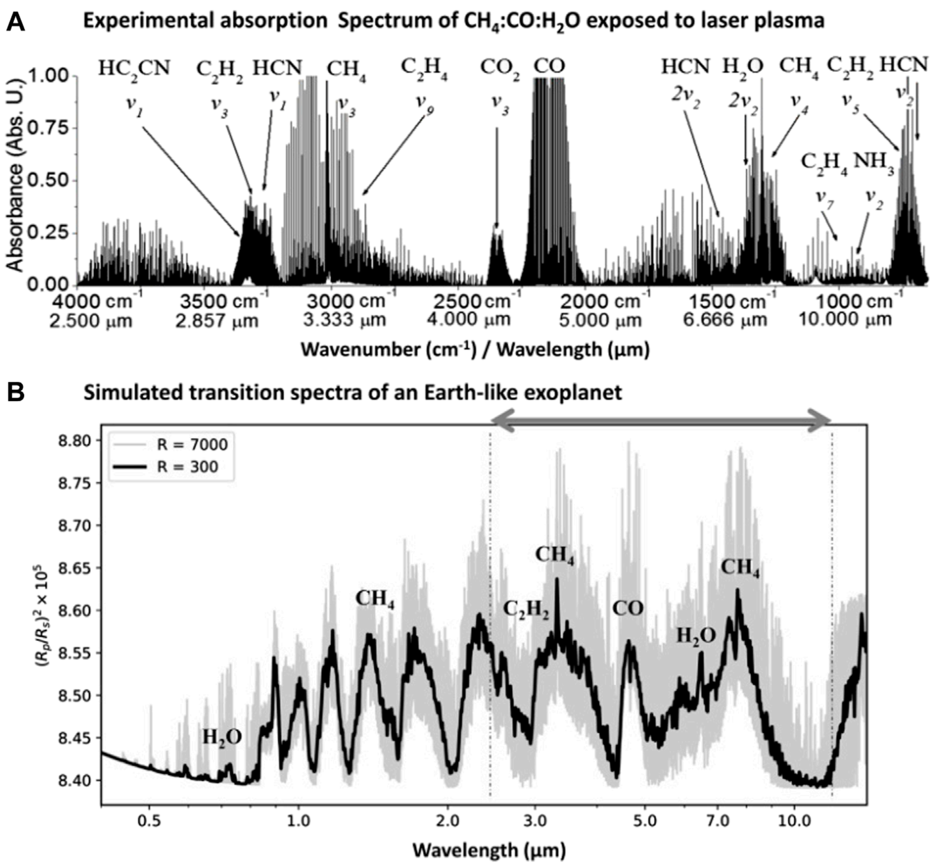

FIGURE 2
Laser-based experiments have been crucial for recent identification of C_2H_2/HCN disequilibrium as indirect evidence of heavy bombardment on early exoplanets with reducing atmosphere (Rimmer et al., 2019). Without a combination of such experiments with sophisticated atmospheric and spectral models, such a prediction is not possible. Chemistry of rather extreme events is not well described and can be understood in close collaboration with *in silico* investigation of reaction networks (Ferus et al., 2017b). The figure is newly compiled from the author´s original dataset published in (Rimmer et al., 2019). The grey arrow in Panel **(B)** shows the wavelength range corresponding to panel **(A)**.

shock expansion of material released from the solid meteorite target (Křivková et al., 2022). The atmospheric entry of a meteoroid does not only result into its sputtering, its fragmentation or ablation (Rogers et al., 2005; Popova, 2006; Vondrak et al., 2008; Silber et al., 2018), or even to meteorite or asteroid impact, if the body is big enough or cohesive (Collins et al., 2005), but also to the random explosion event that has been observed many times for smaller bodies and which are well-known from the case of the Tunguska event in 1908 (Napier and Asher, 2009). Explosive events during atmospheric entry have been recently investigated and explained by (Tabetah and Melosh, 2017; Tabetah and Melosh, 2018); when a meteoroid hurtles through the Earth's atmosphere, high-pressure air in the front of the object infiltrates cracks and pores in the rock, generating a great deal of internal pressure. This pressure is sufficient to cause the object to effectively explode from its core, even when the meteoroid material is strong enough to resist the intense external atmospheric pressures. There's an extreme pressure gradient between the high-pressure air in the front of the descending body and the low-pressure region behind it. If the air can move through the fissures and cracks in the body of the meteorite, it can easily get further inside it and cause fragmentation into pieces. The eventual break-up of a 17–20 m asteroid can release the energy that is equivalent to approximately 500 kt of TNT. As mentioned above, this can be hardly simulated in the laboratory, especially when we are also interested in its chemical evolution. On the other hand, advanced supercomputing techniques can help understanding the fundamental mechanisms at a molecular level by pushing further the limits of laboratory exploration.

4 Conclusion

Laser-based experiments are an excellent tool for generating laboratory plasma for the simulation of specific phenomena which are inaccessible by standard experimental approaches. The laser radiation is a powerful, precisely characterized, and versatile energy source. Such experiments can provide a realistic simulation of extreme states of matter in supernovae explosion shocks, the interiors of gas giants, explosions and plasma jets (Villagrán-Muniz et al., 2003), astrophysical accretion processes, nuclear fusion, hypervelocity atmospheric entries, space weathering, impacts and meteors (Ferus et al., 2014b; Ferus et al., 2017b; Rimmer et al., 2019) and partly also the simulation of lightning (Wooding, 1972; Borucki, 1985; Borucki and McKay, 1987; Borucki et al., 1988; Sobral et al., 2000; Sobral et al., 2002; Navarro-González et al., 2001a; Villagrán-Muniz et al., 2003). Meteor science has recently broadened to include spaceborne observation of meteor events. Laser simulations play irreplaceable role in ground based support of future space missions (Czech Ministry of Transportation, 2021) by providing knowledge for evaluation of the meteor spectral data for detection, identification, classification and triangulation of meteors (Coradini et al., 1994; Martin and Boyd, 2012; Chen et al., 2020; Petri, 2020; Leiser et al., 2022), as well as space debris surveillance and statistics (Loehle et al., 2017b; Leiser et al., 2022), the detection of explosions, rocket launches (Qian et al., 2005; Langford et al., 2007), or for impacting mass flux and distribution statistics (Silber et al., 2018; Rambaux et al., 2021). Laser experiments also perfectly fit into the landscape of contemporary exoplanetary science. Exoplanets serve as natural laboratories, but for the rigorous interpretation of spectral observations, systematic experimental and theoretical data are needed to support models of planetary environments and spectral retrieval. Only a combination of experiments with models and observations will provide deep insights into exoplanet chemistry and will serve for an extrapolation of chemical and physical parameters broadening our knowledge about evolution and future of our Solar System (Rimmer et al., 2019; Ferus et al., 2021).

Author contributions

MF came up with the idea and prepared initial material for the paper. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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