

Characterization of Titan Entry Radiative Heating in the Low Density Electric Arc Shock Tube

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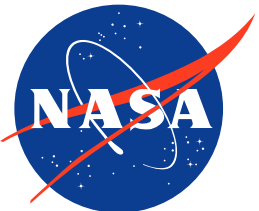
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Extending aftbody radiative heating characterization for Dragonfly's entry at Titan

Motivation:

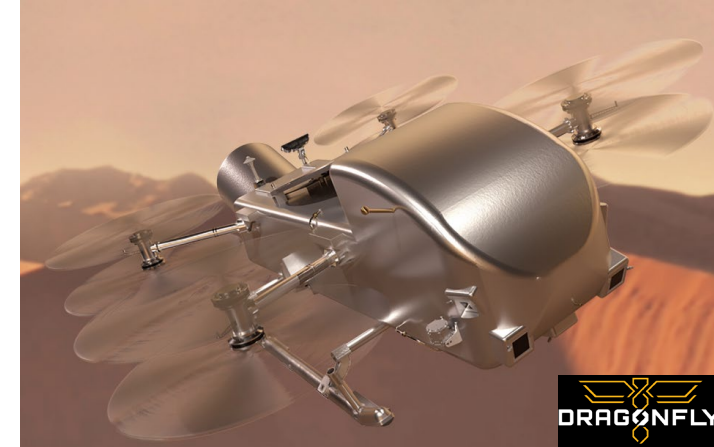
- Dragonfly mission planned to launch in 2028^(a)
- Radiation is dominant on the aftbody for the Dragonfly entry at Titan^(b)
- Benchmark data needed for TPS performance and DrEAM data analysis

Previous work at EAST:

- TS61^(c) → CN radiation investigated for Titan representative mixtures
- TS65A^(d) → aftbody radiation characterized for Dragonfly's lower altitude trajectory
shortcomings in predicted CN radiance highlighted using DPLR+NEQAIRv15.1

Objectives:

- TS65B → to extend aftbody radiative heating characterization at higher altitude using LDST
- Evaluate CN non-Boltzmann model in NEQAIR at lower pressures



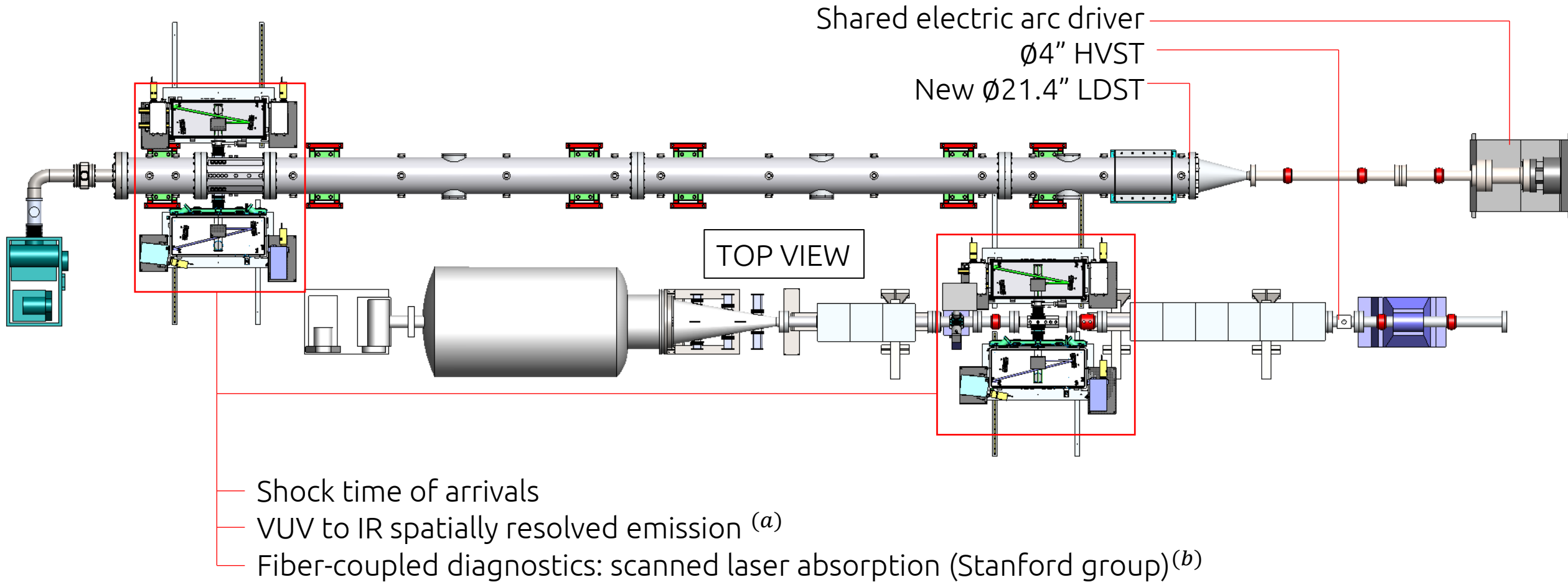
(a) Lorentz R. D. et al. – Dragonfly: A Rotorcraft Lander Concept for Scientific Exploration at Titan - Johns Hopkins APL Technical Digest, Vol. 34, No. 3, 2018.

(b) Johnston C.O. et al. – AIAA 2019-3010

(c) Brandis and Cruden – AIAA paper 2017-4534

(d) Tibere-Inglesse A. et al – AIAA paper 2023-3730

Shock layer radiation measurements in the NASA Ames Electric Arc Shock Tube



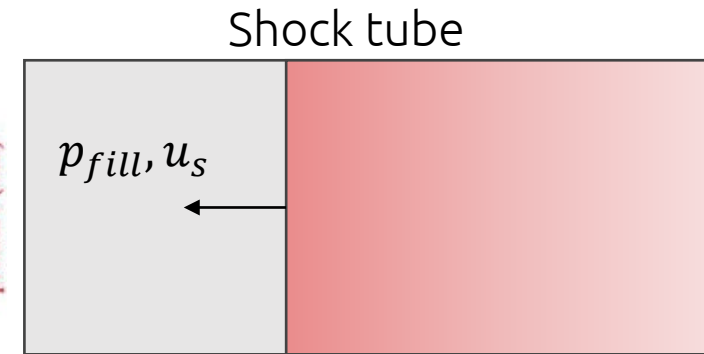
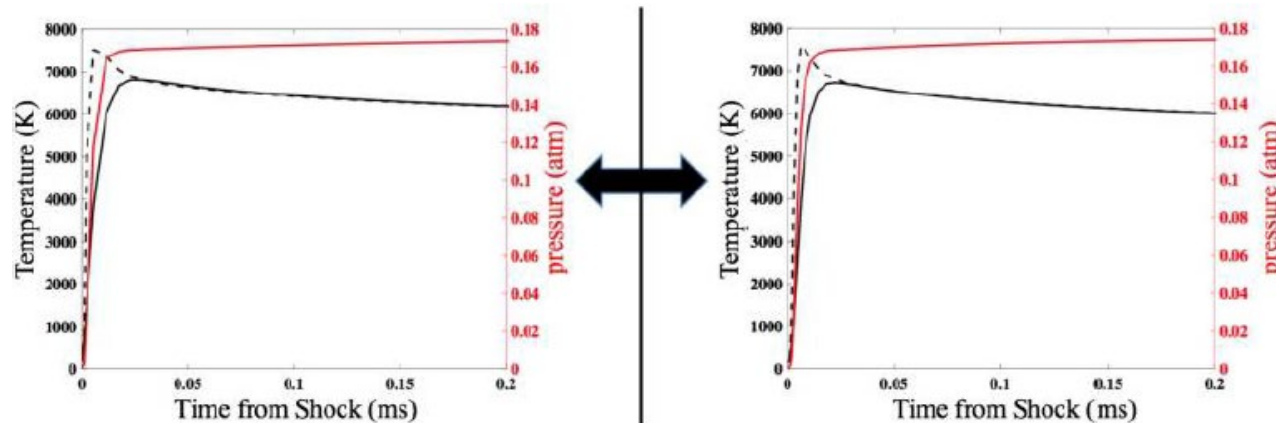
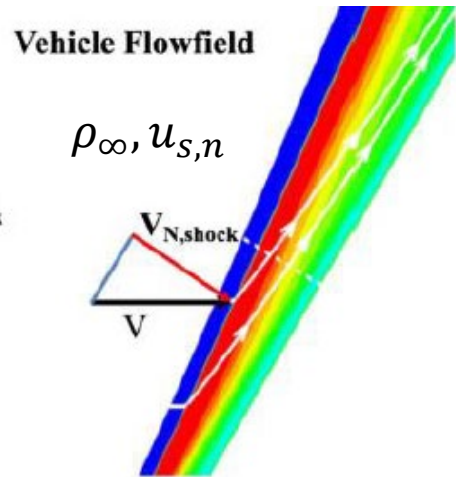
(a) B.A. Cruden – Absolute Radiation Measurements in Earth and Mars Entry Conditions – VKI Lecture series (2014)

(b) E. Chang et al. – AIAA paper 2023-2713

Similarity approach for aftbody radiative heating characterization in EAST

Shock Tube Informed Bias (STIB) for aftbody radiation^(a)

- Streamlines oblique to the shock are relevant for aftbody heating
- Similarity in particle time found behind both a normal and oblique shocks with the same normal velocity
- The tangential velocity component increases the applicable test time. Binary scaling can further increase it
- Expansion not captured in shock tube, but aftbody radiation is dominated by emission close to the shock



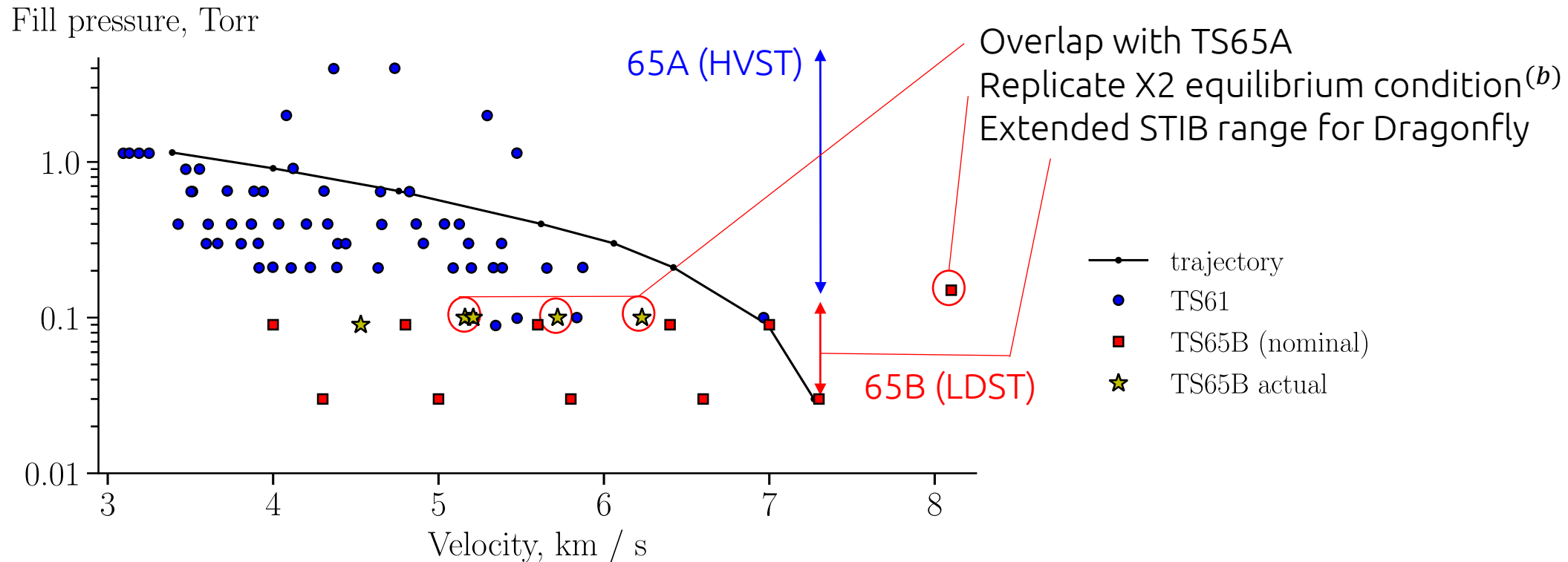
Figures reproduced from (a,b)

(a) Johnston C.O. – JTHT 35 (2) 2021

(b) Johnston C.O. – AIAA 2022-2396

Test series 65B overview

- Mixture: 97.8% N₂/ 2.2% CH₄ → upper bound for Titan^(a)
- Test time scales as $\sim pD^2 \rightarrow$ LDST allows measurements at lower fill pressures
- Fill pressure 0.03/0.09 Torr, velocity 4-7.2 km/s
- Shots completed targeting overlap with TS65A at 0.1 Torr around 5.2 km/s

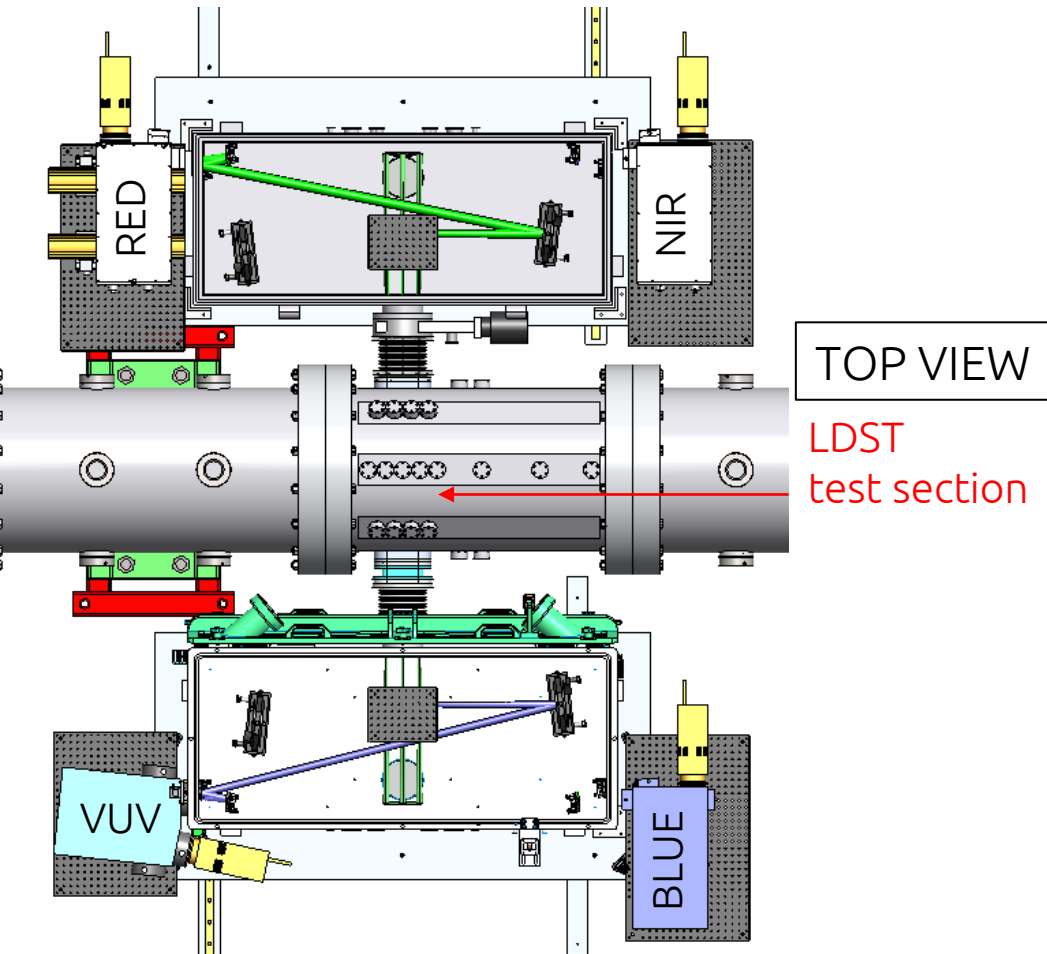


Emission spectroscopy setup

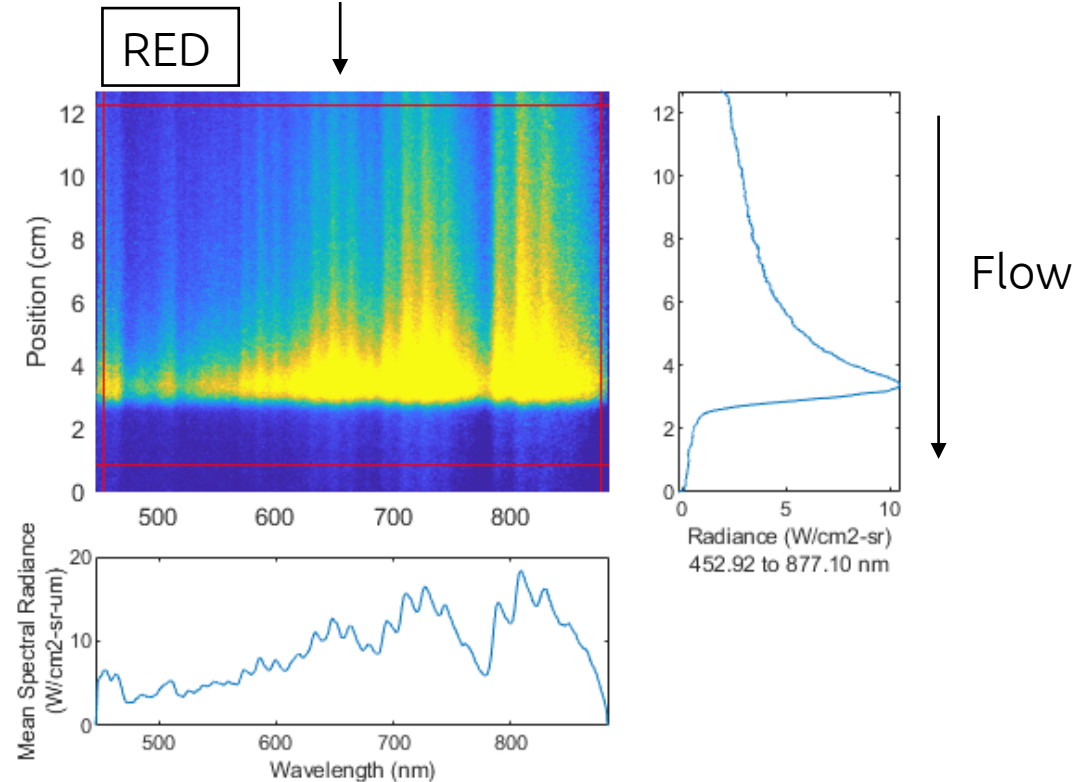
VUV to NIR emission spectrometers

CN Red ($A \rightarrow X$) and CN Violet ($B \rightarrow X$) dominant, C_2 (Swan), N_2

	VUV	UV	Vis/NIR	NIR
Range [nm]	170-390	330-500	500-880	970-1390
Resolution [nm]	1.74	1.2	4.2	7.0

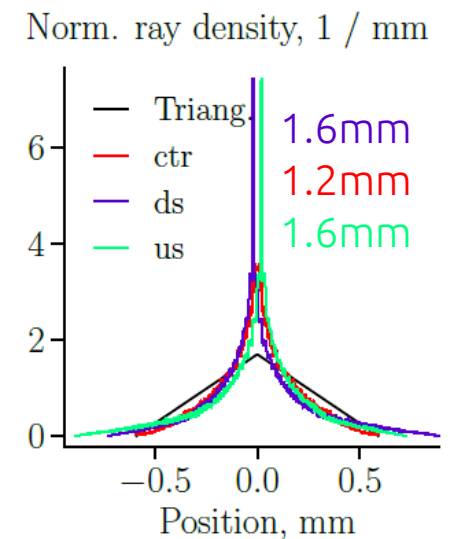
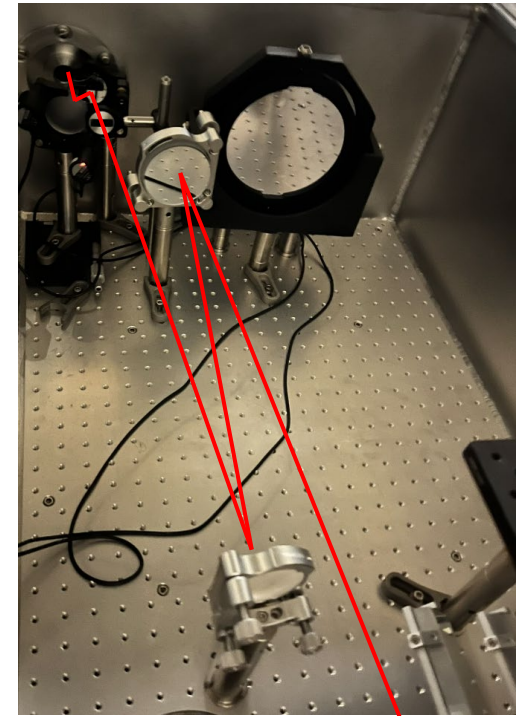
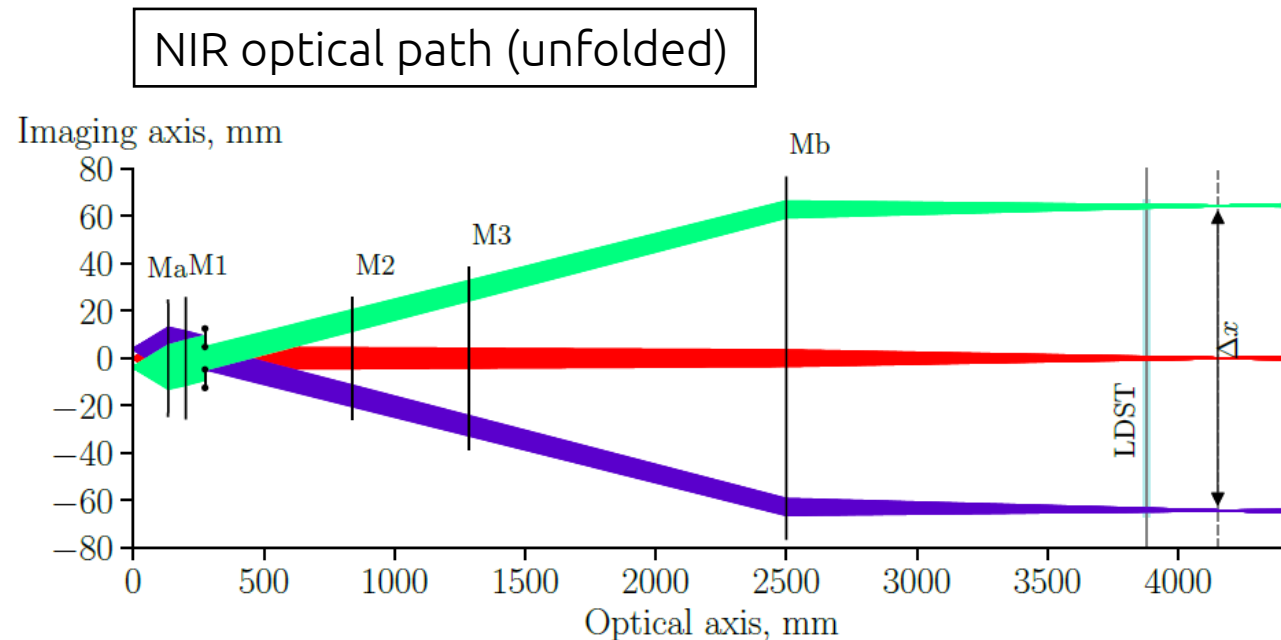
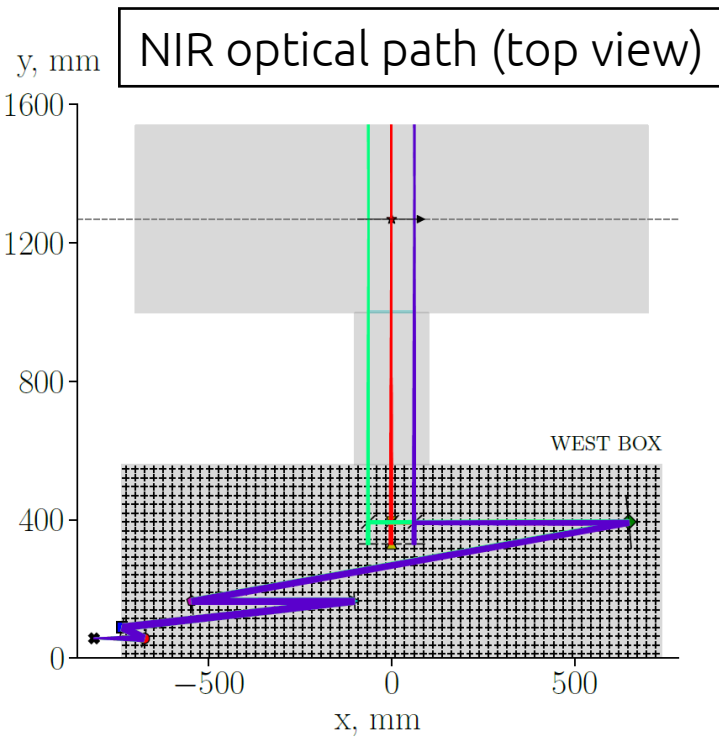


Line-of-sight radiance $L(\lambda, y)$
across tube diameter



Improved optics to optimize spatial resolution of NIR

- Telecentric optics previously installed for VUV-Vis during EAST major update
- New NIR $f = 2.3$ m primary mirror
+ increased optical path length between powered mirrors for near telecentricity
- Near telecentricity achieved, with similar optical resolution to VUV-Vis
~1.6 mm base width/~10x improvement with respect to telescopic on LDST



Modeling

DPLR/NEQAIR

- Similarity: centerline shock tube flow/stagnation line flow into a blunt body at steady state
- Multi-temperature with 21 species - 36 reaction kinetics (Gokcen^(a) + correction for reaction #21^(b))
- Non-Boltzmann (Electronic CR at Quasi Steady-State (QSS) regime)

Transformation to exp. particle time is required to account for differences in post-shock flow velocities^(c)

$$u(x) = \frac{\rho_\infty u_\infty}{\rho} \left(1 - \sqrt{\frac{x}{\Delta_m}} \right)$$

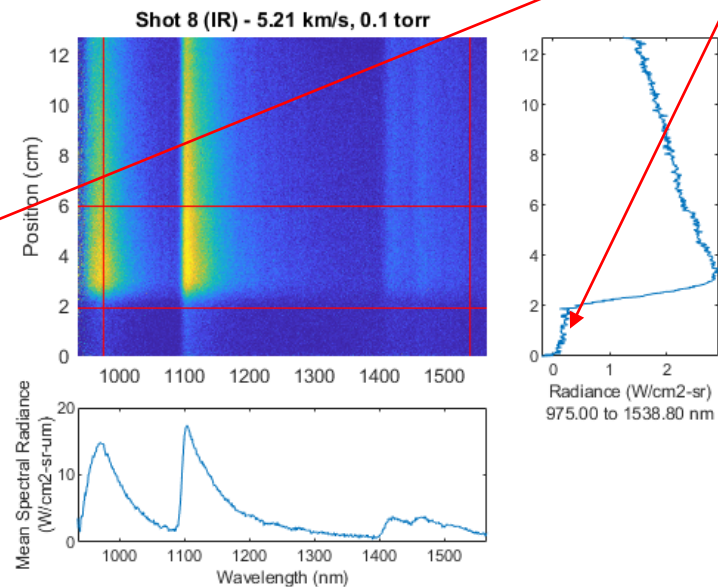
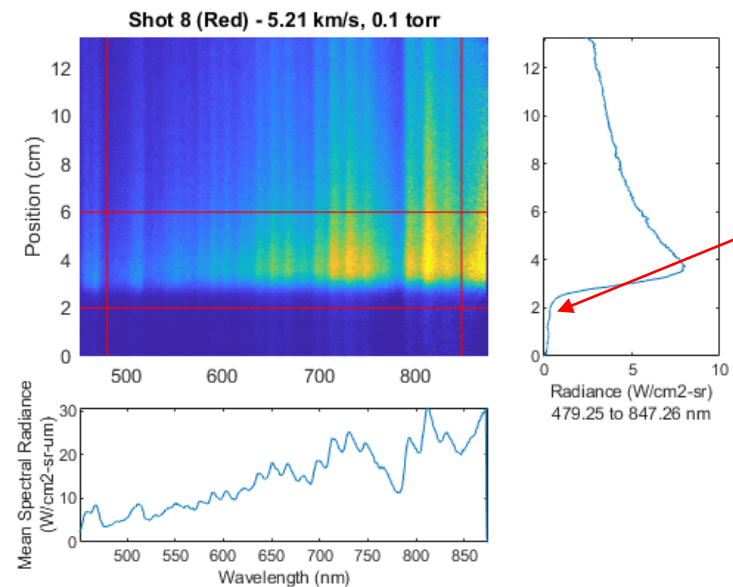
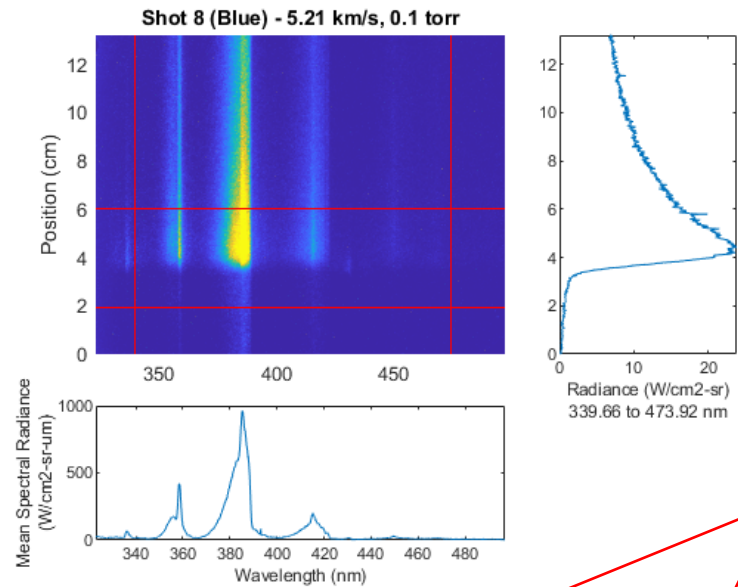
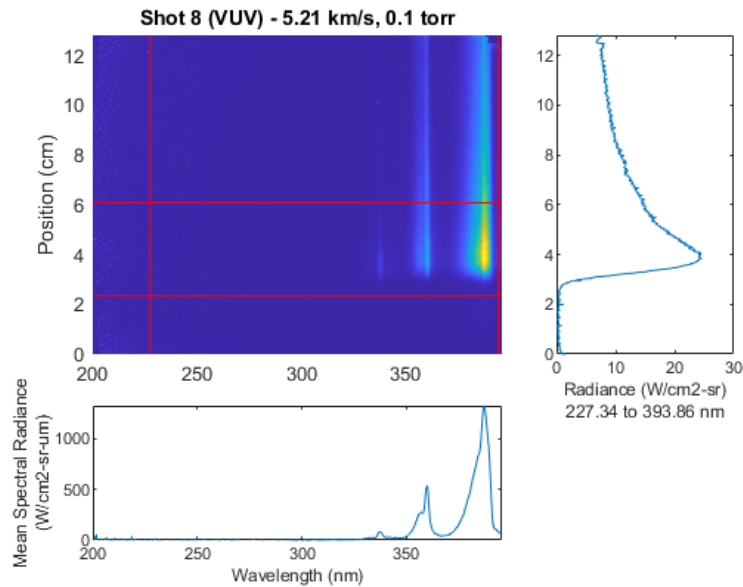
Mirels length^(d) : $\longrightarrow$ $\Delta_m = \frac{D}{16\beta^2} \left(\frac{\rho_0}{\rho_{w,0}} \right)^2 \frac{u_0}{u_\infty - u_0} \frac{u_0}{v_{w,0}}$ $\longleftarrow$ Post-shock conditions approximated at equilibrium (upper bound for Δ_m)

distance between shock and contact surface at steady-state
 $t \approx \int 1/u \, dx$

(a) Gokcen – JTHT 2007 / (b) Johnston et al. - AIAA 2019-3010

(c) Clarke et al. – JTHT 2023 / (d) Mirels – Phys Fluid 1963

LDST data overview

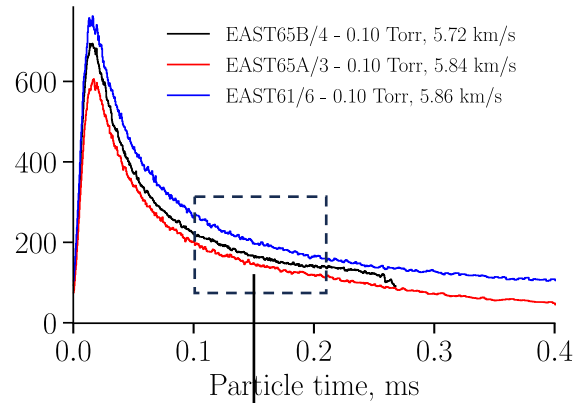


- No significant contamination observed Al, Fe, or Cr (driver gas)
Na, Ca or K (test gas)
- Long test times realized
- Higher signal-to-noise ratio compared to 4" shock tube (2.5x on visible range)
- Significant signal ahead of shock observed on Red/IR
- Large path length, long test slug, and recently manufactured surface likely contribute to diffuse reflection

Comparison to previous HVST data

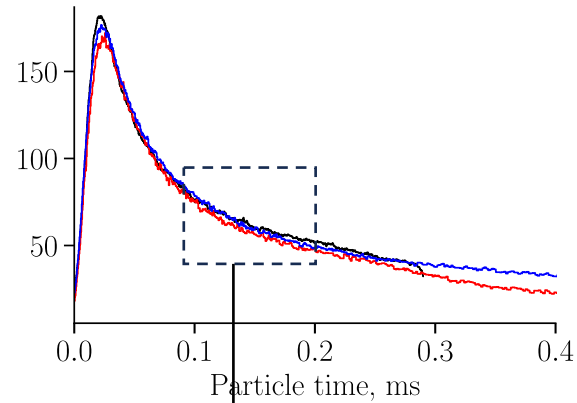
“VUV”

Vol. radiance [330:392nm], mW / (cm³ sr)



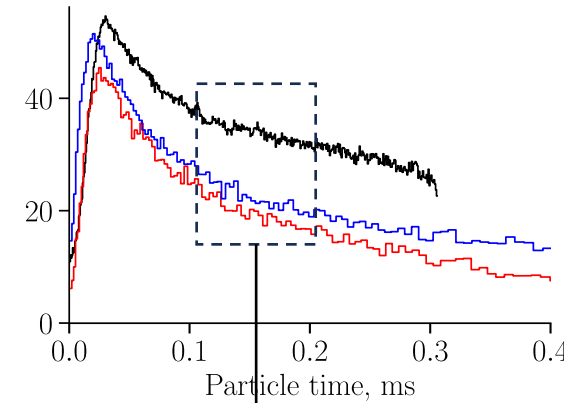
“Red”

Vol. radiance [500:880nm], mW / (cm³ sr)



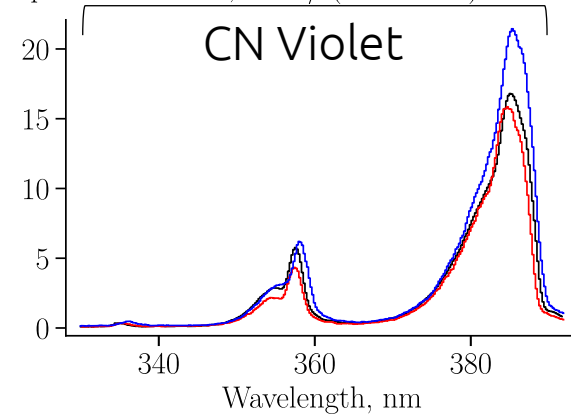
“NIR”

Vol. radiance [970:1390nm], mW / (cm³ sr)

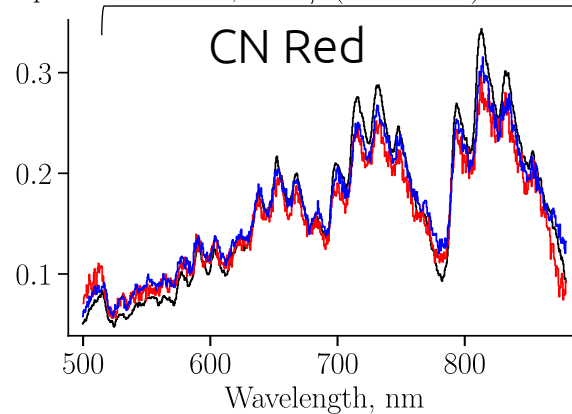


- Radiance is scaled by tube diameter for comparison
- Predicted self absorption accounts for ~20% diff. below 500 nm, negligible above
- “Red” data are consistent
- “VUV” data: 65A/3 lower quality calibration reported, self absorption would bias towards larger intensity than 61/6
- “NIR” possibly affected by larger diffusely reflected signal, to be further investigated on larger data set

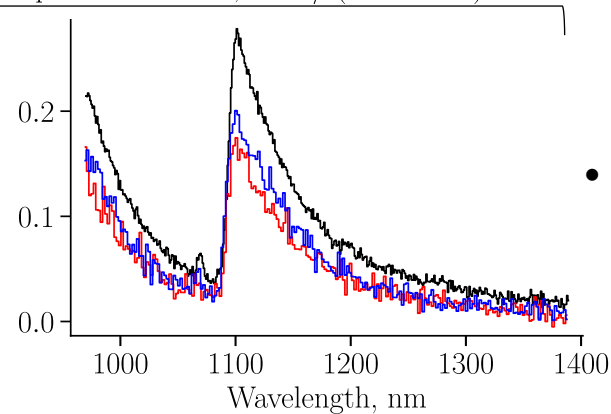
Spectral radiance, mW / (cm³ nm sr)



Spectral radiance, mW / (cm³ nm sr)

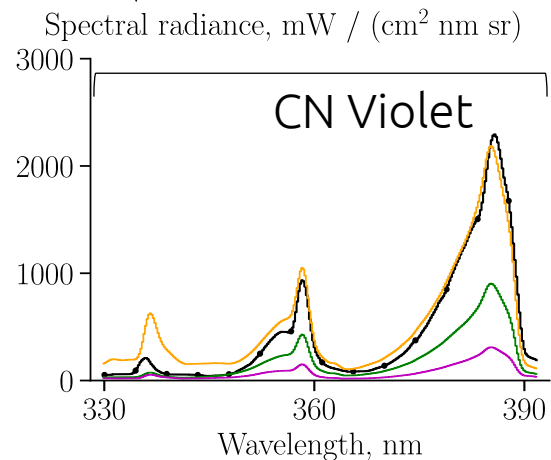
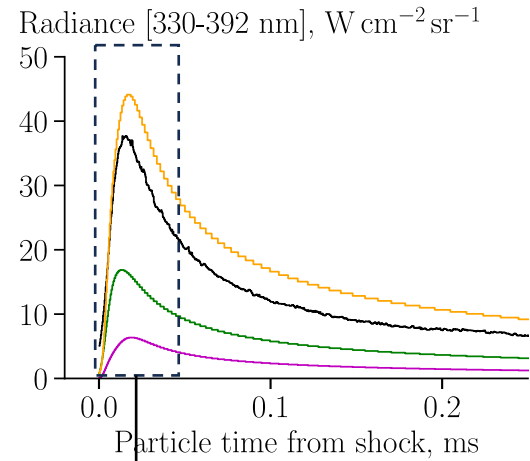


Spectral radiance, mW / (cm³ nm sr)

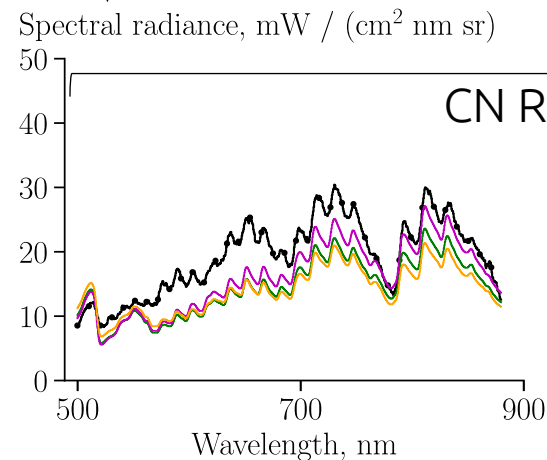
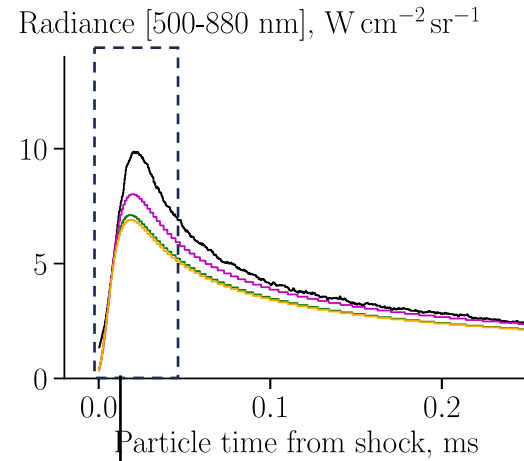


Comparison to DPLR + NEQAIR at 0.1 Torr, 5.72 km/s

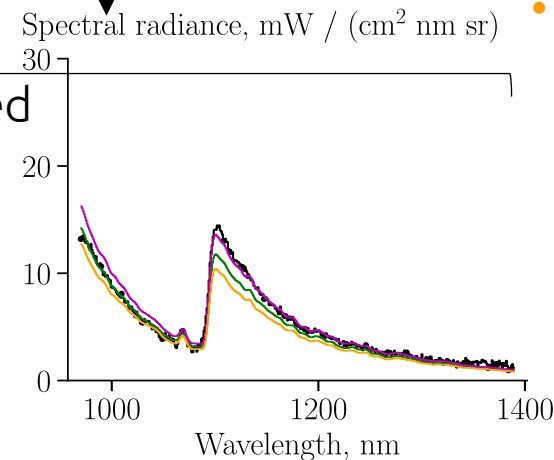
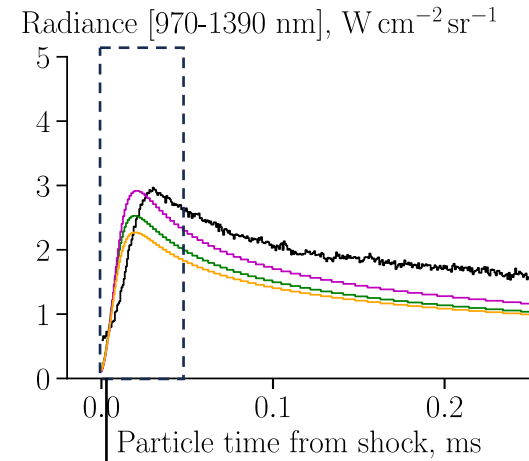
"VUV"



"Red"



"NIR"

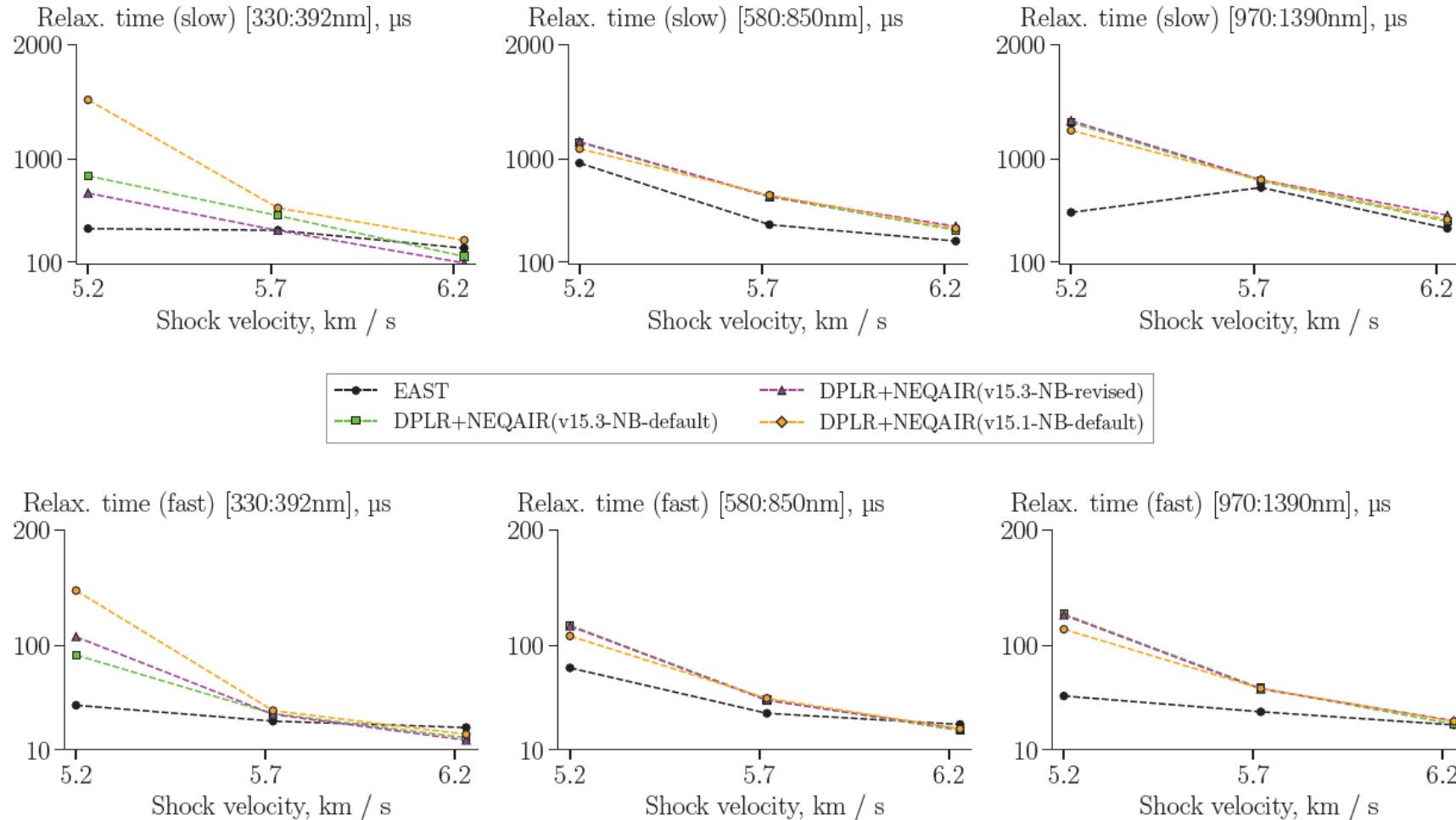


- Measured radiance
- DPLR+NEQAIRv15.3 (default QSS rates)
-2x on CN Vio/ -1.3x on CN Red
- DPLR+NEQAIRv15.3 (revised QSS rates)
Electron exc./diss. rates are larger
Heavy particle dissociation included
CN Red improved/CN Vio largely off
- DPLR+NEQAIRv15.1 (default QSS rates)
different exc. rate computation
large impact on CN Violet
effect on CN Red less relevant

Relaxation times

$$\frac{I - I_{\text{eq}}}{I_{\text{max}} - I_{\text{eq}}} = \alpha \cdot \exp(-t/\tau_1) + (1 - \alpha) \cdot \exp(-t/\tau_2)$$

↑



- Assumed functional form provides good fit and allows extrapolation to larger particle times
- Characteristic times separated by about 10x:
faster thermal relaxation, followed by slower chemical relaxation
- Predicted values typically larger, but trends are consistent

Conclusions and future work

- New LDST inaugurated in September 2024
Ongoing TS65B to characterize radiative heating bias for Dragonfly's entry at Titan
- Slower post-shock flow deceleration/Increased test time/increased SNR
Diffuse reflection effects on OES to be monitored/stronger self absorption predicted
- Quantitative comparison to HVST observed
need for further data to resolve discrepancies in UV and NIR

Conclusions and future work

DPLR/NEQAIRv15.3 at 0.1 Torr, 5.2-6.2 km/s:

- CN Violet (UV) underpredicted through $\sim 250 \mu\text{s}$ from shock by at least 2x
- CN Red (Vis) underpredicted by $\sim 1.3\text{x}$ before $100 \mu\text{s}$, decreasing error towards larger particle times
- Revised non-Boltzmann rates improve CN Red and degrade CN Violet predictions
- NEQ radiance underpredicted/relaxation times overpredicted, but trends are consistent

NEQAIRv15.1: consistent results with previous findings

NEQAIRv15.3: improvements supported by TS65A and TS65B

underprediction at 0.1 Torr extends towards larger particle times than higher pressures
currently under investigation

Future work:

Extend STIB + calibration study of CN excitation model in NEQAIR

Combine OES with LAS measurements (scanned/broadband)

Thank you for your attention!

Questions?

Acknowledgements

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