Selected laser-induced plasma spectroscopy: From medical to astrophysical applications

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Abstract. This work discusses laboratory experiments using atomic and molecular spectroscopy for diagnosis of laser-induced phenomena of interest in the field of medicine, and in astronomy for the understanding of recorded spectra from selected stars. Photo-acoustic spectroscopy utilizes femtosecond laser-pulse trains for diagnostic and therapeutic applications. Optical emission spectroscopy explores nominal nanosecond laser-induced, nano-particle plasma and its detection sensitivity. The study of laboratory plasma generated in selected gas-mixtures reveals insights for the interpretation of white dwarf spectra.

1. Introduction

The availability of pulsed laser radiation with widths that are several dozen quintillionth (10⁻¹⁸, atto), quadrillionth (10⁻¹⁵, femto) to a few billionth (10⁻⁹, nano) of a second allows one to interrogate physics phenomena in the field of medicine, e.g., femtosecond radiation for diagnostic and therapeutic purposes. Medical objectives comprise delivery of specific amounts of radiation with tailored laser pulses and specialized detection. Medical applications include use of nano-particles, photo-acoustic imaging [1] with excitation from several dozen femtosecond radiation [2, 3], study ultrashort biochemical phenomena [4], and novel applications of sub-femtosecond or attosecond laser pulses [5].

Alternatively, high peak-irradiance of a few Giga- to Tera- Watt per square-centimeter obtained from a few nanosecond pulse-width radiation can generate conditions for plasma experiments that aid in the understanding of white dwarf stars [6] and their evolution. The laser-induced plasma from a single, focused high peak-power is analyzed for the determination of plasma parameters and species distributions. Essential analytical aspects are recognition of the various “fingerprints” of plasma radiation, viz. atomic and molecular signatures in the near ultra-violet to near infrared regions [7].

Laboratory measurements of laser-induced plasma is accomplished with temporally- and spatially-resolved laser spectroscopy. Application of a few nano-second duration pulses generate plasma that is investigated utilizing various analysis techniques. Atomic and diatomic molecular spectra reveal species that can be selected for the characterization of expansion following optical breakdown in gases and near solid surfaces. Recorded data are analyzed [8, 9] using techniques such as computed tomography [10] to resolve phenomena along line-of-sight emission spectroscopy measurements. Time-resolved studies of expansion dynamics provide values of electron density after initiation of
the plasma. Atomic line shapes in gas breakdown indicate similarities with profiles measured in laser ablation: A diagnostic gas flow may reveal so-called percolation effects due to the formation of nano-clusters, thereby causing a variation of density across the plasma [11, 12]. Nano-materials with sizes up to 100-nm indicate significant changes in the properties of matter [13], thereby offering improvements in potential applications of laser induced plasma. It has been verified that the signal-to-noise ratio of emitted plasma radiation increases upon the addition of a thin layer of nano-material to the surface of analytes, and these effects are quantified with nano-particle laser-induced breakdown spectroscopy (NELIBS) [14]. The physical mechanisms that explain the enhancements can be considerable complex and may require discussions of localized surface plasmon resonances [14]. Nano-particle enhanced laser-induced plasma spectroscopy (NELIPS) focuses on the interaction of high peak power radiation with nano-scale material [15, 16, 17]. The nano-materials reveal physical properties that are different from bulk-material [18], and consequently, there are opportunities to further enhance laser-induced breakdown spectroscopy that is typically applied in an ambient laboratory environment leading to presence of ionized air species [19].

In addition, diatomic molecular cyanide (CN) spectra are measured after initiation of optical breakdown plasma in gaseous mixtures. The CN molecule is evident in many forms in nature and is produced in many industrial processes, such as chemical and drug production, electroplating, iron and steel production, pesticide, and plastic manufacturing. Although cyanides are present within many living organisms and created through man-made processes, they are highly toxic and can be lethal. Study of the CN radical [20, 21, 22] is of interest to the medical community, for example, optical spectroscopy monitoring of CN for the purpose of reversing physiologic effects due to cyanide [23].

2. Experimental arrangements

2.1. Femtosecond experiments

The photo-acoustic experiments utilize 7.3 nano-Joule, 70 femtosecond, near infrared laser pulses that are delivered from the Spectra Physics Tsunami Ti:Sapphire laser device [2]. Goals of photo-acoustic spectroscopy include imaging associated with computed tomography. Soft tissue diagnosis and therapy relies on the application of individual and of the order of 1 million pulses, respectively. For this medical application of femtosecond radiation, the temperature rise can be calculated from the heat transfer equation that includes a source term to represent the near delta-distributed absorption [2]. The difference between infected and healthy soft tissue [24] can be investigated based on the respective photo-acoustic spectral signatures [2, 3].

2.2. Nanosecond experiments

The experiments include measurement of spectra from nano- and bulk- materials and determination of the sensitivity of nanosecond laser-induced plasma spectroscopy (LIBS). A standard LIBS experimental arrangement is used [15, 16, 17, 18], and it includes the Quantel Brilliant B Nd:YAG laser device. Maximum energies per pulse are 480 mJ, 180 mJ, and 95 mJ at the wavelengths of 1064 nm, 532 nm, and 355 nm, respectively. The emitted light from the nano- and bulk- surface plasma is collected with a 25 µm optical fiber and coupled to the 25 µm entrance opening of an SE 200 Echelle spectrograph. The spectrograph is equipped with an Andor iStar DH734-18F intensified charge-coupled device (ICCD) that shows a pixel size of 13 µm 13 µm. The optical resolution and resolving power amount to 0.05 nm/pixel and 2500, respectively. The data acquisition is controlled with KestrelSpec ® 9.6 software. Systematic studies have been communicated [15, 16, 17, 18] that explore the effects for different parameter sets, e.g., energy per pulse, fluence, time delay, type of nano-material, or nano-material diameter. Wavelength calibration
is accomplished with a low pressure Hg lamp, and the recorded data are subjected to absolute
calibration procedures discussed in measurements of ionized nitrogen spectral lines [19].

The experiments of gaseous hydrogen optical breakdown in the laboratory [20, 21, 22, 25, 26]
utilize attenuated Q-switched, 150-mJ, 6-ns pulsed Nd:YAG radiation from a Quantel model
Q-smart 850, a 0.64-m Yobin Yvon Czerny-Turner type spectrometer and an ICCD, Andor
technology model iStar DH334T-25U-03, to capture data. In this work, the laser-induced plasma
is generated by focusing 1064-nm radiation parallel to the spectrometer entrance slit.

3. Results

3.1. Photo-acoustic spectroscopy

For photo-acoustic imaging [1], it is important to utilize radiation pulse-widths that are shorter than
thermal relaxation times [2, 3]. Heat dissipation is described by the thermal conductivity, but the
temperature rise during the application of a single laser pulse leads to a pressure variation that can
be recorded by distributed sensors.

The average measured temperature rise of, for example, dentin caused by ≃ 3.2 million
laser pulses amounts to 5 Kelvin [2]. Such an increase in temperature would be sufficient to induce
necrosis of cancerous cells. The average increase in temperature is estimated to be 1.6 μK.
Computation of the temperature increase due to a single laser pulse leads to a value of 2 μK,
consistent with the measured average increase of each pulses in a 3.2 million pulse train.
Advantages of femtosecond radiation include negligible thermal and mechanical exposure.
Specialized beam delivery is desirable in form of a Bessel beam that is non-diffractive in an ideal
realization. For photo-acoustic spectroscopy, elongated focal volume laser-excitation is
advantageous for scanning the target material, the volumetric target distribution is constructed using
acoustic detection and computed tomography. Practical realization of Bessel beams include lens-
axicon optical configurations. Figure 1 illustrates calculated converging and diverging lens-axicon
maps that are scaled separately from minimum to maximum [27]. The extended peak irradiance
along the optical axis resembles a Bessel beam. For a singlet focal length, f_{lens}, an axicon apex angle, α_{axicon}, and refractive index, n_{axicon}, the focal ring occurs at r_{ring} = (n_{axicon} - 1) α_{axicon} f_{lens}. For a 1-degree converging lens-axicon doublet, computed and measured focal volume distributions agree [3].

![Figure 1. Irradiance for (a) converging, α_{axicon} = -0.5°, (b) diverging, α_{axicon} = +0.5°, lens-axicons.](image-url)
The color bars indicate an irradiance range of one order of magnitude, but for different minimum to maximum scaling for (a) and (b). $f_{\text{ens}} = 100$ mm, $n_{\text{axicon}} = 1.52$, 1064-nm radiation, 5-mm laser beam diameter, and 10-mm lens aperture. In the limit of $\alpha_{\text{axicon}} \to 0$, the focal ring and focal lines collapse to the usual lens focal spot at $f_{\text{ens}} = 100$ mm.

3.2. Atomic emission spectroscopy

Experimental laboratory studies of laser-induced optical breakdown in hydrogen gas reveal atomic emission spectra that serve as a guide for analysis of astrophysical absorption spectra from white dwarf stars. Ultra-high pure hydrogen gas at a pressure of $0.76 \times 10^5$ Pa is introduced to a chamber. At a rate of 10 Hz, focused radiation generated 100 consecutive laser-induced plasma events [25, 26]. Figures 2 and 3 display individual spectra of hydrogen alpha, H$\beta$, and hydrogen beta, H$\alpha$ lines that are recorded along the spectrometer slit. The spatially resolved spectra along the slit indicate electron density variations for a particular time delay. Moreover, the recorded images are relevant for application of Abel- and Radon- inverse algorithms [28] for the determination of the electron distribution along the line of sight.

**Figure 2.** H$\beta$ spectra for a time delay of 200 ns. (a) H$\beta$ map, logarithmic relative-intensity scaling and banded pseudo-color display, (b) scaled average, electron density $N_e^{100} = 2.7 \times 10^{17}$ cm$^{-3}$.

**Figure 3.** H$\alpha$ spectra for a time delay of 200 ns. (a) H$\alpha$ map, logarithmic relative-intensity scaling and banded pseudo-color display, (b) scaled average, electron density $N_e^{100} = 2.9 \times 10^{17}$ cm$^{-3}$. 
The pseudo-colored images, figures. 2 (a) and 3 (a), indicate the full-width-half-maxima for both Hβ and Hα, asymmetric peak separation and red dip-shift of Hβ, and red shifts of Hα, and a slight variation along the slit height. The averages, obtained by summing the spectra along the slit, yield significantly Stark-broadened line profiles.

An overview of the hydrogen Balmer series electron-density diagnostic can be obtained using the Inglis-Teller estimate [29]. Figure 4 illustrates the log-log graphical display of electron density versus principal quantum number of the last term observed in the series.

![Figure 4](image-url)

**Figure 4.** Limits for hydrogen Balmer series lines in electron-density diagnostics.

Clearly, Hβ is well-suited for electron-density measurements from 1 to $5 \times 10^{17} \text{cm}^{-3}$. For electron densities above $60 \times 10^{17} \text{cm}^{-3}$, Hβ at 486.14 nm will be merged with Hγ at 434.05 nm. In practical terms for Hβ in laser plasma, the peak-separation and the redshift [25, 26] may be used to infer electron density up to $\approx 60 \times 10^{17} \text{cm}^{-3}$, or the Inglis-Teller limit (see figure. 4). In turn, Hα may show self-absorption effects for electron densities larger than $\approx 20 \times 10^{17} \text{cm}^{-3}$.

The electron density is inferred by using standard Stark tables [30, 31], recent advances in analytical theory of Stark broadening [32], or by utilizing the recently communicated empirical formulae for Hβ and Hα widths [33],

$$\Delta w_{H\beta}[^\text{nm}] = 4.5 \left( \frac{N_e [\text{cm}^{-3}]}{10^{17}} \right)^{0.71 \pm 0.03}, \quad (1)$$

$$\Delta w_{H\alpha}[^\text{nm}] = 1.3 \left( \frac{N_e [\text{cm}^{-3}]}{10^{17}} \right)^{0.64 \pm 0.03}. \quad (2)$$

The expansion dynamics, governed by the strength of the shock wave, may cause higher electron density near the shock wave than in the center. This can be investigated utilizing computed
tomography or Abel and Radon inverse transform techniques. With emission spectroscopy, one usually measures an average along the line-of-sight, and frequently one also averages over the extent of the laser plasma. With a variation of electron density across the plasma, a temperature variation is expected due to isentropic expansion [34]. The average line-of-sight temperature can be evaluated using the integrated line to 10-nm continuum ratios [30]. Figure 5 illustrates the ratios and the estimated error ranges that are primarily due to difficulties in the determination of the free-electron Bremsstrahlung background [25, 26]. The data points are illustrated with estimated error bars along the dotted and dashed calculated ratios [30] for Hβ and Hα, respectively. For example, the Hβ and Hα data points at 75 ns time delay indicate an average temperature of $\simeq 70$ kK, and a temperature range from $\simeq 60$ kK to 80 kK.

![Figure 5. Computed Hα and Hβ line to 10-nm continuum ratio](image)

For the experiment, 1064-nm, 150-mJ, 6-ns laser pulses are used for the generation of micro-plasma in hydrogen gas at a pressure of $0.76 \times 10^5$ Pa (11 psi). The date points from high to low temperature indicate experimental results for 25-ns, 50-ns, 75-ns, 150-ns, and 275-ns time delays from optical breakdown.

The average temperature can be inferred as well by evaluating the integrated line profiles, $I_\beta$ and $I_\alpha$, for Hβ and Hα, respectively. The Boltzmann plot method requires the ratio of the integrated line profiles (that need to be corrected due to the finite spectral window in the experiments, i.e., $1/0.85$ and $1/0.91$ factors for Hβ and Hα, respectively) for the determination of the line-of-sight-average temperature,

$$T_e(\text{eV}) = \frac{1}{\ln \left[ 0.46 / \left( I_\alpha / I_\beta \right) \right]}^{1.5}.$$  (3)

### 3.3. Molecular emission spectroscopy

Diatomic molecular emission spectra from the cyanide (CN) molecule are recorded subsequent to optical breakdown in a laboratory cell filled with a 1:1 mixture of research grade carbon dioxide (CO₂) and ultra-high pure nitrogen (N₂) at atmospheric pressure. In a rigorous study [21, 22], various time delay steps are selected for determination of the first CN recombination signals, and for the assessment of the CN spatial distribution in the expanding laser-induced plasma.
Figure 6 displays radial positions versus wavelength of the Abel-inverted CN spectra for a time delay, \( \tau \), of \( \tau = 1.2 \) \( \mu \)s and \( \tau = 3.7 \) \( \mu \)s. The separate pseudo-color ranges from blue to red in figure 6 (a) and (b) corresponds to linear scaling from minimum to maximum.

![Figure 6](image.png)

**Figure 6.** Abel-inverted CN spectra for determination of the spatial distribution along the line-of-sight. (a) Time delay \( \tau = 1200 \) ns, indicating increased CN signals in a spherical shell (b) \( \tau = 3700 \) ns, indicating smooth CN distributions.

For the CN diagnostic, measurement of spatial and concentration variations may be required. The application of integral transforms to shock-wave dominated expansions allows for the determination of the spatial distribution from measured line-of-sight spectral data. For the earlier of the two time-delays, one recognizes in figure 6 (a) stronger signals near 1 mm than at center. In turn, for the longer time delay of 3700 ns in Figure 6 (b), there appears to be a rather smooth variation with radius. Figure 7 illustrates spectra at selected radial positions of the Abel-inverted images in Fig. 6. The rotational structure is not really resolved in the Abel-inverted spectra, but the 193.09-nm carbon line [35, 36] in second order (near 386.18 nm) is recognizable in figures 6 (a) and 7 (a). The spectral fitting utilizes the nonlinear fitting routines and a spectral database for the CN-violet system[37].

![Figure 7](image.png)

**Figure 7.** Individual spectra from Figure 6, and determined diatomic CN excitation temperature. (a) Time delay \( \tau = 1200 \) ns, \( T \approx 8600 \) K (b) \( \tau = 3700 \) ns, \( T \approx 7900 \) K. The spectral peak (*) originates from neutral carbon, measured in 2nd order. The data fitting considers CN contributions only.
3.3.1. Nanomaterial plasma spectroscopy

The application of nano-particles in laser spectroscopy has been instrumental in enhancing detection of weak signals, e.g., utilization of collective electron oscillation (plasmon) for the improvement of signal to background and signal to noise, thereby allowing one to measure with increased sensitivity. In the application-weighted research that utilizes laser-induced breakdown spectroscopy (LIBS), addition of nano-particles causes more efficient and faster seed electron production than for conventional LIBS [38].

In nano-material plasma spectroscopy, investigations focus on the physical processes for bulk- vs. nano- material. However, data for bulk material may be readily available, but data for nano- material need to be inferred from the bulk data. In this work, zinc oxide (ZnO) and silver (Ag) nano-material is investigated to evaluate signal enhancements, but for example, ZnO shows a variety of biomedical applications [39] in part due to its low toxicity and biodegradability. Objectives in laser-induced plasma spectroscopy include determination of parameters such as electron density and temperature for the description of laser-induced plasma. Measurement of electron density can be accomplished, for example, by evaluating line widths and shifts, but in general by determining atomic spectral line shapes. Subsequently, different realizations of thermodynamic equilibrium can be investigated: (i) complete thermodynamic equilibrium for electron densities larger than \( \approx 10^{19}/\text{cc} \), (ii) local thermodynamic equilibrium for electron density in the range of \( 10^{16}/\text{cc} \) to \( \approx 10^{19}/\text{cc} \), and (iii) partial local thermodynamic equilibrium in the range of \( 10^{12}/\text{cc} \) to \( 10^{16}/\text{cc} \).

In optical spectroscopy, measurements rely on existence of optically thin lines or the availability of bench-mark data to assess the level of self-absorption in plasma emission. Figure 8 illustrates laser-ablation and a typical plasma distribution when averaged over a few microseconds after plasma generation with a 5 nanosecond high peak power of typically 1 MW/cm\(^2\) to 1 GW/cm\(^2\) laser pulse. The figure also shows a measured self-reversed silver line originating from silver nano-material of size \( 90 \pm 10 \) nm [17].

![Figure 8](image_url)

**Figure 8.** (a) Self-absorption and self-reversal in laser ablation plasma. (b) Spectral radiance of the self-absorbed, asymmetric, silver Ag I, 327.9-nm line. The center wavelength, \( \lambda_0 \), indicates the unperturbed atomic line position. The spectral width, \( \Delta \lambda_0 \), is a measure of electron density. Self-absorption may diminish the signal, leading to a larger width, \( \Delta \lambda_{\text{exp}} \), in turn, biasing the electron density diagnostic to higher values. Self-reversal occurs at \( \lambda_0 \) as indicated. For the 327.9-nm line, asymmetric self-absorption occurs, with apparent blue- and red- shifted peaks.
The threshold fluence diminishes as the nano-particle size is reduced, in turn causing enhancement factors for nano-material versus bulk. Of the order of 10 × signal enhancements occur as the laser fluence is reduced from 20 to 2 J/cm² [15].

For ZnO nanomaterial, the threshold fluence reduces close-to-linearly and by a factor of five from 0.2 J/cm² to 0.04 J/cm² as the ZnO nano-material is reduced from 100 nm to 20 nm [16]. Wavelength dependency studies reveal that 355-nm radiation may lead to 100 × larger signals from 30-nm ZnO nano-material than from bulk-material. Figure 9 illustrates typical enhancement factors for 95-nm silver nano-particles [16, 17].

Previous nano-material work [15, 16, 16, 17] invites the following conclusions: (i) There is a pronounced stronger emission from the nano-based target plasma than that from the corresponding bulk; (ii) The plasma is initiated at lower fluence for nano-material than for bulk-material; (iii) There is a wavelength dependence of the plasma ignition threshold. The threshold fluence for bulk-material, \( \phi_{\text{th, bulk}} \), and nano-material, \( \phi_{\text{th, nano}} \), is modeled using thermal and laser terms,

\[
\phi_{\text{th, bulk}} = \left( \rho L_V + 8\pi^2 m_e \varepsilon_0 c^2 / e^2 \frac{\varepsilon_i}{\lambda_{\text{laser}}^2} \right) \ell_T
\]

\[
\phi_{\text{th, nano}} = \left( \rho^{\text{nano}} L_V^{\text{nano}} + 8\pi^2 m_e \varepsilon_0 c^2 / e^2 \frac{\varepsilon_i}{\lambda_{\text{laser}}^2} \right) D_{\text{nano}}.
\]

The constants \( m_e \), \( \varepsilon_0 \), \( c \), and \( e \) denote mass of the electron, vacuum permittivity, speed of light, and elementary charge. The thermal conduction length, \( \ell_T \), for bulk-material is replaced by the nano-material diameter, \( D_{\text{nano}} \), and similarly, the density, \( \rho \) and latent heat, \( L_V \), are replaced by the nano-material counterparts, \( \rho^{\text{nano}} \) and \( L_V^{\text{nano}} \). The laser term is proportional to the first ionization potential, \( \varepsilon_i \), and inversely proportional to the square of the wavelength, \( \lambda_{\text{laser}}^2 \).

For nanosecond laser excitation, multiple photon absorption leads to ionization and plasma initiation. The Keldysh parameter, \( \gamma \), distinguishes between multi- or multiple-photon ionization versus tunnel-ionization. For \( \gamma < 1 \), tunnel-ionization occurs. The Keldysh parameter is evaluated for application to laser-ablation [15], and it depends the ionization energy, \( E_i \), and the laser wavelength, \( \lambda \), pulsewidth, \( \tau_{\text{laser}} \), and fluence, \( \phi \),

\[
\gamma = 1.036 \times 10^5 \frac{1}{\ell(\text{nm})} \sqrt{\frac{E_i(\text{eV})\tau_{\text{laser}}(\text{ns})}{\phi(\text{J/cm}^2)}}.
\]
For example, using the ionization energy for zinc, $E_i = 9.4$ eV, in ZnO 30-nm nanomaterial studies, one finds for $\tau_{\text{laser}} = 5$ ns, and a fluence of 20 J/cm$^2$ at the fundamental 1064-nm wavelength for Q-switched Nd:YAG devices, the Keldysh parameter equals $\gamma = 150$ [15]. For shorter laser pulses of the order of 10 fs, and for a fluence of 1 J/cm$^2$, the Keldysh parameter is of the order of 1. For sub-fs or atto-second laser pulses, and otherwise similar laser parameters, the Keldysh parameter will be less than one, indicating tunnel ionization as the Coulomb barrier will appear static at the atto-second time-scale.

3.4. Astrophysical spectroscopy

Analysis of astrophysical white dwarf star absorption spectra utilizes both benchmark hydrogen emission experiments and theory that explains the recorded data. In astrophysics, the gravitational redshift [40], $v_g$, serves as a measure for the mass of a white dwarf. The gravitational redshift is usually expressed using WD mass, $M$, and radius, $R$, in solar units,

$$v_g [\text{km/s}] = 0.636 \frac{M}{R},$$

or in terms of wavelength shift, $\Delta \lambda$,

$$v_g = c \frac{\Delta \lambda}{\lambda}.$$  

Time-resolved Balmer series $H_\beta$ and $H_\alpha$ lines however indicate red shifts of the central $H_\beta$ dip, $\Delta \lambda_{H_\beta}^\text{ds}$, and the $H_\alpha$ line, $\Delta \lambda_{H_\alpha}$,

$$\Delta \lambda_{H_\beta}^\text{ds} [\text{nm}] = 0.14 \left( \frac{N_e [\text{cm}^{-3}]}{10^{17}} \right)^{0.67 \pm 0.03},$$

$$\Delta \lambda_{H_\alpha} [\text{nm}] = 0.055 \left( \frac{N_e [\text{cm}^{-3}]}{10^{17}} \right)^{0.97 \pm 0.03}. $$
The WD companion (Sirius B) to the brightest star (Sirius A) visible from earth, shows a gravitational redshift of $v_g = 75$ km/s, using $M = 0.984$ and $R = 0.0084$ in solar units, or $M/R \approx 120$. One would expect gravitational shifts of $0.16$ nm at $H\alpha$ and $0.12$ nm at $H\beta$ that is smaller than the $H\beta$ central dip shifts for $N_e = 10^{17}$ cm$^{-3}$.

Several white dwarf spectra are readily accessible in the Montreal database [6], or from the Keck Observatory Archive (KOA) database. Figure 10 displays the HG 7-85 white dwarf from the Hyades cluster [26, 41, 42].

![Figure 10](image)

**Figure 10.** Hyades cluster white dwarf HG 7-85, recorded with a resolving-power 40,000 Echelle-spectrometer. (a) $H\beta$ expanded region, (b) $H\beta$ center portion. Individual orders of the recorded Echelle spectrum are combined and fitted using only two Lorentzians (see text).

The spectrum in Figure 10 is recorded using an Echelle spectrometer with a resolving power of 40,000 [42, 43]. The fitting of the WD absorption spectrum utilizes variable amplitudes and backgrounds of two Lorentzian profiles, $L_i(\lambda)$, $i = 1, 2$, as function of wavelength, $\lambda$, with center-wavelengths, $\lambda_i$, and full-width half-maxima (FWHM), $\Gamma_i$, $L_i(\lambda) = \frac{1}{\pi} \frac{\Gamma_i/2}{(\lambda-\lambda_i)^2 + (\Gamma_i/2)^2}, i = 1, 2$. (11)

The width of the broad Lorentzian line shape implies an electron density of $3.1 \times 10^{17}$ cm$^{-3}$ (see Eq. (1)). The narrow Lorentzian would imply an electron density that is over two orders of magnitude smaller than that of the broad profile. The gravitational redshift of the HG 7-85 equals 44 km/s which would be consistent with the 0.08-nm center-shift of the fitted broad Lorentzian. While modeling of WD-atmospheres continues to be of interest in astrophysics [44], the results displayed in Figure 10 may indicate absorption from a dense and at least two orders of magnitude less dense WD atmosphere. However, inspection of the narrow absorption in figure 10 (b) shows asymmetry and additional narrow features that indicate the need for further modeling [42] of WD atmospheres. As one systematically adds the time-resolved data for $H\beta$, one obtains a profile that nearly resembles a single Lorentzian [20]. Appropriate fitting of the resulting, near Lorentzian profile would require at least two Lorentzians, i.e.,
the sum of a narrower and broader Lorentzian for modeling of emission spectra [20]. The standard two-peak appearance of H\(\beta\) is hardly discernible due to addition of line profiles [44]. The requirement of fitting with two-Lorentzians is also encountered in modeling line-of-sight, laser-ablation spectra [11, 12]. However, experimental realizations of white dwarf absorption profiles [45, 46], studies of asymmetric line shapes [47, 48, 49], and non-equilibrium thermodynamics are of current research interest [50, 51]

4. Conclusions
Laser spectroscopy continues to offer analytical diagnosis of various physics phenomena. The applications that are elaborated in this work include medical diagnosis and therapy of soft and hard tissues using femtosecond radiation. High peak-power from a nanosecond laser device usually generates plasma that is composed of atomic and molecular signatures. Better sensitivity can be accomplished when utilizing nano-particles or nano-material in typical laser-induced breakdown spectroscopy. The analysis of measured spectra yields the parameters of laser-induced plasma. Moreover, astrophysical absorption spectra from white dwarf stars can be interpreted with results from laboratory experiments.

Extensions of especially applications to the field of medicine include identification of process indicators, such as cyanide, that may be diagnosed with nanosecond radiation. However, it may require femto- to atto- second pulses to diagnose phenomena such as light interaction in the rods and cones of the eye, or in the study of electron dynamics.

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