Laboratory hydrogen laser-plasma and white-dwarf stars line shapes

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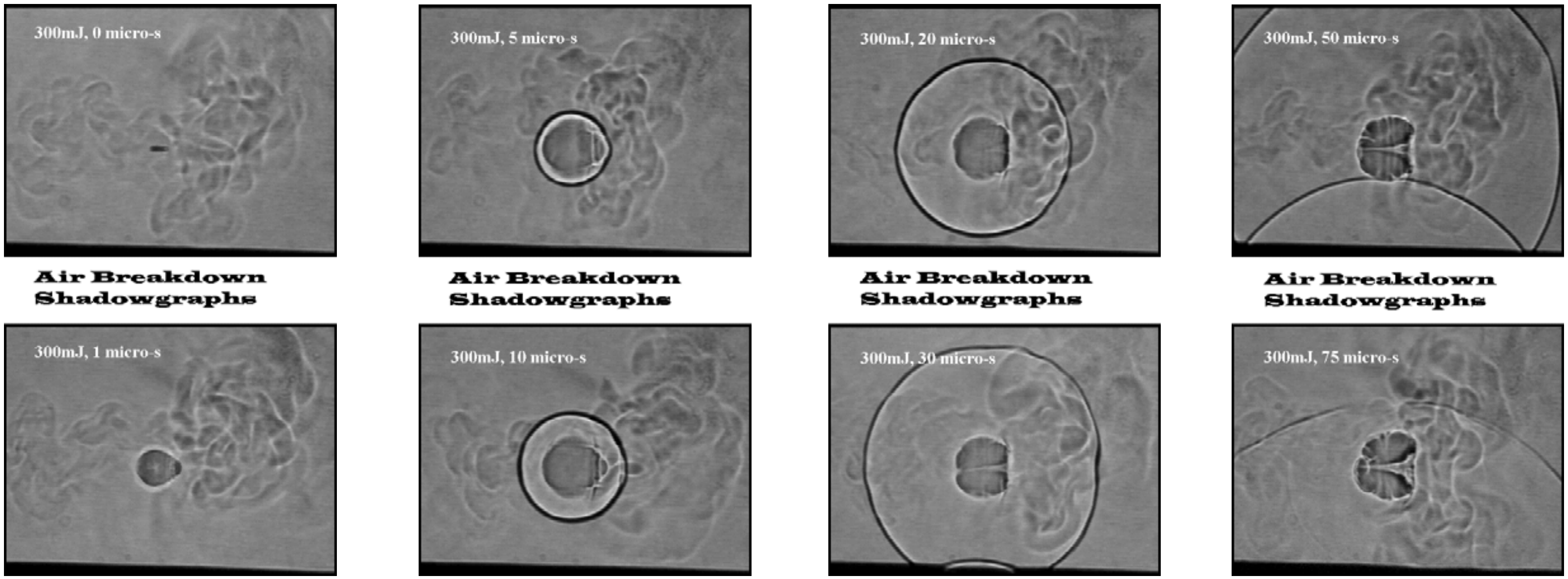
Center for Laser Applications

Overview

- Laser plasma fundaments
- Stellar astrophysics spectra
- Optical breakdown in laboratory air
- Atomic hydrogen spectra: H_α and H_β
- Abel inverted atomic spectra
- Molecular CN spectra
- Abel inverted molecular spectra
- Atomic and molecular superposition spectra
- Nano-particle laser-induced plasma
- Conclusions

Laser plasma shadowgraphs



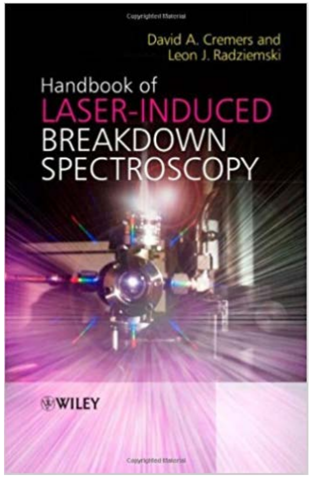
Temperature and density distribution at center, or at the “plasma kernel”; self-absorption? Energy/pulse: 300 mJ, 4 ns pulses; image size: 36 x48 mm; Double images showing fluid phenomena;

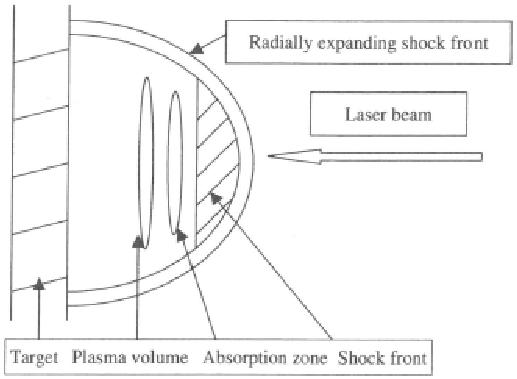
- Laser-induced expansion;
- Atomic spectra, molecular spectra;
- Equilibrium consideration in plasma kernel;
- Chemical imaging using molecular spectra;

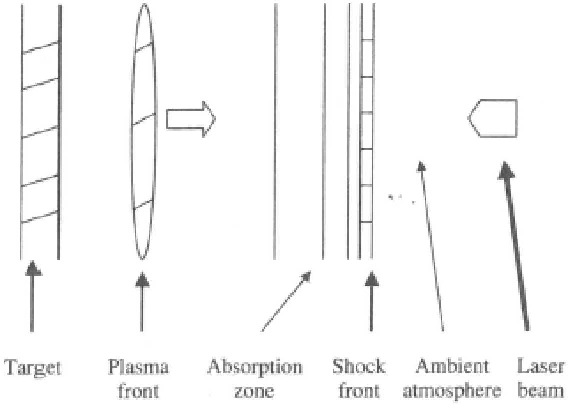
Visualization of Laser-Induced-Plasma, C. Parigger et al. OSA 1996;
http://view.utsi.edu/cparigge/osa96/index.html

Laser plasma fundamentals

Post ns breakdown phenomena: plasma front, absorption front, shock front







- Laser-supported combustion (LCD) for low, above threshold irradiance: energy deposited behind shock + plasma radiation moves absorption front towards laser;
- Laser-supported detonation (LSD) for higher irradiances, the shock front heats gas leading to absorption;
- Laser-supported radiation (LSR) for highest irradiances, the radiation from the plasma heats atmosphere, absorption zone is coupled to plasma front;

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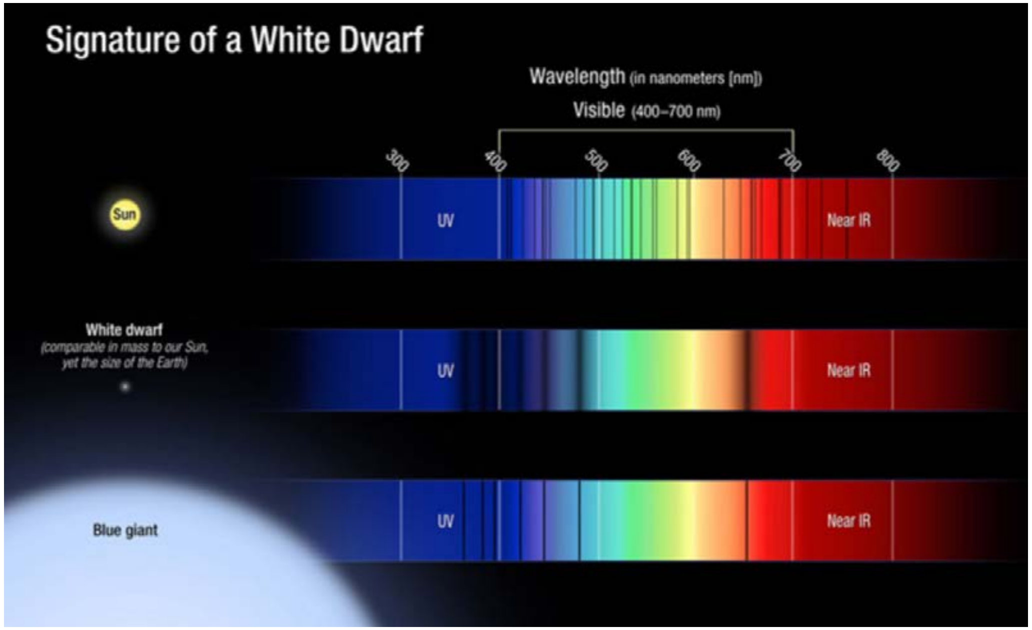
Stellar astrophysical spectra



Is it possible to measure laboratory micro-plasma, measurements, and analysis to apply in astrophysical studies?

Will time-resolved spectroscopy make it possible to measure accurate atomic and molecular spectra at high temperatures?

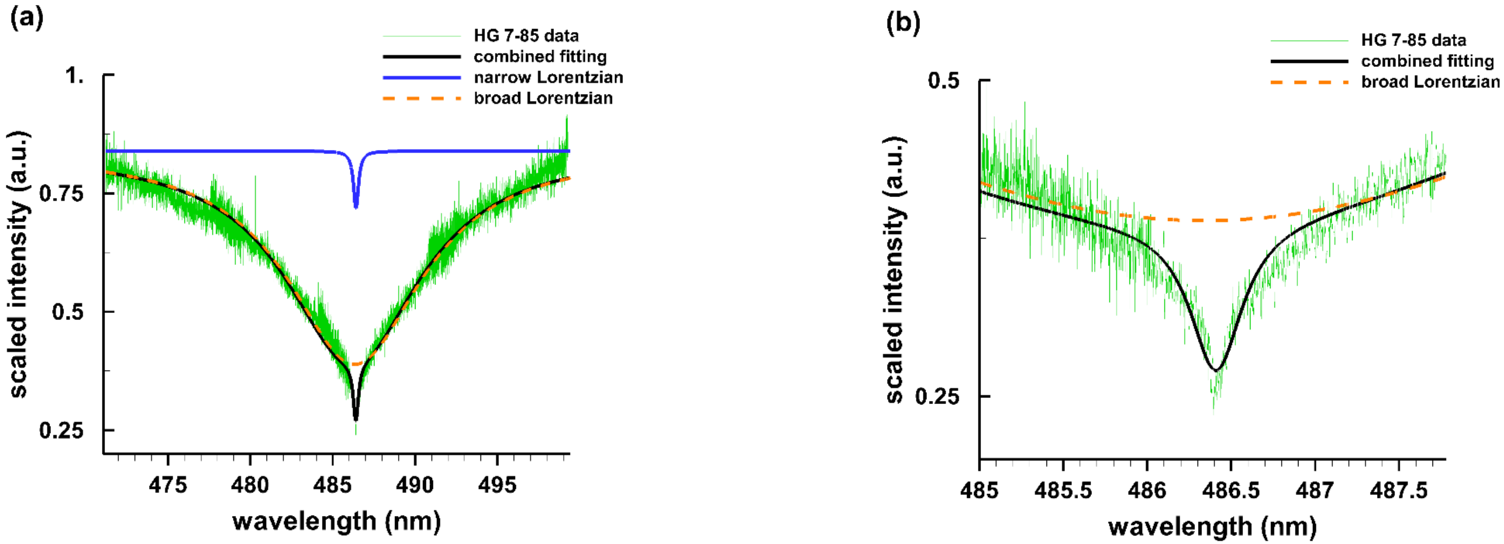
Atomic processes in plasma, Laser-induced breakdown spectroscopy?

Sirius B: 26 kK, Procyon B: 7.9 kK

Measurement of emission spectra?

http://dev.montrealwhitedwarfdatabase.org/tables-and-charts.html

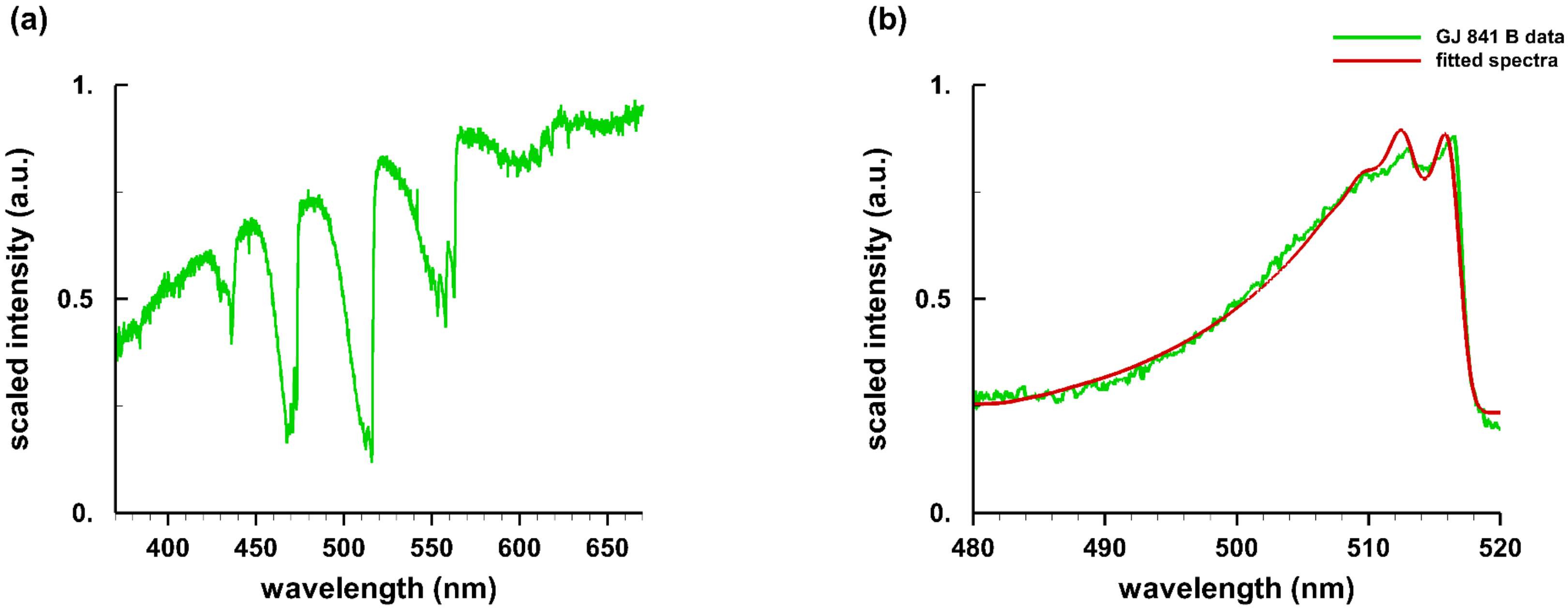
Hyades cluster WD HG 7-85



Hyades cluster white dwarf HG 7-85, recorded with a resolving-power 40,000 Echelle-spectrometer. (a) H expanded region, (b) H center portion.

Center λλ: 486.22 nm, redshift: 0.08 nm; Grav. redshift: 44.3 km/s (0.072 nm)

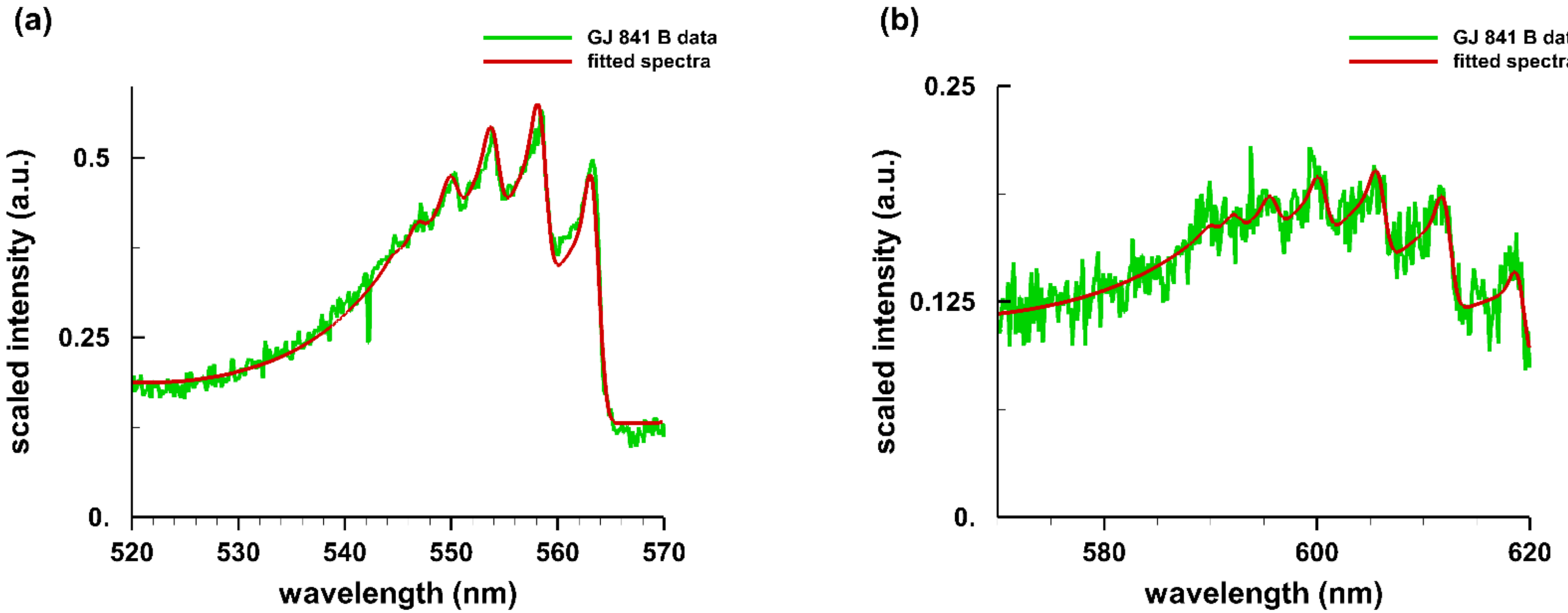
C_2 Swan spectra modeling of WD spectra



White dwarf GJ 841 B. (a) C_2 Swan absorption spectrum. (b) $\Delta v = 0$, $T = 7.1$ kK, $\delta\lambda = 1.8$ nm.

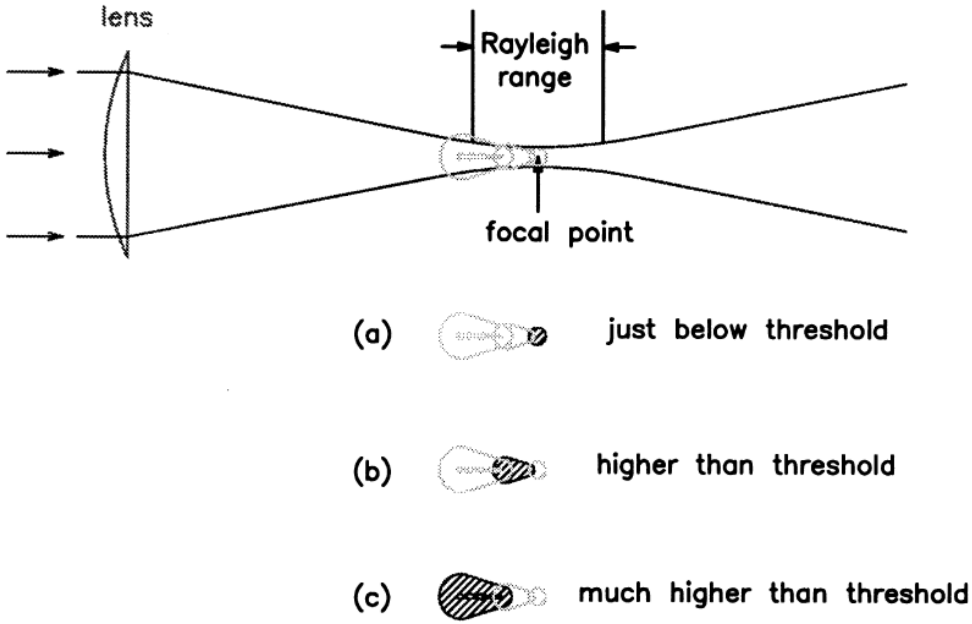
C.G. Parigger et al., Atoms 6 (2018) 36

C_2 Swan spectra, contd.



(a) Δv = -1, T = 4.5 kK, δλ = 1:5 nm, (b) Δv = -2: T = 4.2 kK, δλ= 1.5 nm.

Laser plasma focal volume



Chen, Lewis, Parigger, JQSRT 67, 91-103 (2000)

$$X_R = \frac{\pi \omega_0^2}{\lambda}$$

$$T \propto I_L^{1/(\beta + 4)},$$

$$V \propto I_L^{4/(\beta + 4)},$$

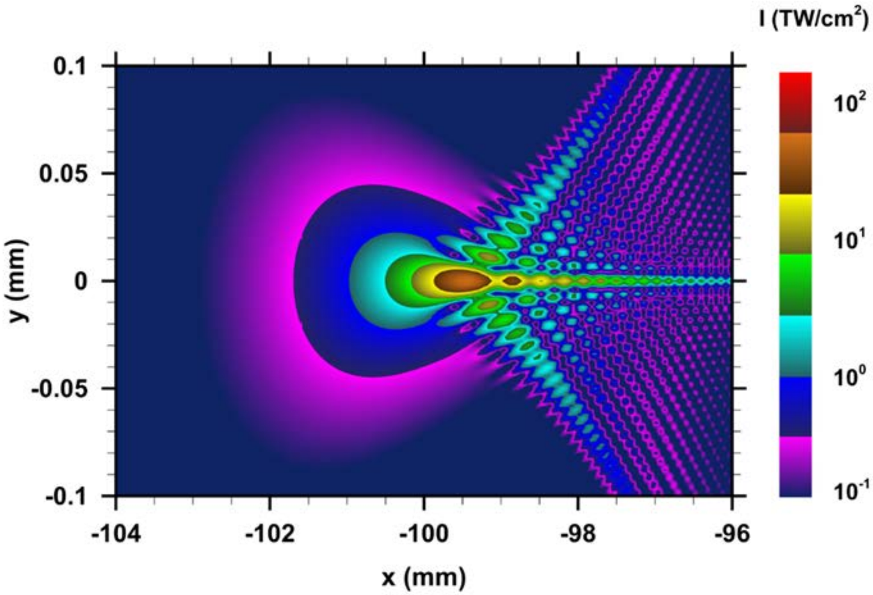
$\beta = 1.6$

Table 1
Irradiance dependant plasma temperature and propagation speed

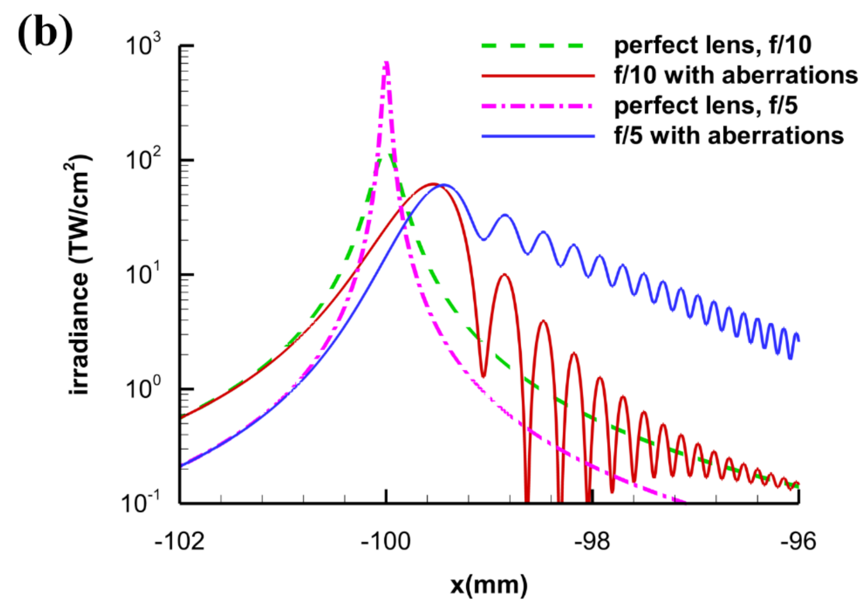
I_L (GW/cm^2)	T (K)	V (km/s)
1.0	104,500	10.0
2.5	123,000	19.0
10.0	158,000	51.0
15.0	169,500	69.0
20.0	178,400	85.0
30.0	191,800	114.0

Focal volume distributions

Results for 800 mJ, 6 ns Gaussian beam (Quantel Q-smart 850); $2w_0 = \left(\frac{4\lambda}{\pi}\right)\left(\frac{F}{D}\right)$



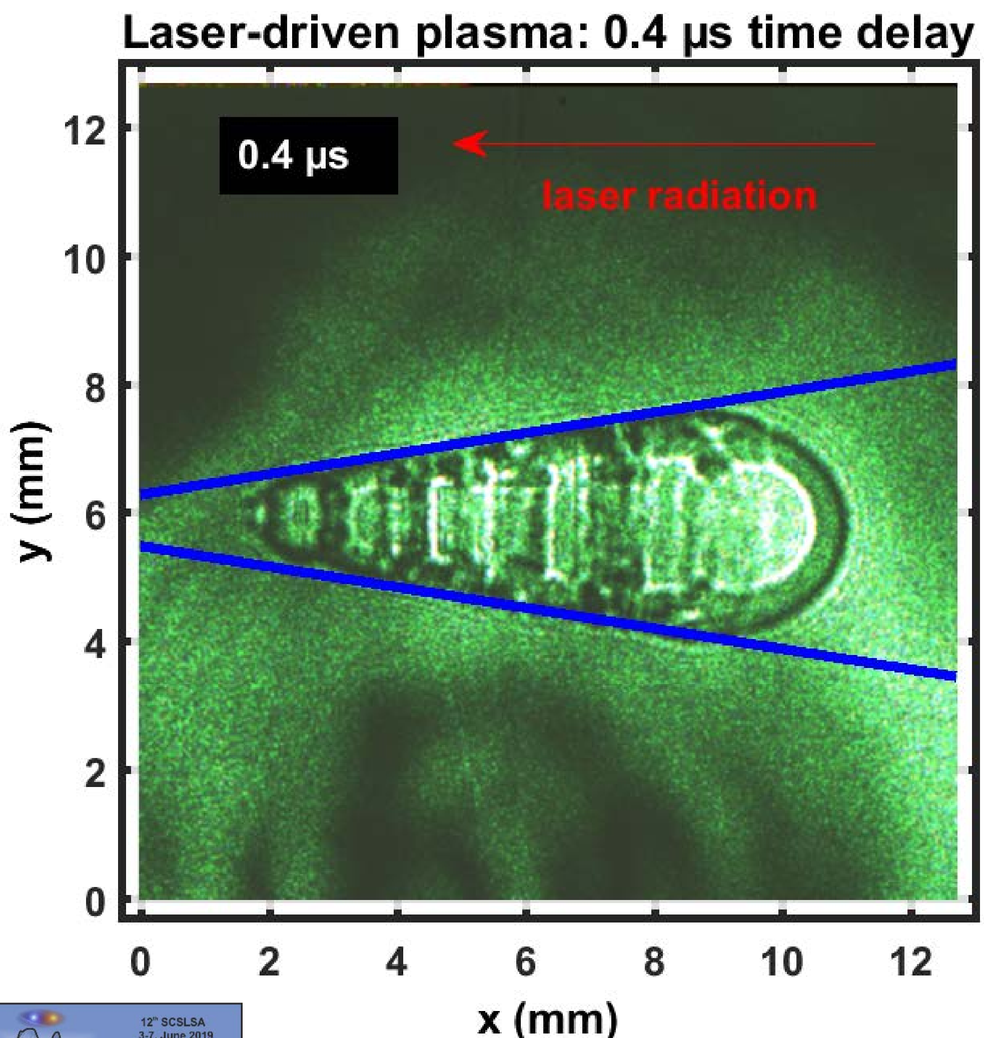
f/5 focusing, Thorlab LA4545



On-axis irradiance distributions

Parigger, Helstern, Gautam, IRAMP 8(1), 2017

Optical breakdown in air

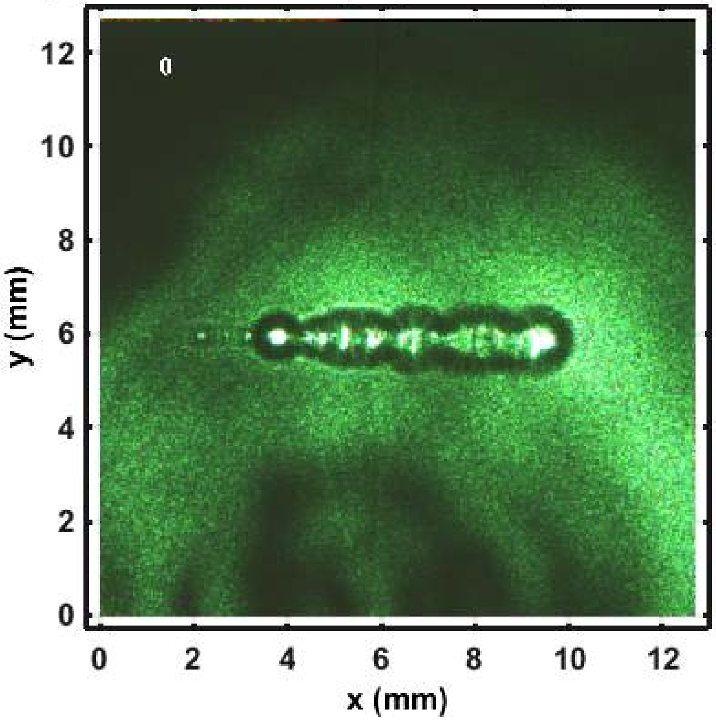


The shock wave maximum expands vertically in excess of Mach 6 (~ 2 km/s), and horizontally in excess of Mach 40 (~ 14 km/s) for a time delay of 0.4 μs. Higher speeds are measured for shorter time delays from generation of the laser plasma. The blue lines indicate a cone and the significant, measured horizontal speed.

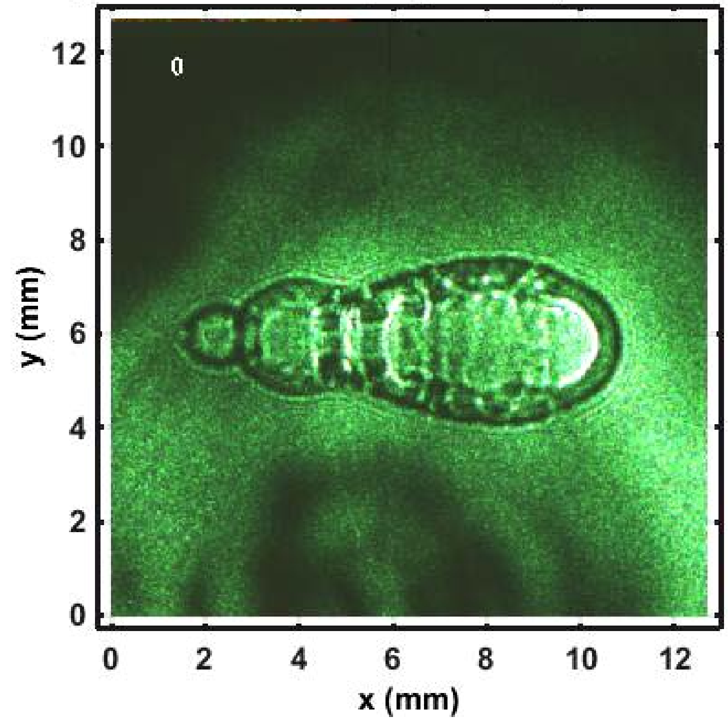
Gautam, Helstern, Drake, Parigger, IRAMP 7, 35-41 (2016).

Optical breakdown in air videos

Laser-plasma shadowgraph: 0.05 μs time delay,

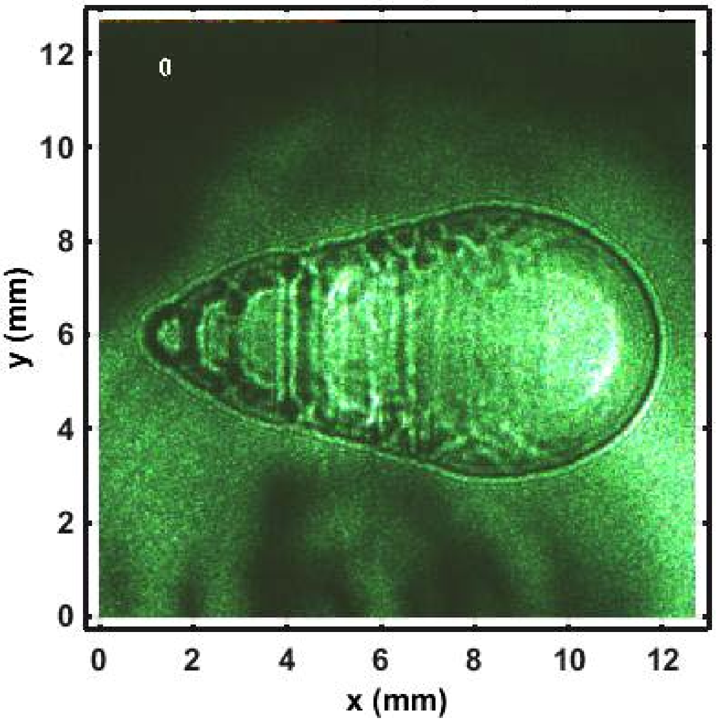


Laser-plasma shadowgraph: 0.4 μs time delay, ai

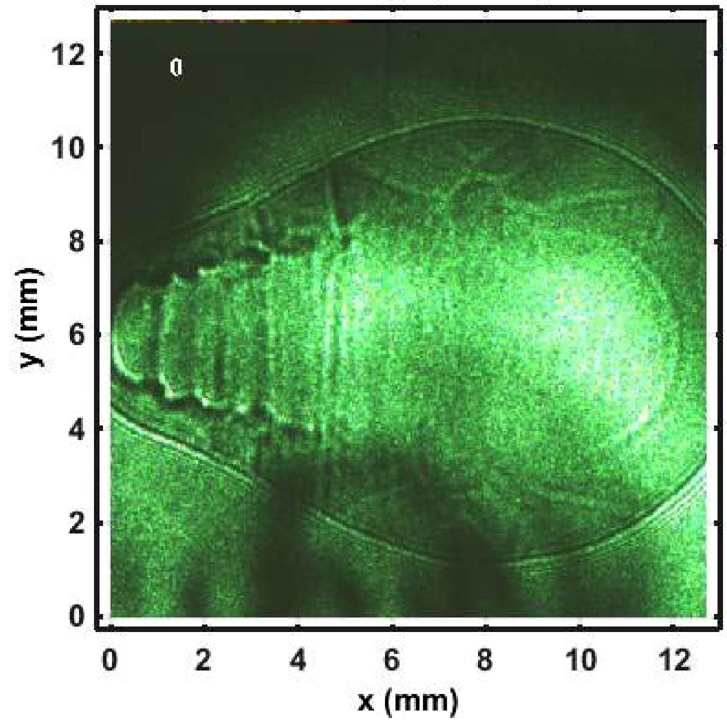


Optical breakdown in air, contd.

Laser-plasma shadowgraph: 1 μs time delay, air



Laser-plasma shadowgraph: 3 μs time delay, air



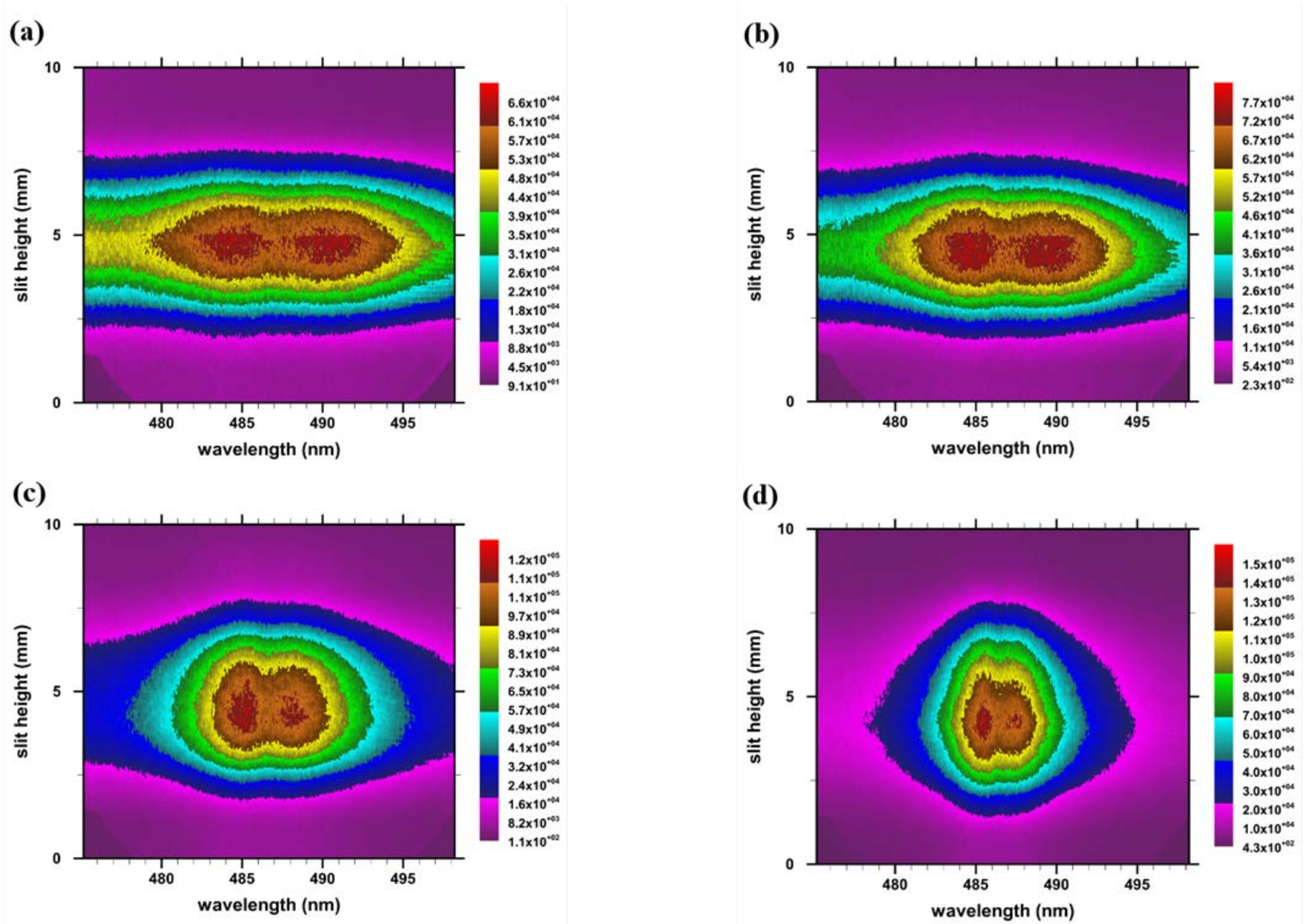
Taylor Sedov: $R(\tau)=(E/\rho\ \tau^2)^{1/5}$

$E = 150$ mJ, $\tau = 0.4$ μs, $\rho_{Air} = 1.2$ kg/m^3, $R_{Air}(0.4\ \mu s) = 1.8$ mm

$E = 150$ mJ, $\tau = 0.4$ μs, $\rho_{Hyd} = 0.09$ kg/m^3 $R_{Hyd}(0.4\ \mu s) = 3.1$ mm

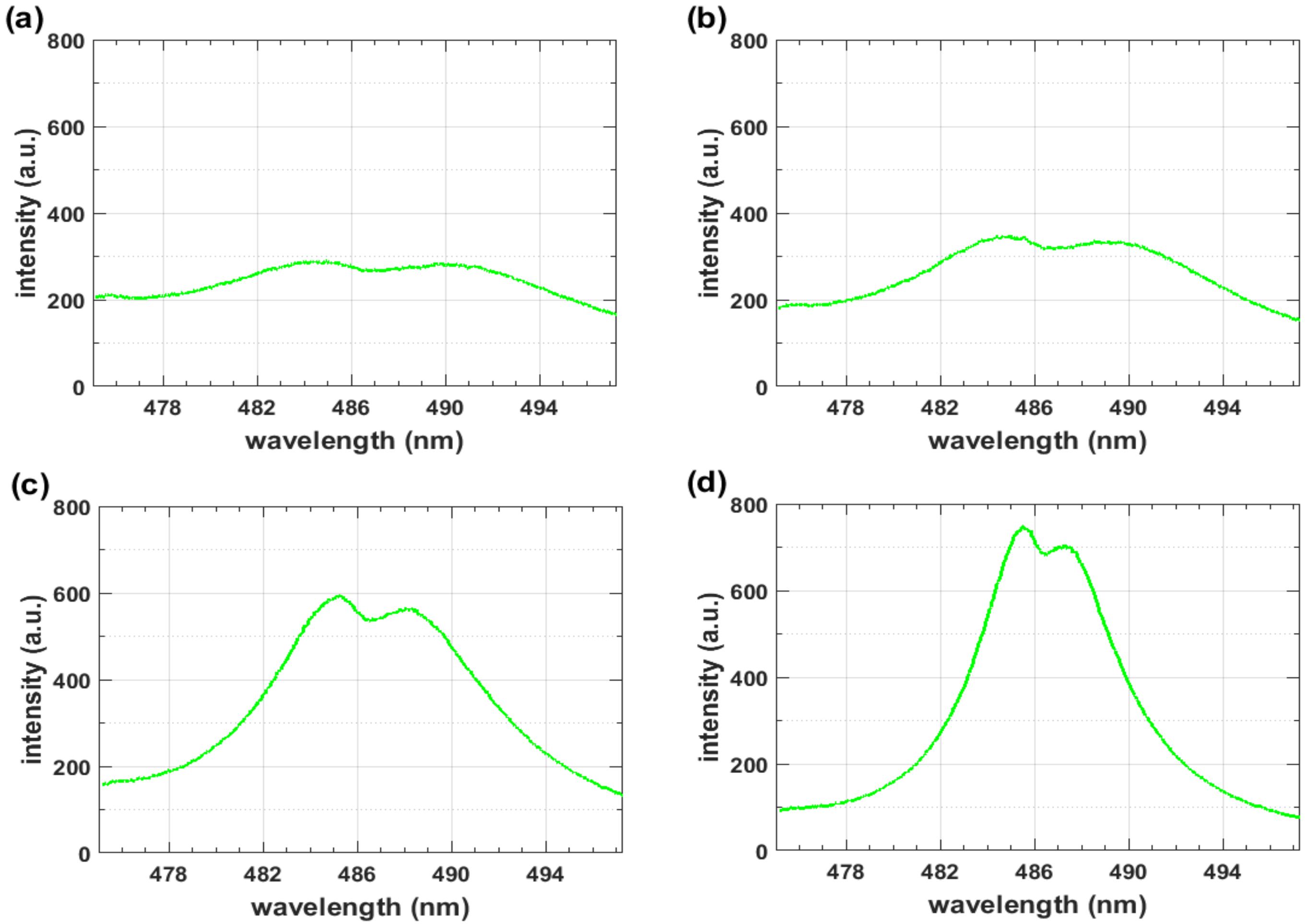
sound velocity ratio:
hydrogen/air ≈ 3.8

Atomic spectra: H_β



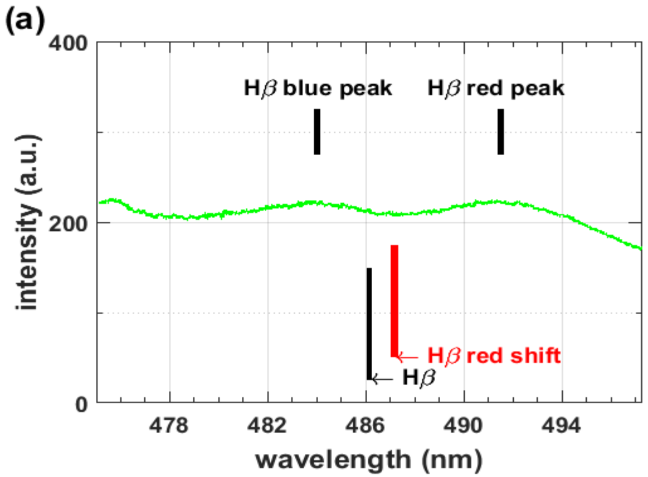
Measured H_β spectra. Gate width: 5 ns, time delay (a) 50 ns, (b) 75 ns, (c) 150 ns, and (d) 275 ns after optical breakdown in hydrogen gas at a pressure of 0.76×10^5 Pa (11 psi)

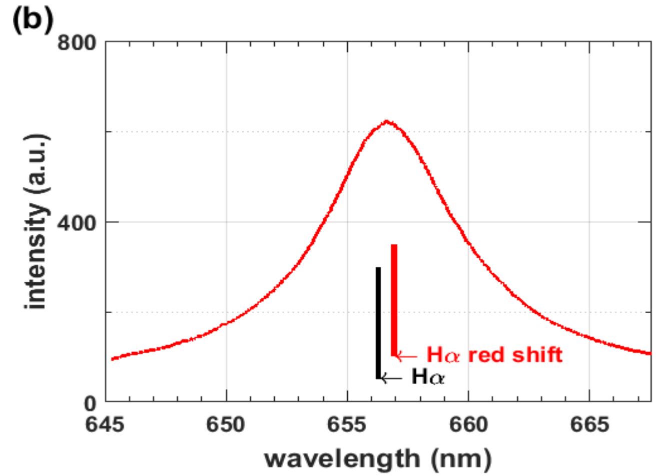
Atomic spectra: H_β , contd.



Average spectra of H_β. Gate width: 5 ns, time delay (a) 50 ns, (b) 75 ns, (c) 150 ns, and (d) 275 ns for a hydrogen gas at a pressure of 0.76×10^5 Pa (11 psi)

Atomic spectra: H_α and H_β





Average (a) H_β and (b) H_α line shapes. Gate width: 5 ns, time delay 25 ns.
H_2 at 0.76 × 10^5 Pa (11 psi)

$$\Delta\delta_{ds}[\mathrm{nm}] = 0.14 \left(\frac{N_e[\mathrm{cm}^{-3}]}{10^{17}}\right)^{0.67 \pm 0.03}$$

$$\Delta w_{H_\beta}[\mathrm{nm}] = 4.5 \left(\frac{N_e[\mathrm{cm}^{-3}]}{10^{17}}\right)^{0.71 \pm 0.03}$$

$$\Delta w_{H_\beta} \sim 32 \times \Delta\delta_{ds}$$

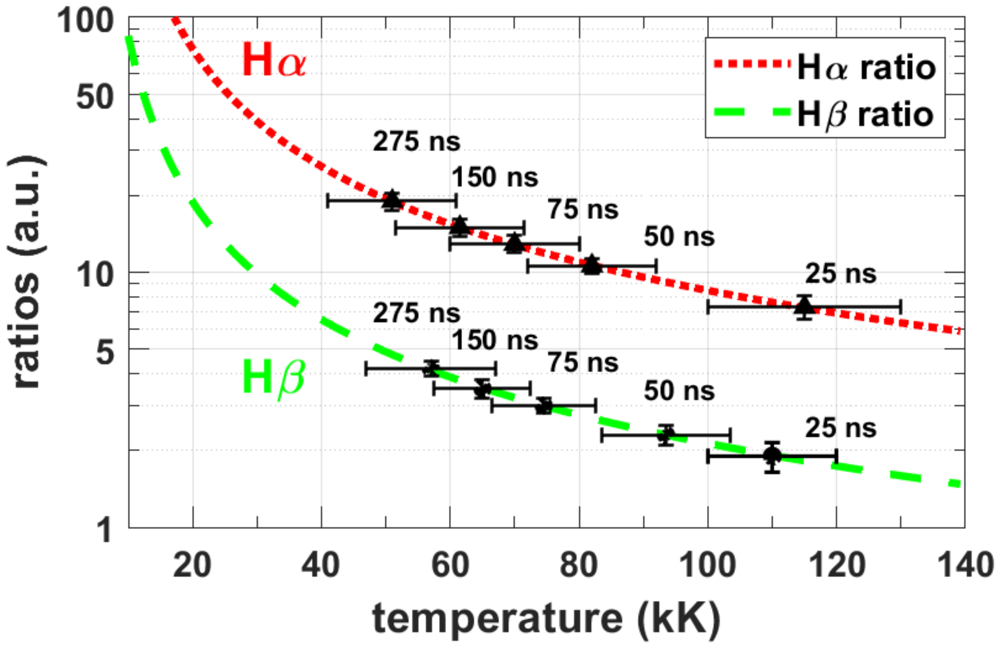
$$\Delta\lambda_{ps}[\mathrm{nm}] = 1.3 \left(\frac{N_e[\mathrm{cm}^{-3}]}{10^{17}}\right)^{0.61 \pm 0.03}$$

$$\Delta\delta_{shift}[\mathrm{nm}] = 0.055 \left(\frac{N_e[\mathrm{cm}^{-3}]}{10^{17}}\right)^{0.97 \pm 0.03}$$

$$\Delta w_{H_\alpha}[\mathrm{nm}] = 1.3 \left(\frac{N_e[\mathrm{cm}^{-3}]}{10^{17}}\right)^{0.64 \pm 0.03}$$

Comment: H_β shift for astrophysical spectra

Atomic spectra: H_α and H_β , contd.



Boltzmann plot:

$$T_e\ (eV) = 1/\ \ln\left[0.46/\left(H_\beta/H_\alpha\right)\right]^{1.5}$$

Comment on Doppler width:

$$\Delta\lambda^D_{1/2} = 7.16 \times 10^{-7} \lambda \sqrt{T/M}$$

$$R = \lambda/\Delta\lambda \sim 4 \times 10^3\ (\Delta\lambda \sim 0.1\ nm)$$

$$\Delta\lambda^D_{1/2}/\Delta\lambda = 0.09\ \sqrt{T[kK]/M}$$

$$T = 64\ kK,\ M = 1:\ \Delta\lambda^D_{1/2}/\Delta\lambda = 0.72$$

$$\Delta\lambda^D_{1/2} = 72\ pm$$

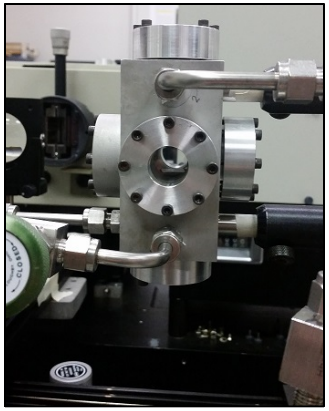
$$\Delta\lambda_V \approx \Delta\lambda_L/2 + \sqrt{(\Delta\lambda_L/2)^2 + \Delta\lambda_G{}^2}$$

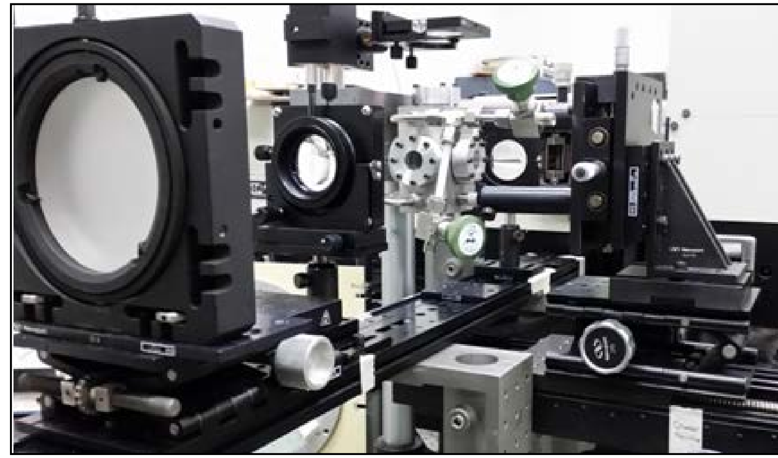
$$\Delta\lambda_V \sim 0.535\ \Delta\lambda_L + \sqrt{0.217\ \Delta\lambda_L{}^2 + \Delta\lambda_G{}^2}$$

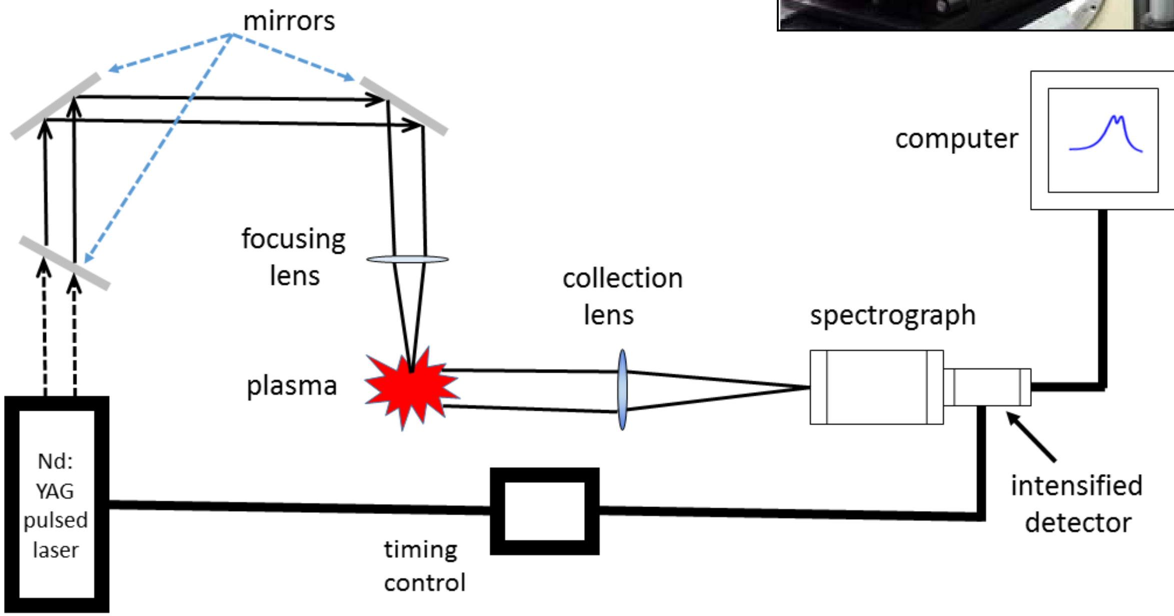
Computed H_α and H_β line to 10-nm continuum ratios. Time delays: 25 ns, 50 ns, 75 ns, 150ns, and 275 ns from optical breakdown using 150 mJ, 6 ns laser pulses at 1064 nm in 0.76×10^5 Pa (11 psi)

Parigger, Helstern, Drake, Gautam, IRAMP 8(2), 2017

Experimental arrangement: Cell







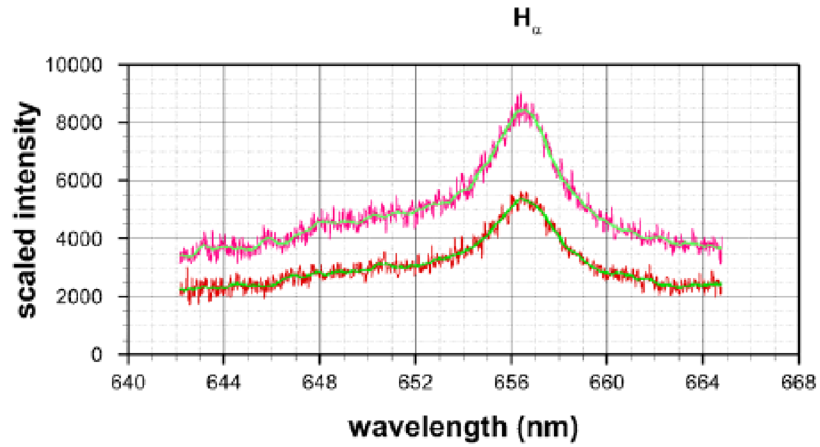
Especially, thanks to David Surmick and Ghaneshwar Gautam!

Self-absorption

Absorption $A_{total} = \int \left(1 - e^{-k(v)l}\right) dv$

N. Omenetto et al., SA 30B (1975) 335;

COG: I.B. Gornushkin et al. SAB 54 (1999) 491



Transmission $T(l, v) = e^{-k(v)\, l}$

Radiative transfer, Boltzmann integro-diff. equation

T. Holstein, PR 72 (1947) 1212;

Escape factor: F.E. Irons, JQSRT 22 (1979) 1

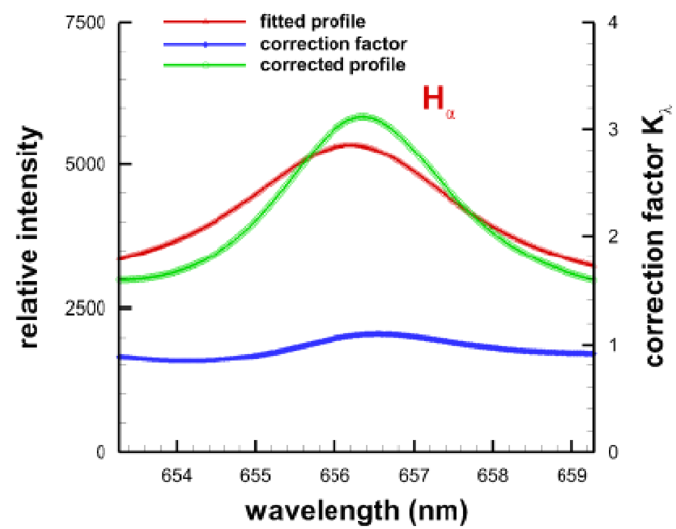
Transmission of flame through flame

for $k(v)\, l \ll 1$: optically thin, absorption $\sim k(v) l$

for $k(v)\, l \gg 1$: $T = 2 - \left(2 - \sqrt{2}\right) = \sqrt{2}$; $A = 2 - \sqrt{2}$

R. Ladenburg, F. Reiche, AdP 347 (1913) 181

T. Fujimoto, Plasma Spectroscopy, Clarendon, Oxford 2004



Doubling mirror for optically thin plasma

Correction factor; self-absorption factor;

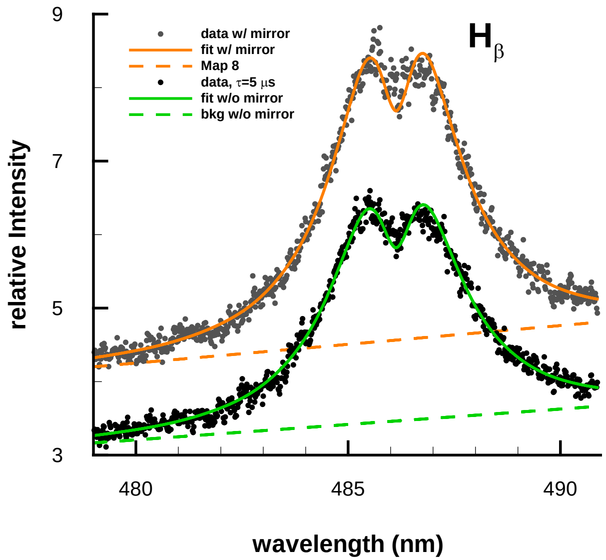
Electron density > 0.1 amg self-absorption

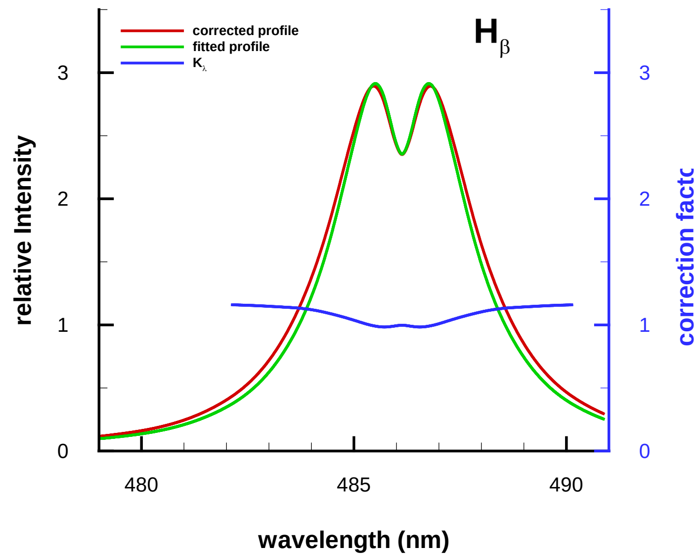
800 ns time delay: minimal self-absorption in SATP air plasma

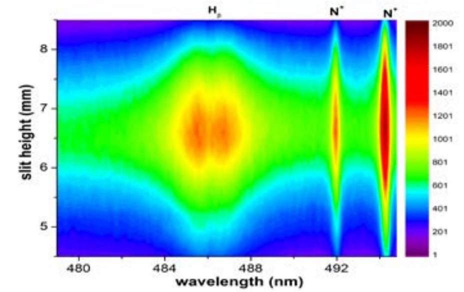
H-Y Moon et al., SAB 64 (2009) 702

Hydrogen β results: Air

Laser-induced breakdown in air







5 μs time delay, 0.73×10^{17} cm^{-3} and 0.69×10^{17} cm^{-3} without and with mirror, respectively. Insignificant self-absorption. $K_\lambda = \log\{y\} / (y - 1)$, with $y = (R_\lambda - 1) / (R_C - 1)$.

$$N_{e,\beta}[m^{-3}] = \left[\frac{\Delta\lambda\ [\mathrm{nm}]}{4.8}\right]^{1.46808} \times 10^{17}$$

$$\log N_{e,\beta}\ [\mathrm{cm}^{-3}] = 16.661 + 1.416 \log \Delta\lambda_{ps}[\mathrm{nm}]\ .$$

G.Gautam et al., JQSRT 170 (216) 189

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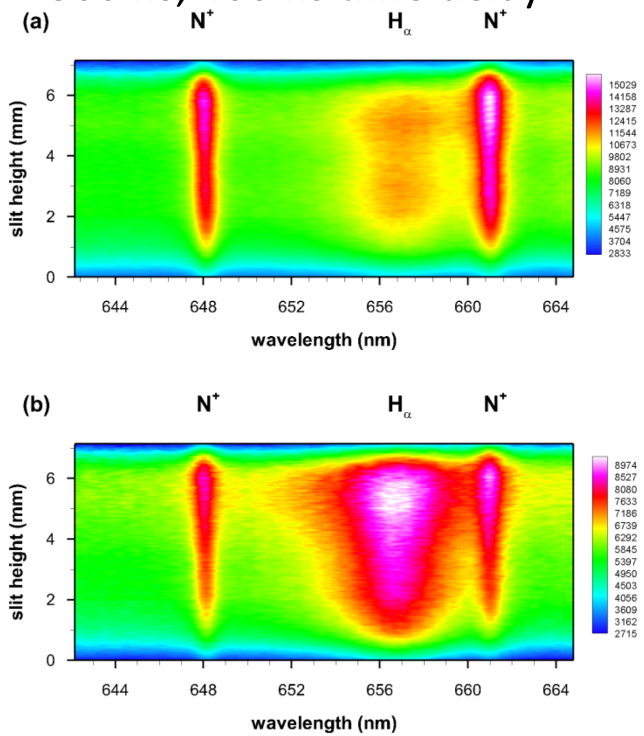
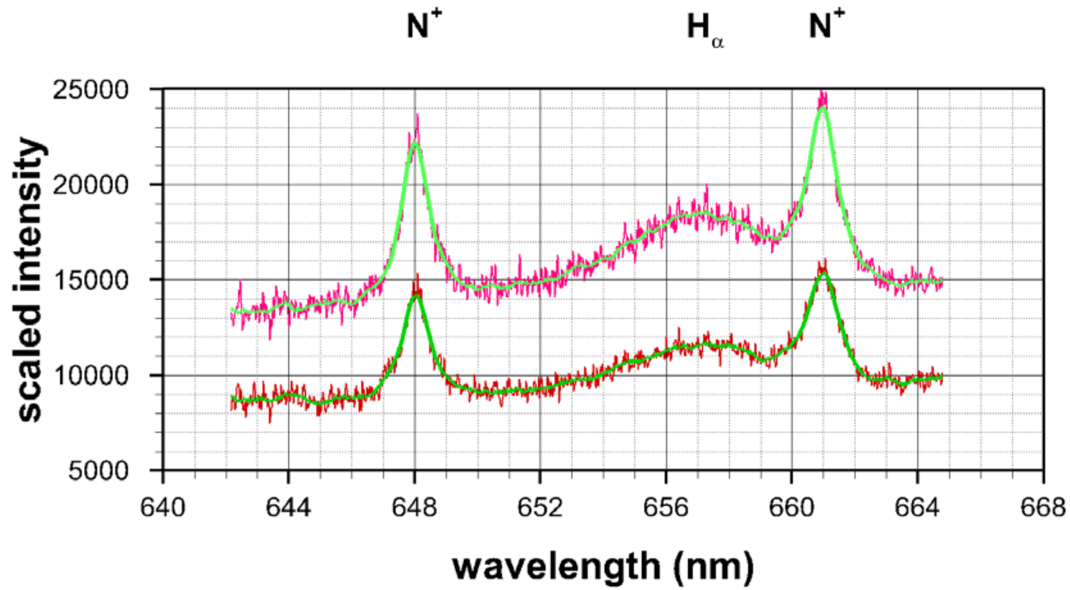
Hydrogen α results: Air

300 ns, 400 ns time delay



The Hα line is red-shifted from 656.28 nm, the N+ lines are only slightly shifted from 648.21 nm and 661.06 nm.

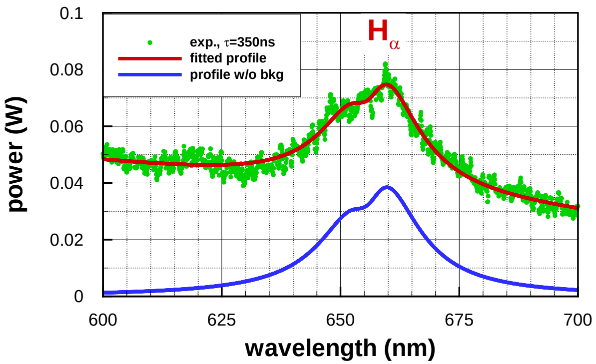
300 ns time delay

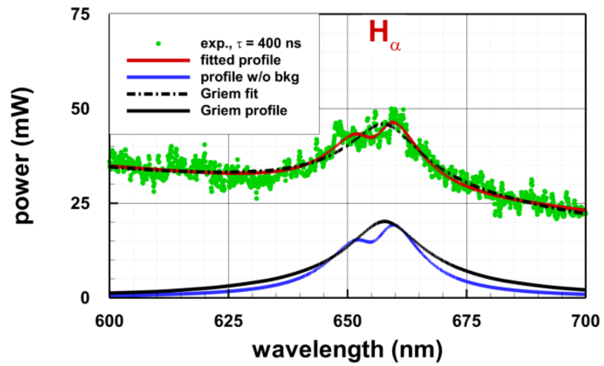


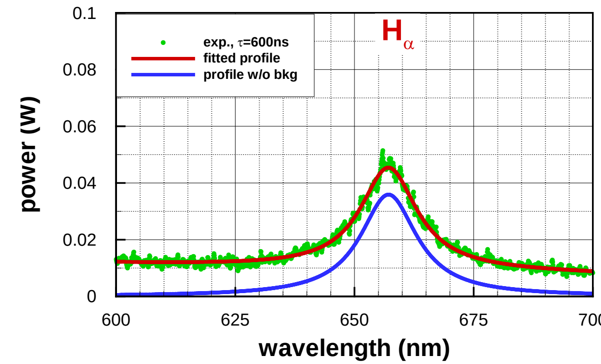
The electron density of 14 to 20 × 10^{17} cm^{-3} determined from the Hα line is higher than 12 to 13 × 10^{17} cm^{-3} obtained from N+ for the 300 ns time delays. Therefore, Hα shows self-absorption for delays of 300 ns; however, the level of self-absorption is insignifcant for delays of 800 ns after optical breakdown.

Hydrogen α spectra

Laser-induced breakdown of ice in air – collaboration with Ashraf M EL Sherbini in Cairo







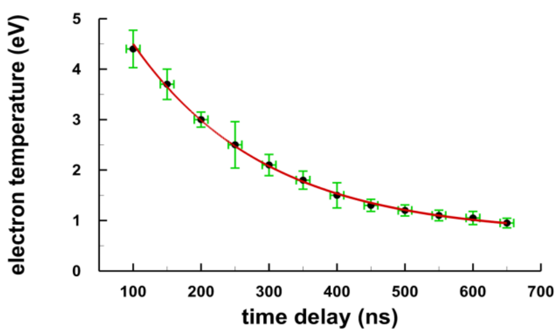
Δτ = 350 ns (left) and Δτ = 600 ns (right). $\Delta\lambda_S$ values of 23 ± 4 nm and 13± 3 nm for the time delays of 350 ns and 600 ns. Ne : 0.7 × 10^{19} cm^{-3} and 0.3 × 10^{19} cm^{-3}. Red shifts δ values are 3.2 ± 0.3 nm and 0.9 ± 0.2 nm, Ne: 0.8 × 10^{19} cm^{-3} and 0.2 × 10^{19} cm^{-3}. Middle image shows comparison with Griem-data fit.

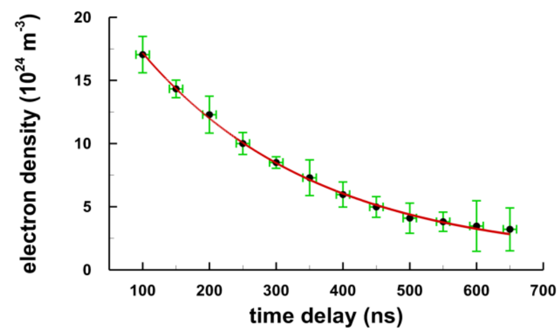
$N_e \approx 9 \times 10^{17}\, \lambda\, [\varepsilon_\lambda^{ff}\, (T_e / E)^{1/2}]^{1/2}$

Absolute emission coefficient!

$$\Delta\lambda_S[\mathrm{nm}] = 5.68 \left[\frac{N_e}{10^{24}}\right]^{0.64\pm0.03}$$

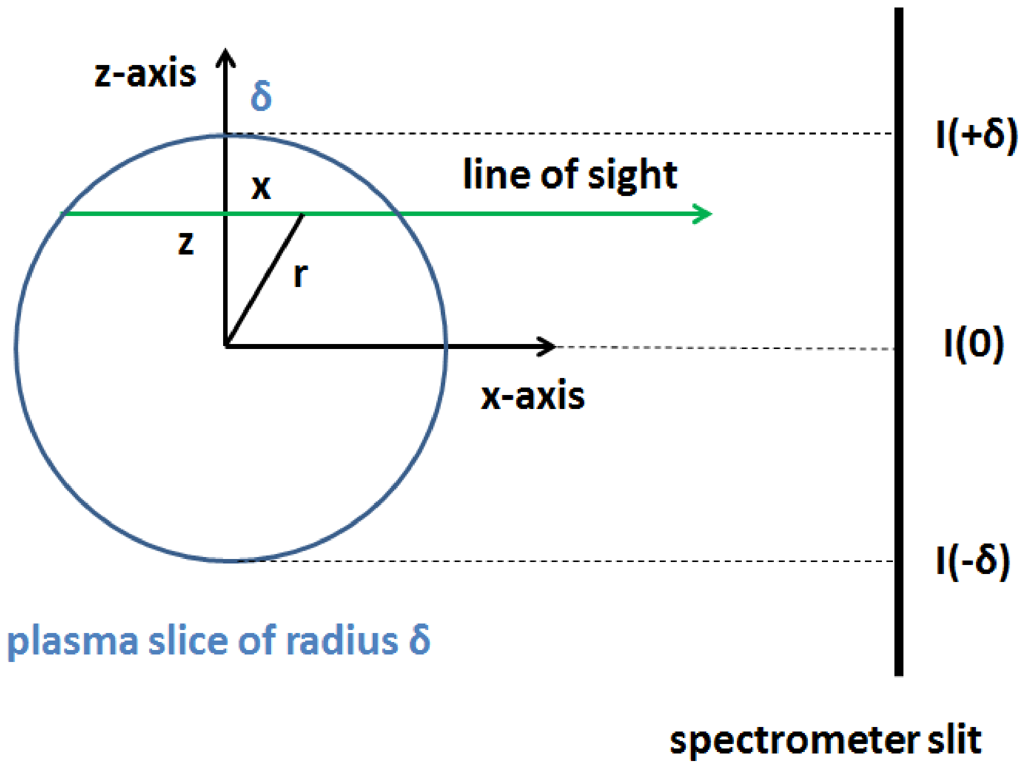
$$\delta[\mathrm{nm}] = 0.543 \left[\frac{N_e}{10^{24}}\right]^{0.97\pm0.03}$$



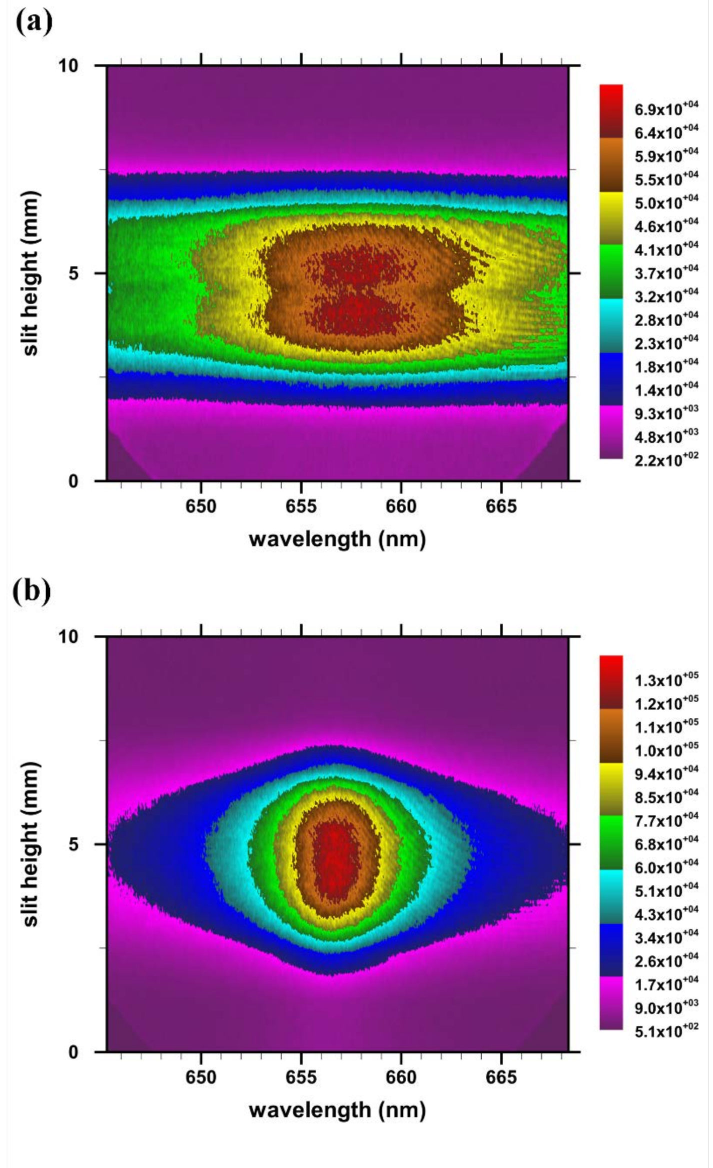


C.G. Parigger et al., OL 40 (2015) 3436

Abel inversion

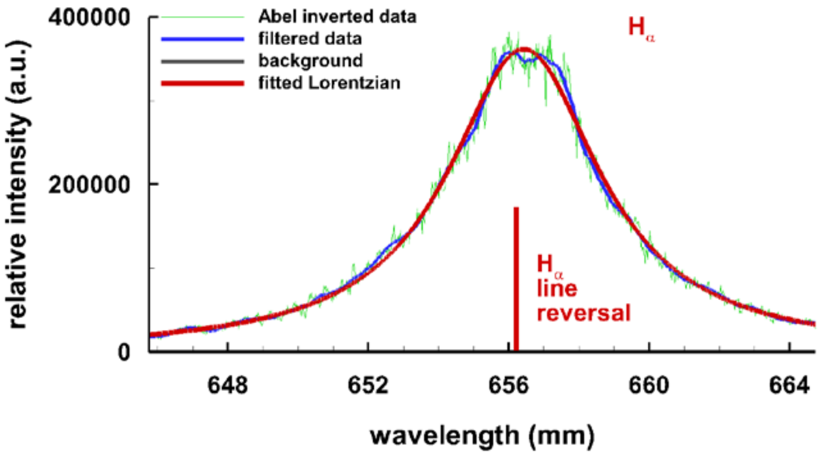


$$I(z,\lambda) = 2\int_{z}^{\rho} \varepsilon(r,\lambda)\,\frac{r}{\sqrt{r^2 - z^2}}\,dr\,,$$

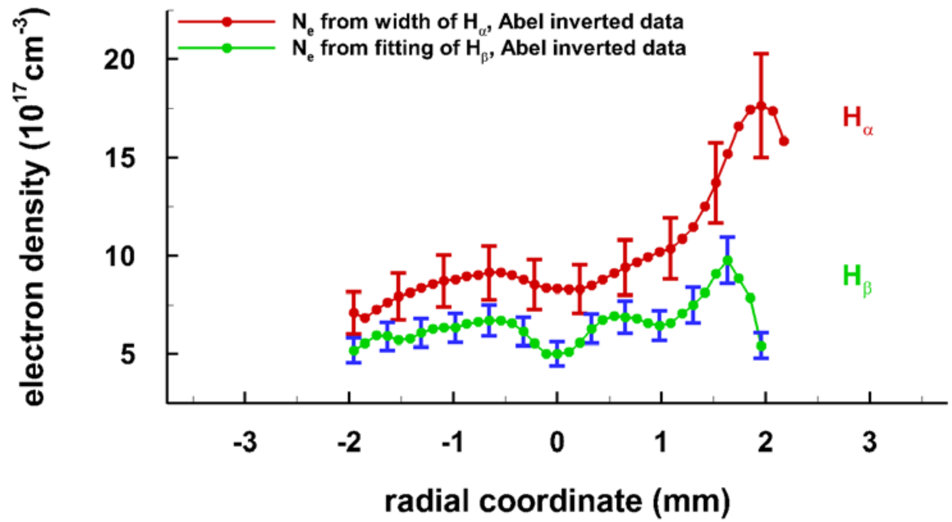


H_α (a) “0” ns (b) 25 ns time delay

H_α and H_β : Abel inversion

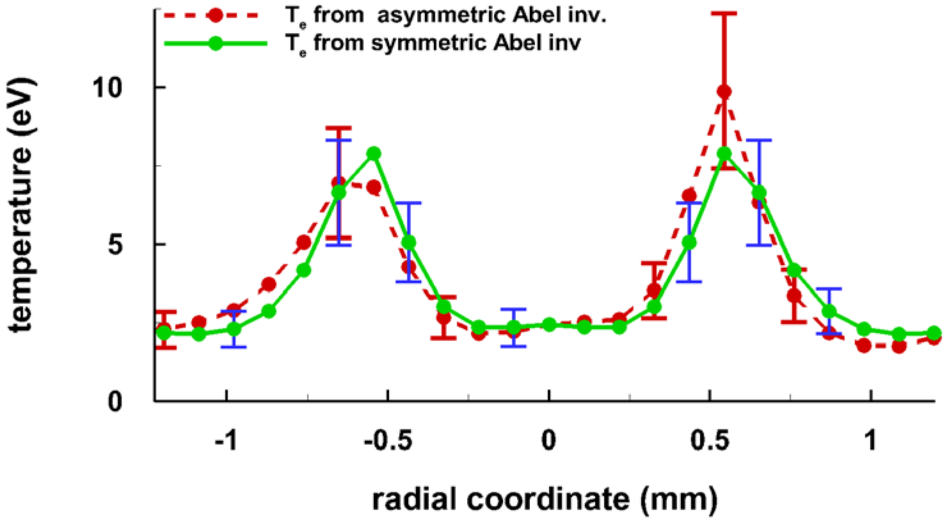


$N_e = 8.4\times10^{17}$ cm^{-3}, UHP hydrogen gas (810 Torr), $\tau = 0.15$ μs.

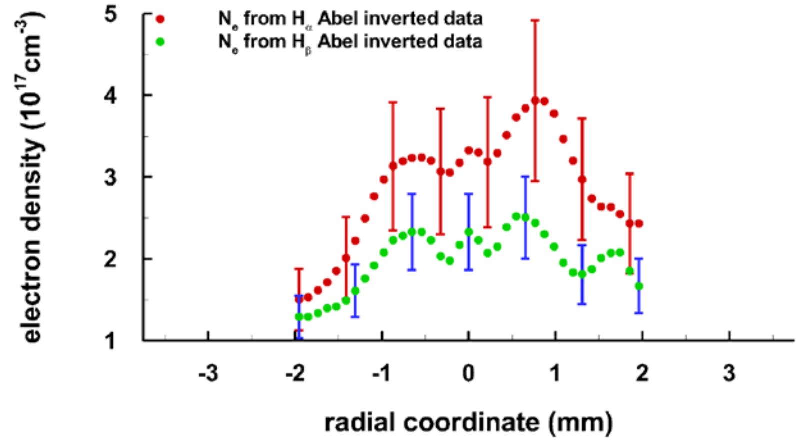


N_e across the plasma from fitting Abel-inverted H_α and H_β line proles.

H_α , H_β and H_γ: Abel inversion



T_e from Boltzmann plots, τ = 0.40 μs.



N_e variation, τ = 0.40 μs. N_e is almost symmetric in the -1 to +1 mm range.

Adiabatic expansion $T_1/T_2 = (N_1/N_2)^{2/3}$
for $T_1/T_2 = 2$, $N_1 = 2.8\ N_2$

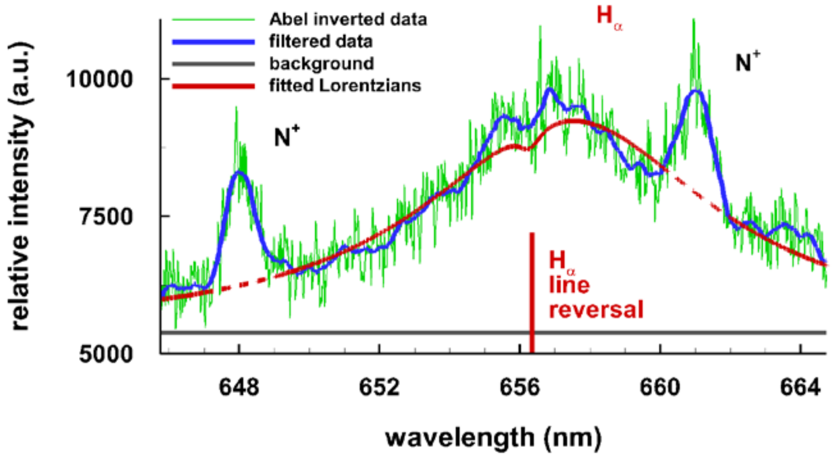
Keldysh parameter: $\gamma = \dfrac{100}{\lambda(\mu m)}\sqrt{\dfrac{E(eV)\tau(ns)}{\varphi(J/cm2)}}$

T_{max} expands at $(1/[5/3]])^{1/2}$, see Mulser&Bauer, High Power Laser-Matter Interaction, Springer, Berlin, 2010

E=13.6 eV, τ=6 ns, φ= 85 J/cm^2(850 mJ in 1 mm^2, λ=1 μm)

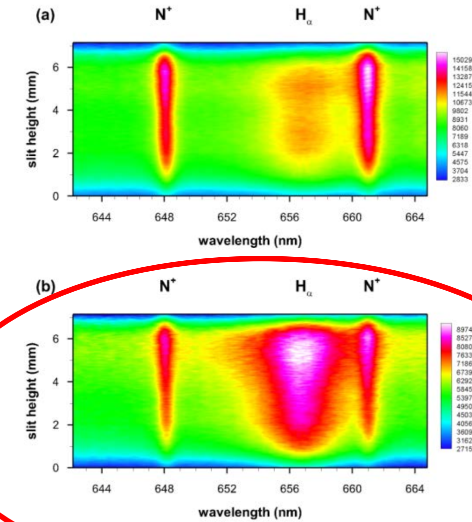
γ = 100 >> 1 multiple photon absorption, no tunnel ionization

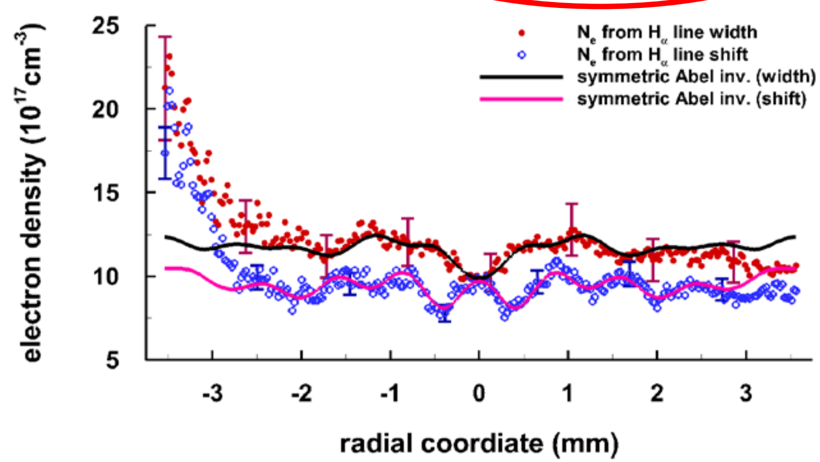
Air breakdown: Abel inversion



SATP air, N_e = 20×10^{17} cm^{-3}, τ = 0.40 µs.

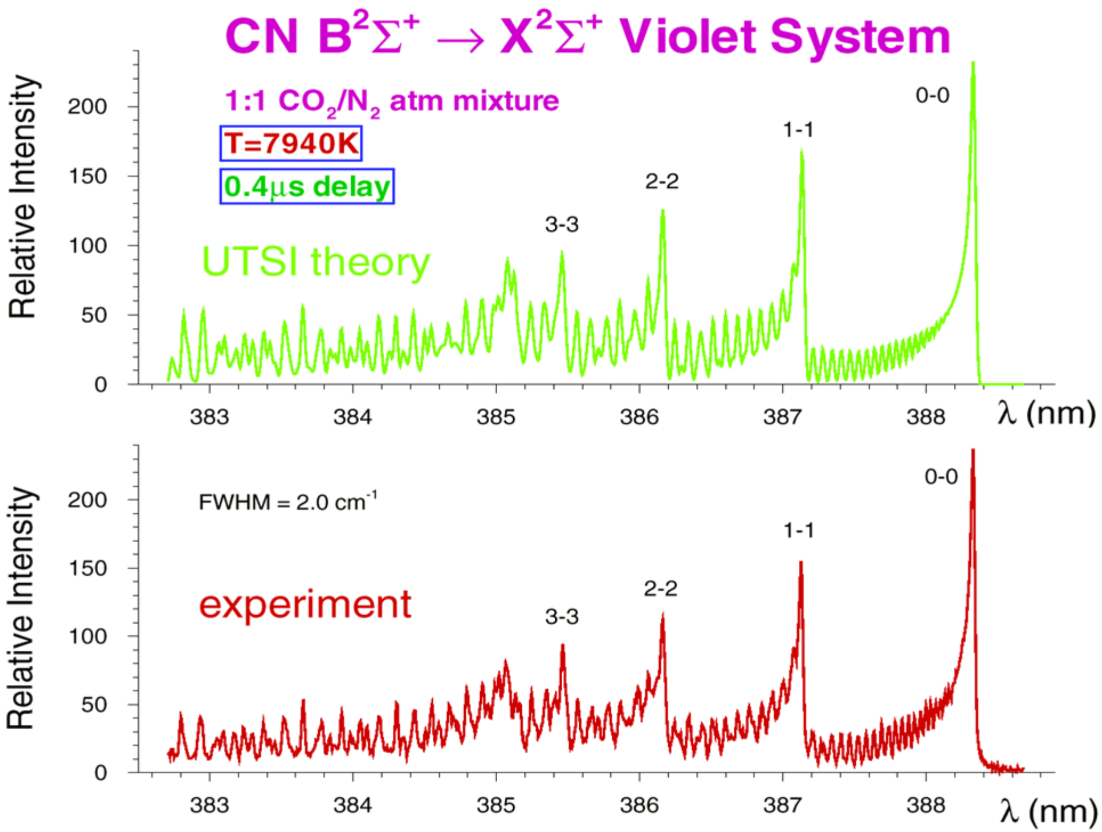
Parigger, Surmick, Gautam,
2017 J. Phys.: Conf. Ser. **810** 012012

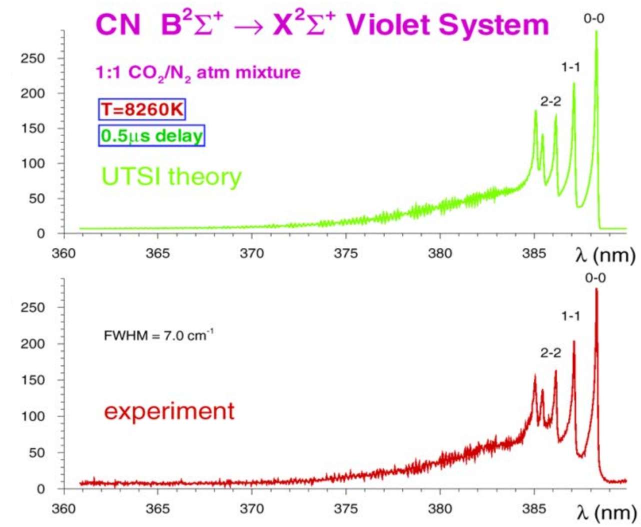




N_e variation from fitting Abel-inverted spectra

CN molecular spectra





Used 35 ps laser radiation,
Actually, 3 × 35 ps in 1 ns

CN Spectrum for Δ ν = 0, resolution ~ 0.04 nm

Hornkohl, Parigger, Lewis, JQSRT **46**, 405 (1991)

12th SCSLSA 3-7. June 2019 Vrdnik, Serbia
12th Serbian Conference on Spectral Line Shapes in Astrophysics

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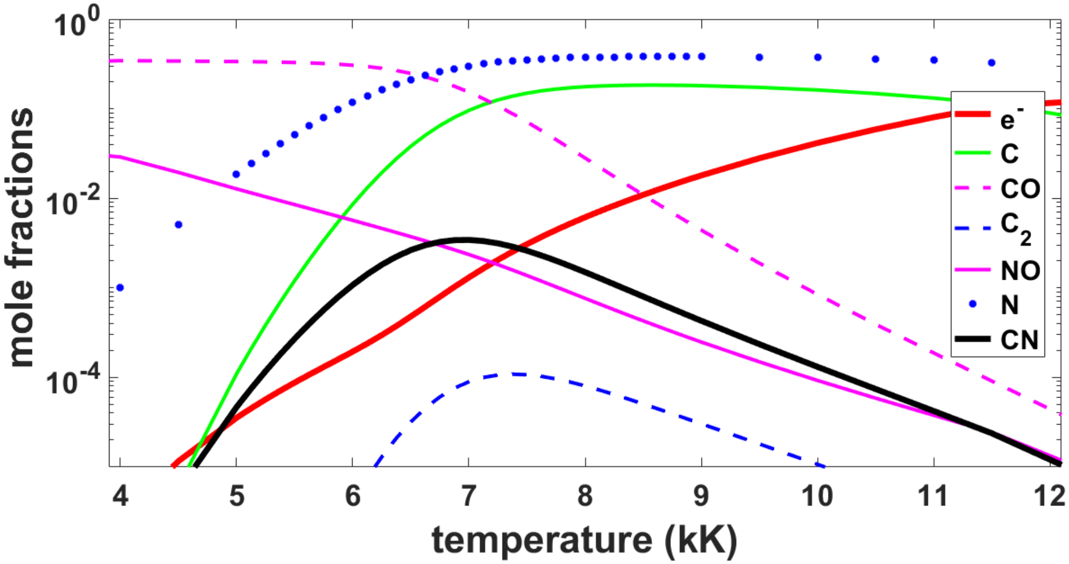
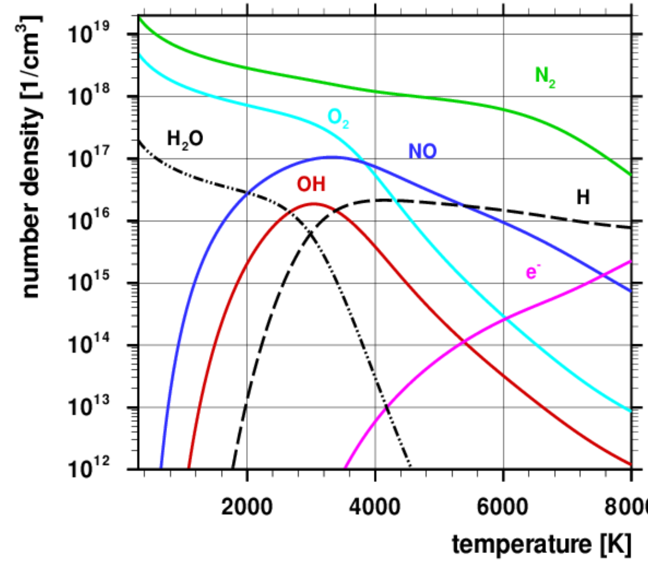
CN molecular spectra



Computed CN mole fraction versus temperature.

In chemical equilibrium, CN shows a maximum near 7 kK for the 1:1 atmospheric CO2:N2 mixture. Computed with CEA-code.

CN fractions in air are about 500 × lower than that for the mixture.



Air, 1 atm.

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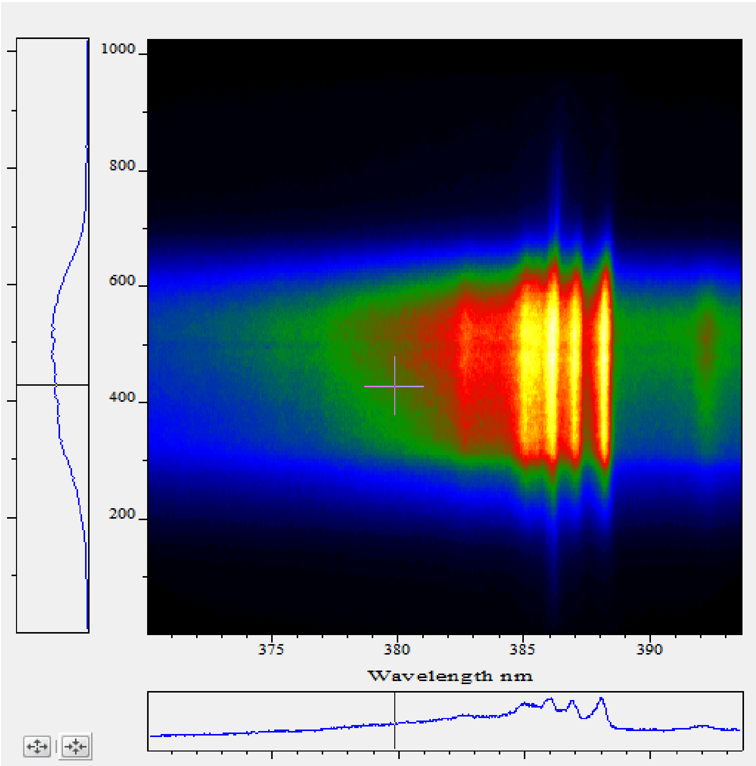
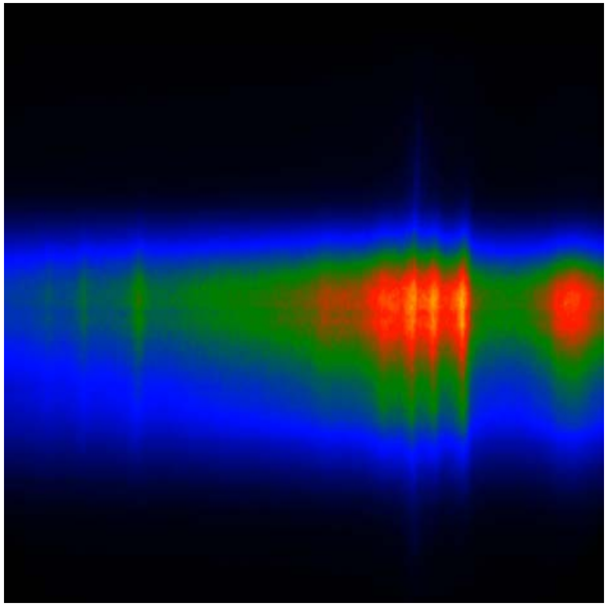
CN Molecular Spectra, contd.

Laser-induced optical breakdown in 1:1 CO_2:N_2 gas mixture.
Raw spectrum: 400 ns time delay, 150mJ, 6 ns.

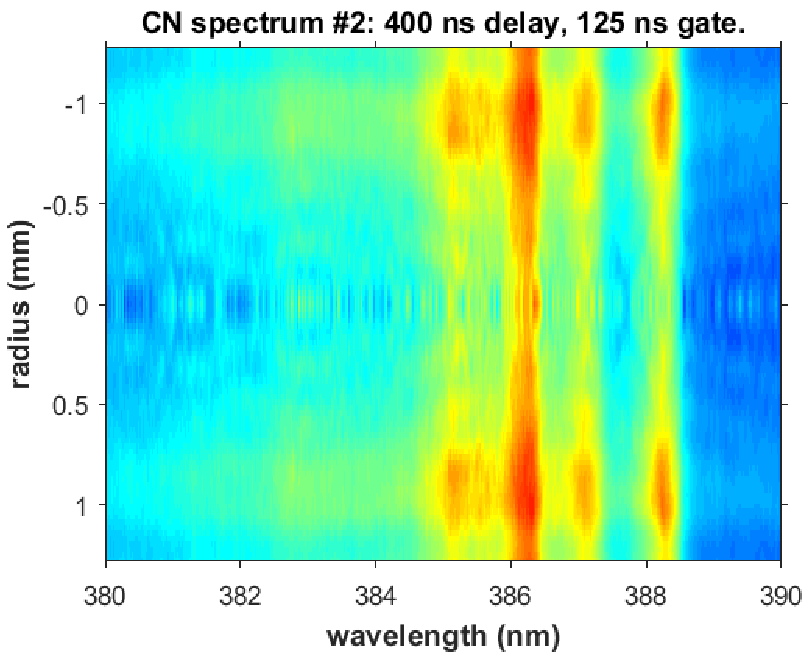


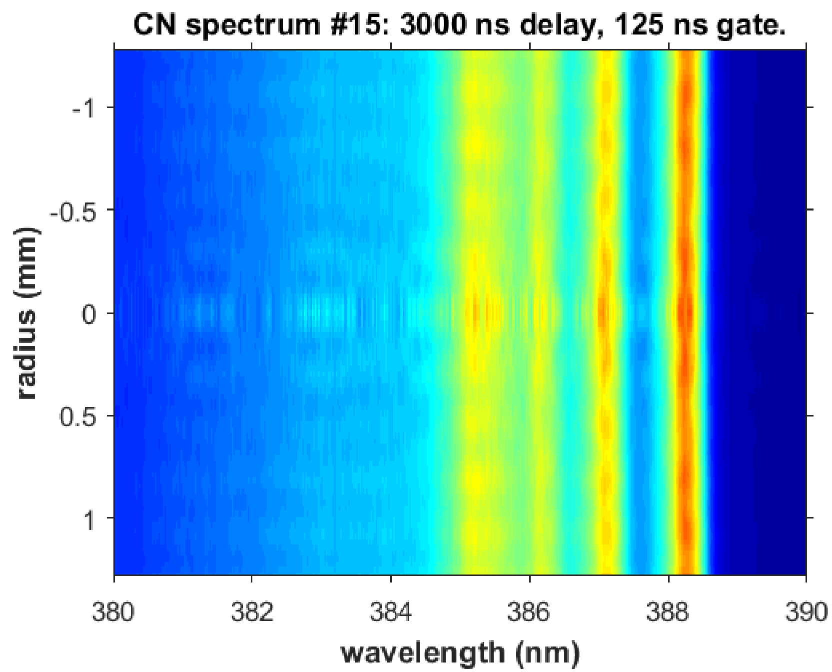
200 ns start, 200 ns steps



Abel-inverted CN spectra

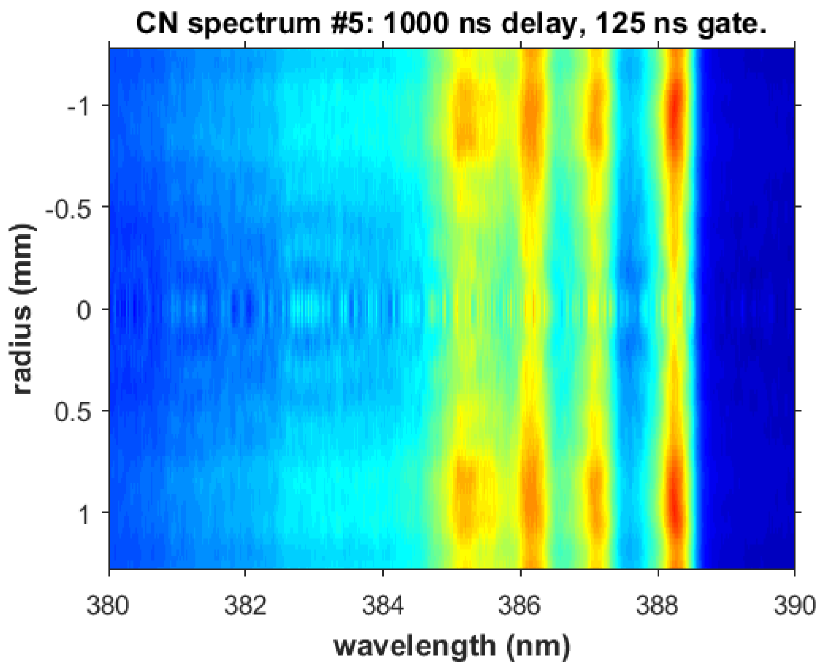
Laser induced breakdown in 1:1 CO_2:N_2

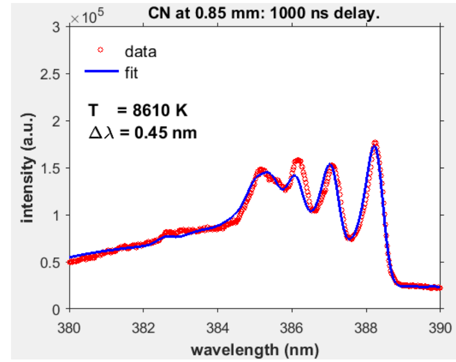


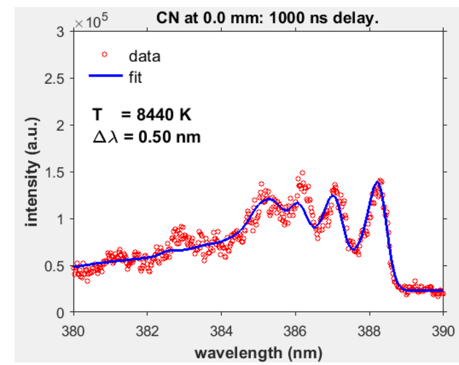


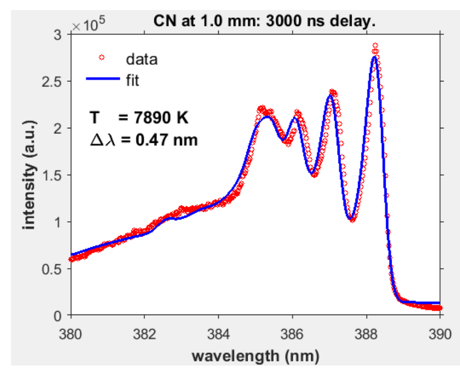
Abel-inverted CN spectra, contd.

Laser induced breakdown in 1:1 CO_2:N_2









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Superposition spectra: H_β and C_2

Atomic and molecular spectroscopy

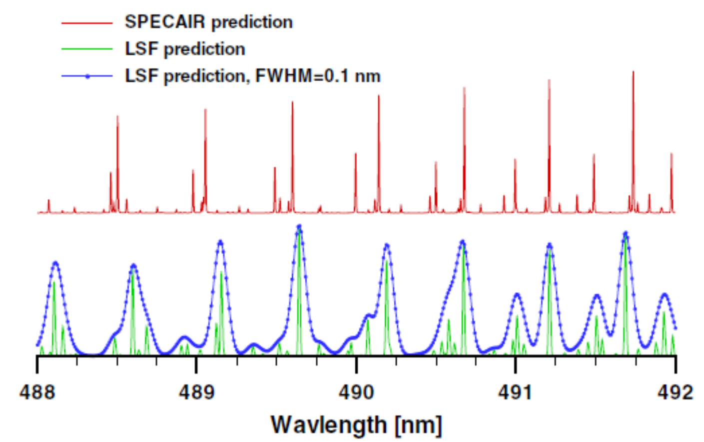


Fig. 4. (Color online) Line positions computed using SPECAIR (top) and line-strength files (LSFs) for C_2 (bottom) for an equilibrium temperature of $T = 5000$ K. The broadened profile (bottom) is computed for FWHM = 0.1 nm.

Analysis of time-resolved superposed atomic hydrogen Balmer lines and molecular diatomic carbon spectra

Christian G. Parigger,[1,*] Alexander Woods,[1] and James O. Hornkohl[2]

1 March 2012 / Vol. 51, No. 7 / APPLIED OPTICS B1

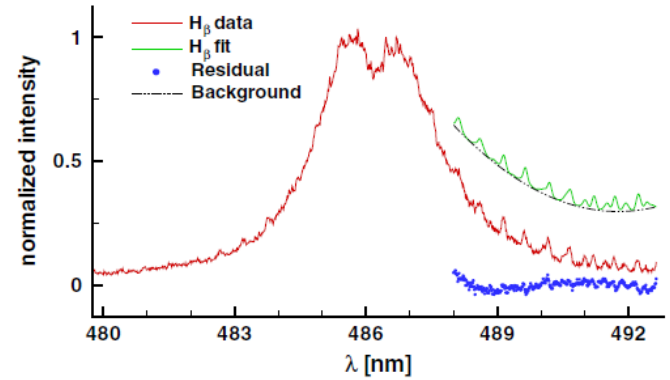


Fig. 5. (Color online) Measured H_β and fitted C_2 Swan band emissions. $\Delta\tau = 2.0\ \mu s$, $p = 2.7 \times 10^5$ Pa. Fitted molecular emission temperature, 0.56×10^4 K; electron excitation temperature, 1.3×10^4 K.

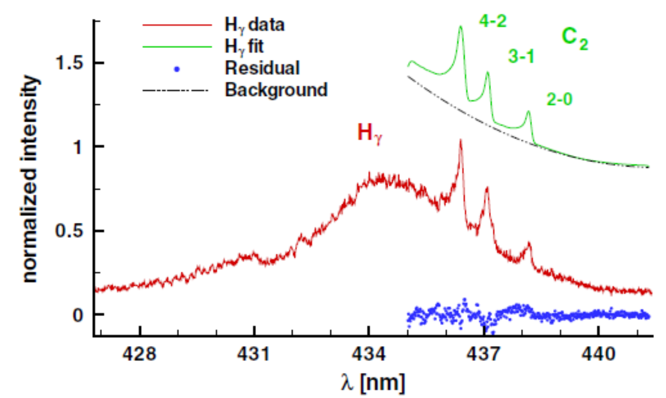
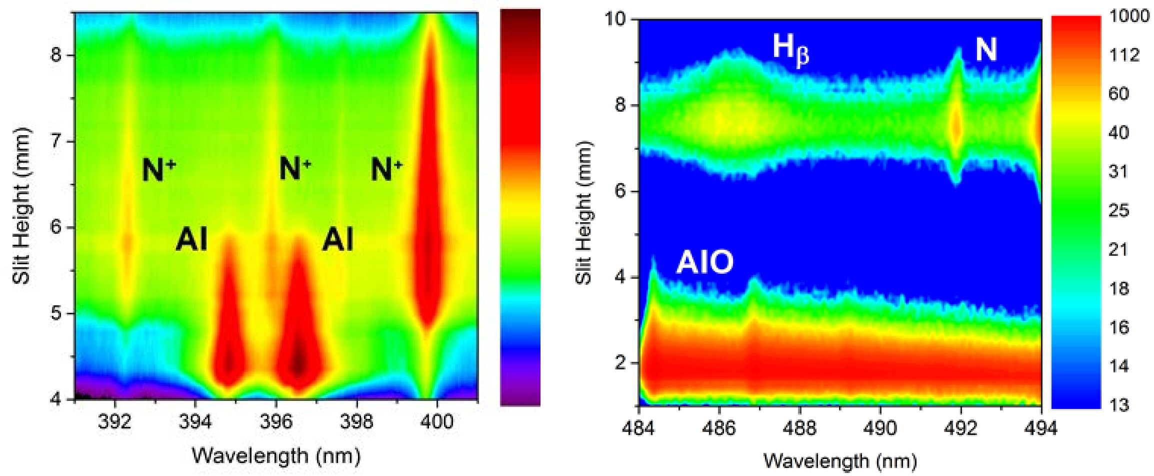


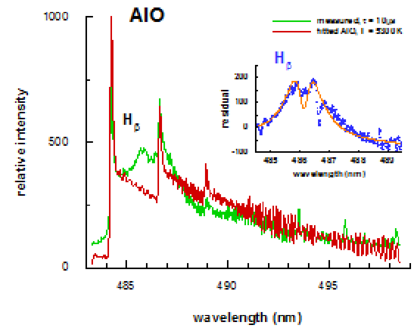
Fig. 8. (Color online) Measured H_γ and C_2 Swan band emissions, $\Delta\tau = 2.0\ \mu s$, $p = 6.5 \times 10^5$ Pa. Fitted molecular emission temperature, 0.48×10^4 K; electron excitation temperature, 1.3×10^4 K.

Superposition spectra: AlO and H_β

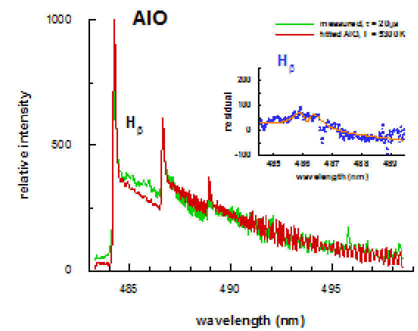
Laser ablation in air



ICCD images of air and aluminium laser breakdown for 0.3 µs (Left) and 10 µs (Right) time delays



10 µs, $N_e = 0.24 \times 10^{17}$ cm^{-3}

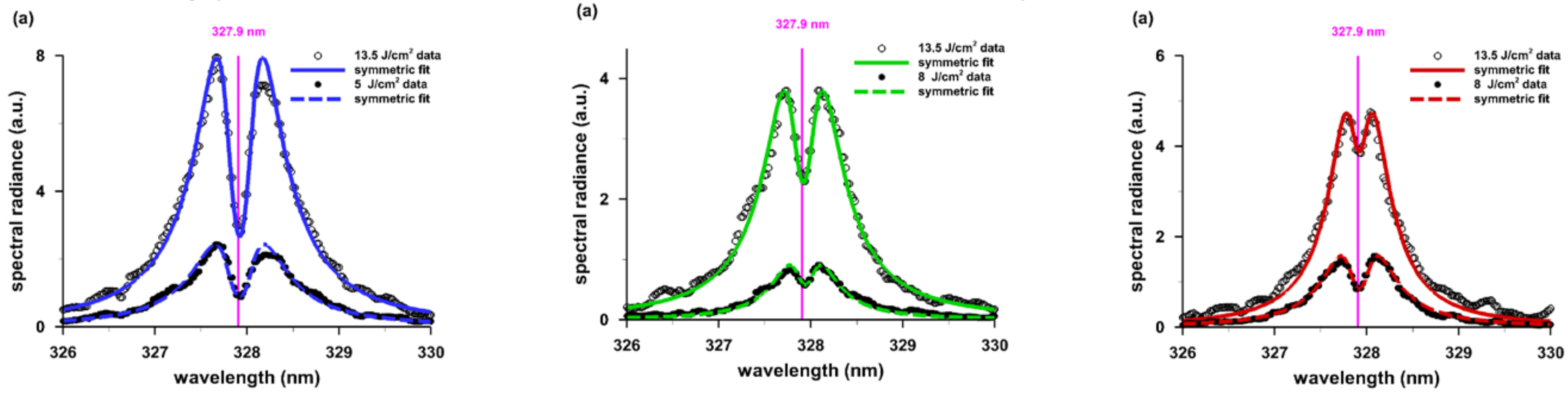


20 µs, $N_e = 0.14 \times 10^{17}$ cm^{-3}

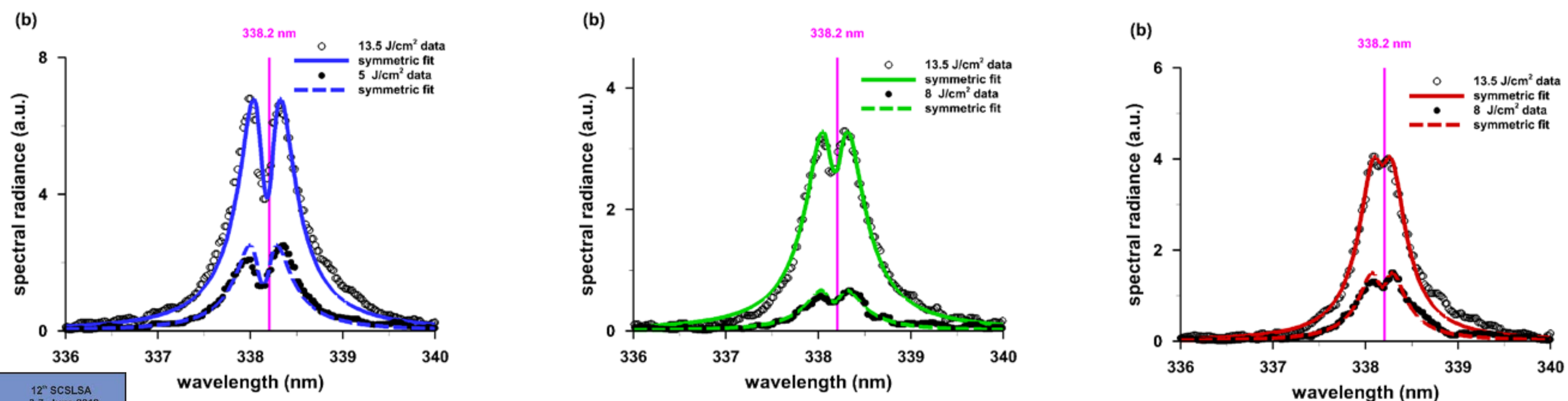
David Surmick, AlO, 2016, PhD University of Tennessee.
Ghaneshwar Gautam, H, 2017, PhD, University of Tennessee.

Nano-particle plasma

100 nm Ag particles, collaboration with Cairo University



Self-reversal of Ag I (top) 327.9 nm, and (bottom) 338.2 nm. Laser wavelengths: 355 nm, 532 nm, and 1064 nm. Fluence of 13.5 and 8 J/cm^2.



Conclusions

- Atomic and molecular emission spectra of the type encountered in laser-induced breakdown spectroscopy occur in astrophysical spectra from white dwarf stars;
- Gas-dynamic expansion affects distribution of the laser plasma, including distributions in the kernel and just inside the expanding shock wave;
- Measured hydrogen electron densities and temperatures in the range of 1 to 100 × 10^{17} cm^{-3} and 10 kK to 120 kK (1 to 10 eV), respectively;
- Abel-inverted hydrogen (H) and cyanide (CN) spectra indicate effets of expansion dynamics, e.g., outgoing electron density and temperature wave;
- Superposition spectra of hydrogen (H) and Swan (C_2) bands, and H and AlO, but really would need spatial and temporal resolution;
- Self-reversal and self-absorption can be an issue for nanomaterial LIBS.