

Laser Absorption Measurements of CN(X) Population and Temperature Evolution in the Low Density Electric Arc Shock Tube

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Accurate prediction of radiation from the cyano radical (CN) during Titan entry is a priority for NASA's Dragonfly mission. In order to validate predictions, previous tests conducted at NASA Ames' Electric Arc Shock Tube (EAST) facility explored low altitude/high density trajectory conditions. For this work, conditions relevant to higher altitudes of Titan entry trajectory were investigated with the new Low Density Shock Tube (LDST) at EAST. Experiments were conducted with test gas 2.2% by mole methane in nitrogen, fill pressures ranging from 0.03 to 0.1 Torr, and shock velocities from 3.8 to 7.6 km/s. A multi-pass diagnostic utilizing tunable diode laser absorption spectroscopy (TDLAS) measured multiple absorbance features of the CN red system around 927 nm and 1128 nm, from which the gas temperature and ground state CN number density were inferred. Measurements suggest close temperature agreement with simulations by the Data Parallel Line Relaxation code (DPLR), and close agreement with CN number density at high incident shock velocities, but exhibit appreciable deviations at low shock velocities, the lowest pressures, and in time periods of thermal non-equilibrium. Additionally, these ground state measurements provide an important benchmark for analyzing non-Boltzmann behavior in the excited electronic states of CN, and aid in the gasdynamic characterization of the LDST.

I. Nomenclature

A	=	integrated area
A_{ul}	=	Einstein A coefficient between u and l
c	=	speed of light
E_{int}	=	internal energy
g	=	state degeneracy
I_0	=	initial intensity
I_t	=	transmitted intensity
J	=	quantum number for total angular momentum
k_B	=	Boltzmann's constant
l	=	lower state
L	=	laser pathlength
M	=	molar mass
n	=	number density

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Q_{int}	=	internal partition function
t	=	time
T_a	=	geometrically averaged temperature
T_e	=	electronic temperature
T_{tr}	=	translational/rotational temperature
$T_{trans.}$	=	translational temperature
T_v	=	vibrational temperature
u	=	upper state
U	=	shock velocity
u	=	velocity
x	=	position
α	=	absorbance
Δ_m	=	Mirels' characteristic length
ν	=	frequency
ν_0	=	center frequency
ρ	=	density
ρ_∞	=	freestream density

II. Introduction

Titan, the largest moon of Saturn, possesses a dense nitrogen atmosphere enriched with complex organic chemistry and an active methane cycle analogous to Earth's hydrologic system [1]. Its surface temperature lies near the triple point of methane, enabling hydrocarbon lakes, clouds, rainfall, and dunes that collectively shape Titan's landscape [2]. Observations have also revealed direct evidence of a subsurface water ocean, potentially stabilized by ammonia and tidal forcing [3]. These characteristics make Titan one of the most compelling locations in the Solar System for investigating prebiotic chemical pathways [4], and even for extraterrestrial life [5]. Motivated by this scientific opportunity, the Dragonfly mission, which is led by the Johns Hopkins University Applied Physics Laboratory and scheduled for launch in 2028, will deploy a rotorcraft lander that leverages Titan's low gravity and dense atmosphere to perform controlled flights between sampling sites [6]. The mission aims to characterize the moon's methanogenic cycle, analyze the composition and evolution of organic material relevant to prebiotic chemistry, and assess possible interactions between the surface and the underlying ocean.

During the delivery of the rotorcraft, the capsule will experience significant heating during its hypersonic atmospheric entry trajectory. In order to adequately design the Thermal Protection System (TPS) for the craft, accurate characterization and prediction of this heating is needed. While the heating on the forebody of the craft has historically been the focus of validation experiments [7][8], radiation on the aftbody has been identified as significant and requiring further characterization [9]. In the Titan atmosphere the cyano radical CN is expected to dominate this radiative flux [10], since the methane is easily dissociated and reacts quickly with the abundant nitrogen.

III. Background

The need for accurate prediction of CN radiative heating has motivated extensive experimental campaigns, in particular at the Electric Arc Shock Tube (EAST) facility at NASA Ames Research Center, which generates and probes shockwaves representative of those generated during Titan entry. Early measurements in EAST experimental campaigns termed Test Series 43 and 45 [7] provided detailed observations of CN radiation under Titan-relevant conditions. Test Series 43 is suspected to have suffered from calibration issues and contamination, while Test Series 45 was conducted prior to the arrival of the Huygens/Cassini mission and therefore explored a broad range of nitrogen-methane-argon mixtures reflecting the large compositional uncertainty at the time. The latter series also reported radiances significantly below model predictions, which it concluded was due to incorrect model representation of CN consumption.

Following major facility upgrades to EAST that improved calibration procedures and cleaning protocols, Test Series 61 was executed using a refined mixture of 1.5% CH₄ and 0.5% Ar in N₂ by mole, consistent with concentration expected from Huygens/Cassini measurements [11]. Test Series 61 produced radiance levels in much closer agreement with models, sometimes differing from earlier data by an order of magnitude, though discrepancies persisted in the decay behavior of the CN Violet (B²Σ⁺ → X²Σ⁺) system and the magnitude of the CN Red (A²Π → X²Σ⁺) emission. Overall, it was recommended that Test Series 61 supersede Test Series 45 for CN radiation under Titan entry conditions.

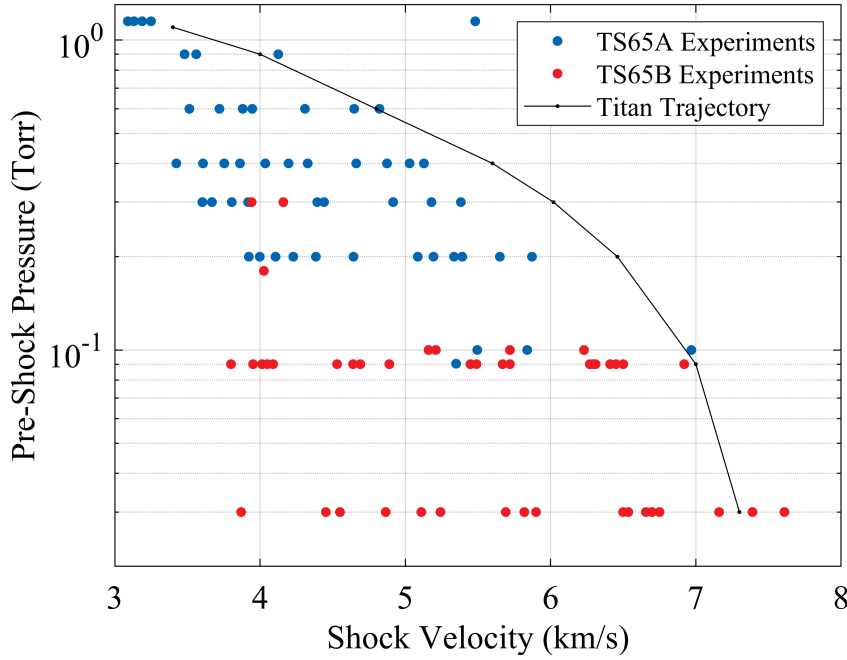


Fig. 1 Experimental conditions for the Titan test series conducted in the High Velocity Shock tube (TS65A) and the Low Density Shock Tube (TS65B).

Experiments similar to Test Series 61 have also been carried out at the University of Queensland in the X2 high-enthalpy shock tube, a piston driven facility [12] [13], and the TCM2 piston-driven facility at Université de Provence [14].

However, EAST Test Series 43, 45 and 61, as well as the work at the X2 and TCM2 only focused on conditions representative of the stagnation point radiation. In order to use shock tube data to analyze the radiation incident on the backshell of an entry vehicle, Johnston et al. developed the Shock Tube Informed Bias (STIB) technique [9]. This technique accounts for the fact that the forebody flow of an entry vehicle is characterized by a detached bow shock and a continuum of oblique shock angles rather than the normal shock geometry of the shock tube. These oblique shock angles can be analyzed using the normal shock relations when the incident velocity is replaced by its component normal to the local shock surface. Consequently, slower shock velocities in the tube correspond to more oblique angles between the incident flow and the shock. To determine the radiation from a specific aftbody location a streamline can be traced back to the shock, and the shock angle at its intersection point can be determined [15]. Assuming similar pressure evolution, the experiment with incident shock velocity corresponding to that normal component then describes the chemistry along that streamline and at that location.

To collect the necessary data for application of this technique, Test Series 65 has been conducted at EAST, with test conditions designed to replicate the range of post-shock states relevant to Titan atmospheric entry. Figure 1 shows a representative trajectory for the Dragonfly spacecraft. For the given ambient pressure expected along the trajectory, the test matrix was constructed to include velocities below the nominal trajectory speed, effectively sampling the range of normal velocities associated with the most probable shock orientations. Computational sensitivity analyses by Cruden et al. [16] were used to determine the distribution of normal velocities most influential to aftbody radiative heating, and these results informed the exact selection of conditions explored in the test series.

This test series was broken into two parts. Test Series 65A was previously conducted at EAST in the High Velocity Shock Tube (HVST) [17], with shock velocities from 3 to 7 km/s and fill pressures from 0.09 to 1.15 Torr. The test gas for this test was a mixture of 2.2% CH_4 in N_2 by mole, consistent with the latest upper bound of CH_4 in Titan atmosphere composition [18]. Measurements of CN were made using both Optical Emission Spectroscopy (OES) [17] and Tunable Diode Laser Absorption Spectroscopy (TDLAS) [19]. However, low pressure gasdynamic effects in the HVST limited the conditions to those expected during low altitude portions of the entry trajectory [20]. To analyze these experiments Tibere-Inglesse et al. [17] employed a non-Boltzmann model to characterize the excited

electronic states of CN. In that work, spectrally resolved radiance from both the CN Red ($A^2\Pi \rightarrow X^2\Sigma^+$) and Violet ($B^2\Sigma^+ \rightarrow X^2\Sigma^+$) systems were analyzed to infer temperature and number densities of the CN(A) and CN(B) states. Discrepancies between measured and predicted temperatures suggested the need for improved shock layer kinetic and excited state formation processes. The CN(A) population was found to remain approximately in Boltzmann equilibrium with CN(X) across the range of tested conditions, while CN(B) populations were underpredicted by as much as 40% at lower velocities and pressures. At higher temperatures and pressures, CN(X) agreed well with model predictions, though CN(B) continued to be underestimated. These results suggest that refinement of the current non-Boltzmann treatment of CN is necessary to achieve more accurate predictions of radiative heating in Titan entry environments.

In addition to the emission measurements, the TDLAS measurements of the ground state CN(X) provide an important benchmark to anchor estimates of Boltzmann populations of the upper states and inferences of excited state excitation kinetics. Chang et al. [19] utilized a laser targeting CN($A^2\Pi \leftarrow X^2\Sigma$) transitions around 926 nm while scan rates between 50 and 500 kHz were employed to resolve post-shock kinetics [19]. Comparisons between temperatures inferred from tunable diode laser absorption spectroscopy (TDLAS) and optical emission spectroscopy (OES) showed agreement within 5% across all conditions. However, at the lower velocity cases, experimentally inferred temperatures were approximately 20% higher than those predicted by kinetic simulations, suggesting incomplete relaxation to equilibrium. Consistent trends were also observed between CN number densities inferred from absorption and emission diagnostics, though CN formation at lower velocities occurred more rapidly than predicted by models.

This work presents the results of the TDLAS applied to the second part of the test series, Test Series 65B. This test series consisted of 59 experiments conducted in the Low Density Shock Tube (LDST) at EAST [21], again each with test gas 2.2% methane by mole in nitrogen. As shown in Figure 1, fill pressures for Test Series 65B ranged from 0.03 to 0.1 Torr and shock velocities were reached from 3.8 to 7.6. The measurements performed using OES are presented in a separate publication [22].

IV. Methods

A. Experimental Facility

In order to replicate the high-enthalpy conditions of reentry, EAST uses a capacitor bank to rapidly deposit up to 1.2 MJ through an electric arc into the driver section of a shock tube. The resulting expansion bursts a diaphragm and propagates a shock wave through an expansion nozzle into the driven section filled with the test gas. The post-shock conditions are calculated using shock velocity measured from pressure and emissions sensors, and the known initial gas mixture and pressure. For Test Series 65B, the Low Density Shock Tube (LDST) was used, since its large inner diameter of 54.31 cm increases test times at low pressures compared to the 10.16 cm HVST [23]. An earlier version of the LDST is described by Bogdanoff and Cruden [21], while the present version is discussed by Fagnani et al. [20].

Laser absorption measurements were made 16.1 m downstream of the driver, through two sets of opposing diagnostic ports positioned 90 degrees apart. Two Nanoplus lasers centered around 926 nm and 1128 nm were fiber coupled to a free space optical setup rigidly mounted to the tube. This setup is outlined in Figure 2. Silver coated mirrors and low profile 'D' mirrors are used to pass the beam either two or three times, effectively doubling or tripling the absorbance

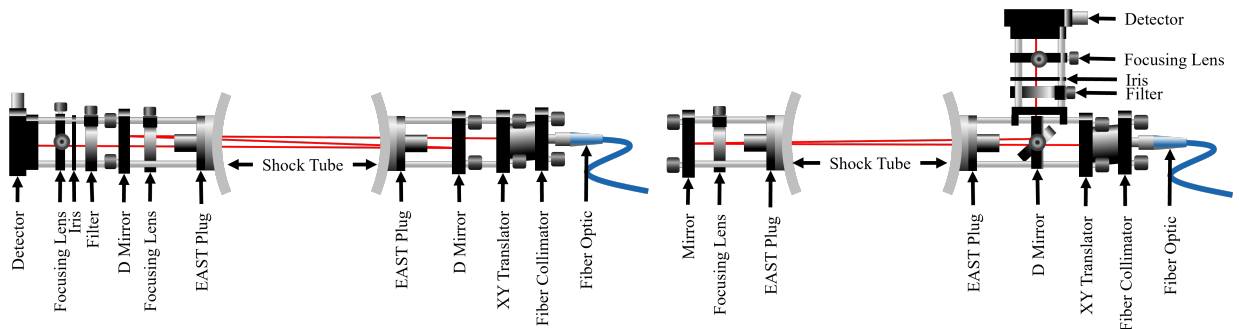


Fig. 2 Schematics of double pass (right) and triple pass (left) configurations for path length amplification through the LDST.

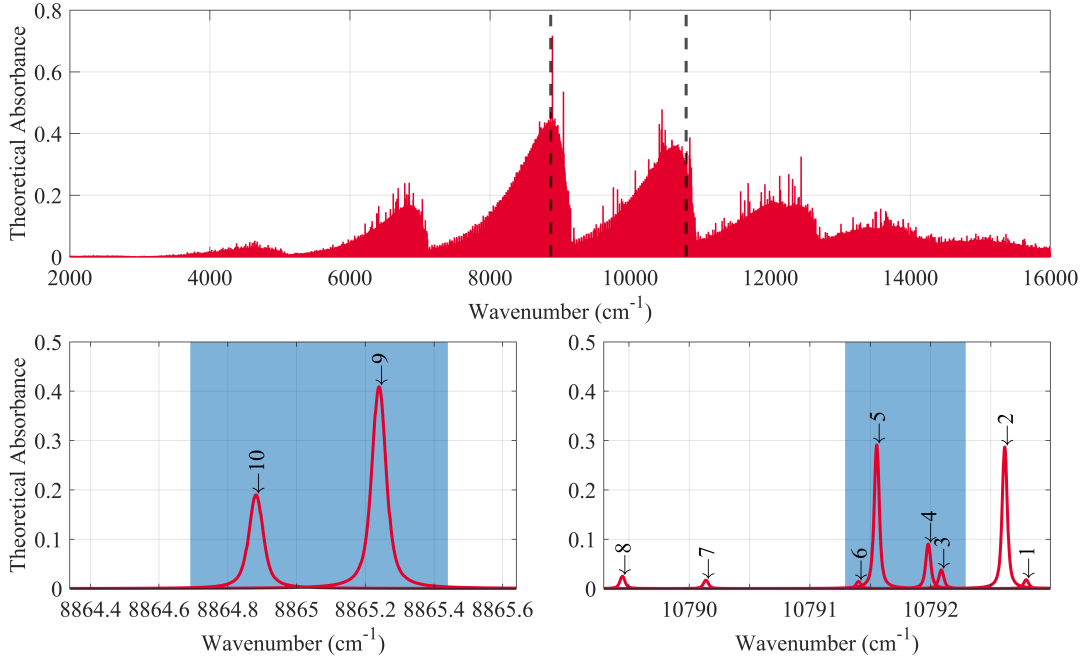


Fig. 3 Theoretical absorption spectrum for the CN Red System ($A^2\Pi \leftarrow X^2\Sigma^+$) at 7000 K, CN(X) number density of 1×10^{14} particles/m³, and pathlength of 108.62 cm (double pass). Bottom plots show the maximum scan range possible with each laser, and the shaded regions show the scan range possible at 1MHz.

level. At less than 2 nanoseconds, the increase in photon transit time is negligible. Additionally, irises and narrow bandpass filters are used to minimize gas emission onto detectors, and long focal length lenses periodically refocus the beams to keep spot size within 1 mm. The axial positions of the beams are maintained to within 5 mm to maintain high spatiotemporal resolution. Lasers are incident on Thorlabs detectors PDA10A2 or PDA10CF, which are sampled at 3 Gs/s and using a 12 bit Gagescope CSE123G2 card.

B. Diagnostic

This work utilizes the principles of tunable diode laser absorption spectroscopy to make non-intrusive, time-resolved measurements behind the incident shock parallel to the shock front. The basis for this spectroscopic sensor was developed by Chang et al. [24] in reflected shock tube experiments. The spectroscopic transitions selected in this work are shown in Figure 3 and the corresponding spectroscopic constants are taken from the ExoMol database and are detailed in table 2 [25–27]. The scan rate in Chang et al. was limited to 500 kHz by the response of the laser controller to the modulation current. However, this work extends the scan rate from 500 kHz to 1 MHz using a bias tee configuration following Nair et al. [28] to better resolve the CN kinetics at the EAST facility. A bias tee bypasses the limit on modulation frequency inherent to the laser controller, enabling direct modulation of the laser. This modulation current is supplied by a Playback PXDAC4800 card. The scan rate is now limited by the physical response of the laser, the frequency of which lags behind the modulated forcing function. This limits the available frequency range during high speed modulation. This effect is shown in Figure 3 - while all numbered transitions are available at modulation rates of 100 kHz, the frequency range during 1 MHz modulation is limited to the shaded region. This region was selected to preserve information from the highest J range possible in the closest proximity.

Figure 4a shows the signal collected by the detector as the laser is modulated through both intensity and frequency both with and without the characteristic dip in power due to a quantum absorption transition of CN. Raw detector signals were first filtered with a notch filter of quality factor 0.4 to remove periodic noise inherent to the photodiode electronics. This filter was centered at 125 MHz for the PDA10CF detector and 230 MHz for the PDA10A2. Background emission was corrected by fitting a cubic spline through the non-lasing portions of the signal and subtracting this fit from the raw data. A background scan was constructed by averaging the first ten laser modulation cycles and subsequently aligned to

Index	Vac. Wavelength	(v',v'')	Branch	J''	Einstein A (s ⁻¹)
1	926.545	(1,0)	<i>qR</i> ₁₂	21.5	4.1031 × 10 ³
2	926.560	(1,0)	<i>qQ</i> ₁	22.5	6.6520 × 10 ⁴
3	926.600	(1,0)	<i>pQ</i> ₁₂	14.5	1.2056 × 10 ⁴
4	926.610	(1,0)	<i>pP</i> ₁	15.5	2.8840 × 10 ⁴
5	926.640	(1,0)	<i>qQ</i> ₂	23.5	6.7043 × 10 ⁴
6	926.660	(1,0)	<i>qP</i> ₂₁	24.5	3.6345 × 10 ³
7	926.762	(1,0)	<i>oP</i> ₁₂	10.5	7.0596 × 10 ³
8	926.810	(4,2)	<i>pP</i> ₂	68.5	2.2546 × 10 ⁴
9	1128.001	(0,0)	<i>qQ</i> ₁	36.5	5.6726 × 10 ⁴
10	1128.012	(0,0)	<i>pP</i> ₂	28.5	2.7678 × 10 ⁴

Table 2 Spectroscopic parameters for the measured transitions of the CN (A²Π ← X²Σ) system [25–27]

each individual cycle. The absorbing and non-absorbing signals, I_t and I_0 respectively, give the absorbance α through the equation

$$\alpha(\nu) = \ln \left(\frac{I_0(\nu)}{I_t(\nu)} \right). \quad (1)$$

Signals were converted from the time domain to the frequency domain using the interference pattern through a Fabry-Perot etalon cavity of known length. Figure 4d presents one such coincident modulation cycle. Peaks within the etalon trace, separated by a known free spectral range corresponding to 0.1 cm⁻¹, provided calibration points for laser wavenumber. A spline was fit to describe the wavenumber as a function of time, enabling transformation of the absorbance data from the time domain to the frequency domain.

The final absorbance is plotted as a function of vacuum wavenumber for the transitions seen on the 1128 nm laser and the 926 nm laser in Figure 4b and 4c respectively. The specific quantum transitions are shown in Figure 3, detailed in Table 2, where the 1128 nm laser targets the (0,0) vibrational band of the CN Red System (A²Π ← X²Σ⁺) and total angular momentum quanta, J, of 28.5-36.5, while the 926 nm laser targets the (1,0) band and J of 14.5-23.5.

Each transition is broadened due to Doppler variance in apparent photon frequency, which presents as a Gaussian profile for each transition in Figure 4b and c. This broadening is a function of temperature through the Maxwell-Boltzmann velocity distribution, and the FWHM is described by

$$\Delta\nu_D = \nu_0 \left(7.1623 \times 10^{-7} \right) \sqrt{\frac{T_{trans.}}{M}} \quad (2)$$

where $T_{trans.}$ is in Kelvin and $M \approx 26$ is the molecular weight of CN in grams/mole [29]. Lines can also be broadened by the uncertainty in energy level introduced by perturbing collisional partners, which is described by a Lorentzian mode. The most widely used theoretical shape of a transition is the Voigt profile, which can account for both broadening modes of the transition. Typically these two broadening modes are convolved to form a Voigt profile which is fit to each transition. Here, it is assumed Gaussian broadening dominates due to the low pressure, so a Voigt profile is used with Lorentzian FWHM restricted to be less than 0.01 cm⁻¹. The fit results for a single scan of each laser are presented in Figure 4, and the area of each transition i can then be determined by integrating these absorbance fits,

$$A_i = \int_{-\infty}^{\infty} \alpha(\nu) d\nu. \quad (3)$$

This observed integrated area is a function of the strength of the transition and the population of the lower state and can be described by

$$A_i = n_{CN(X)} \frac{LA_{ul,i}g_{u,i}}{8\pi c\nu_{0,i}^2 Q_{int,CN(X)}} \exp \left(-\frac{E_{int,l,i}}{k_B T} \right) \left(1 - \exp \left(-\frac{\Delta E_{int,i}}{k_B T} \right) \right). \quad (4)$$

It is important to note that the last term, which accounts for stimulated emission from the upper state, assumes an upper state population in rovibronic equilibrium with the absorbing state. The validity of this assumption varied with the

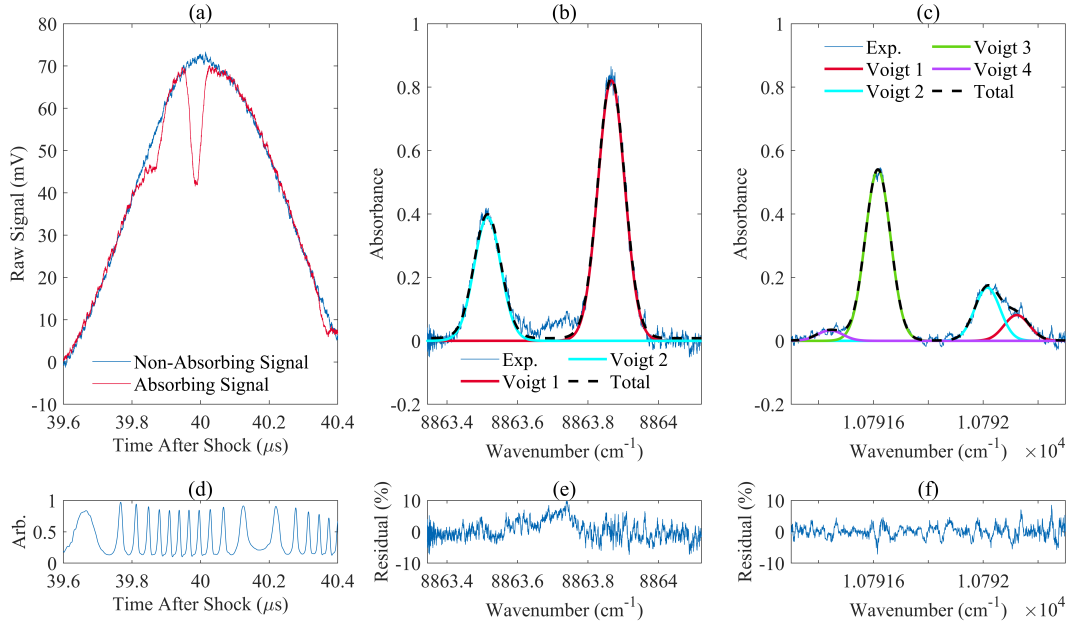


Fig. 4 a) Laser signal around 926 nm with and without the presence of CN in shot 40. d) Laser signal through a Fabry-Perot cavity. b) Absorbance signal for laser around 1128 nm and the fit Voigt profiles. e) Residual of profiles fit for 1128 nm laser. c) Absorbance and fits for laser around 926 nm. f) Residual for 926 nm laser.

degree of non-equilibrium. Of these variables, all except number density and temperature are known, either through the experimental setup or the spectroscopic parameters in Table 2. Two different methods were considered to infer temperatures and number densities. In the first, theoretical integrated absorbances were computed for each transition as a function of rovibrational temperature and CN(X) number density, and using this function these variables were inferred based on a weighted least squares fit to the measurements of all of the integrated areas following Finch et al. [30]. In the second, the temperature was constrained using the measured Doppler temperature and a weighted least squares fit was applied to extract the number density, with feature weights inversely proportional to the squared uncertainty of their fitted areas. The technique yielding the smallest overall uncertainty assumed rotational equilibrium with the translational temperature.

V. Results and Discussion

During Test Series 65B, 59 experiments were run, though some did not produce usable data due to challenges with maintaining shock planarity and timing of the trigger to the data acquisition systems. Fill pressures of 0.03 and 0.09 Torr are analyzed here, though larger pressures were sometimes used for diagnostic development. As stated previously, gas mixtures of 2.2% CH₄, 97.8% N₂ by mole were used for all shots since this is the expected upper bound for methane concentration in the Titan atmosphere [18], and therefore thought to produce the upper bound for emission.

A. Temperature and Number Density Inferences

As discussed previously, two complementary approaches were used to infer a temperature and CN(X) number density from the measured absorbance spectra. In the first approach, the rotational temperature and number density were fit simultaneously using all available transitions, an example of which is shown in black in Figure 5 for shot 40, in which a 4.01 km/s shock was incident on a 0.09 Torr fill. In the second approach, the translational temperature was obtained directly from the Doppler broadening of each transition, and this temperature was then used in equation 4 to independently infer the number density at the same time. The results of this Doppler-based method are shown in red in Figure 5. The two techniques produce consistent values during the period of uniform post-shock flow, but diverge significantly at early times ($t < 20 \mu\text{s}$) and again after approximately 150 μs . Number densities inferred from the two

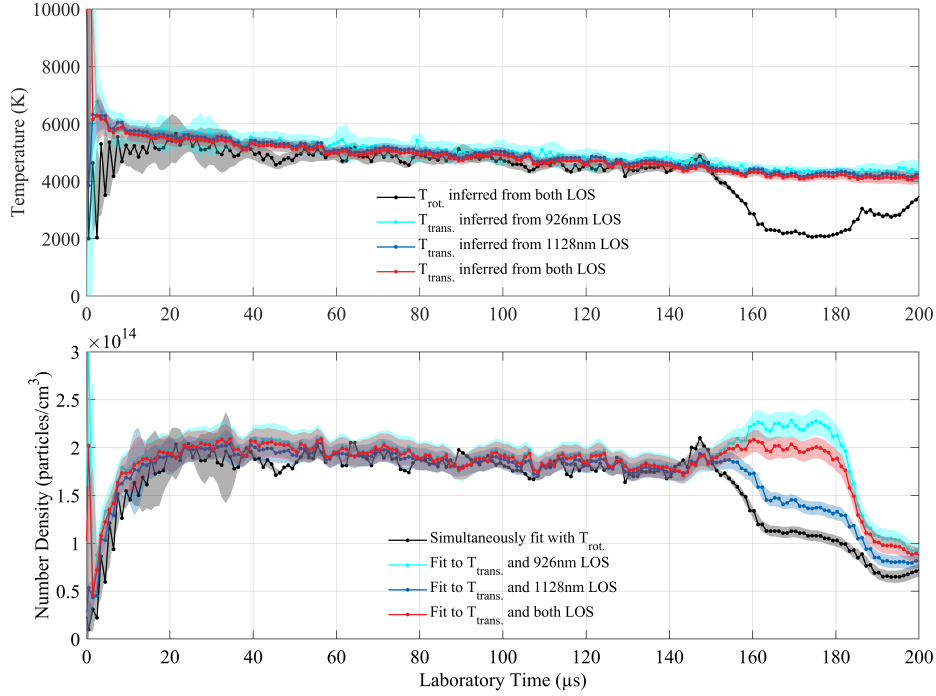


Fig. 5 Inferred temperature and CN number density results via four temperature inference methods along each line of sight and overall for Shot 40, in which a 4.01 km/s shock was incident on a 0.09 Torr fill.

methods also separate substantially in the late-time region.

To examine this divergence further each laser was analyzed independently by extracting the Doppler temperature and fitting the number density using only the transitions observed on that LOS. These independent inferences are shown in dark blue and cyan in Figure 5. The results indicate that the laser at 926 nm observes relatively larger apparent integrated areas than the 1128 nm. Because the spectrum near 926 nm contains transitions from lower rotational quantum numbers compared to the 1128 nm region, an inflation of these features causes the rotational-temperature fit to return an artificially low temperature. This, in turn, drives the simultaneously inferred number density downward, since the line strength of these transitions scales inversely with temperature.

This asymmetry between the two lines of sight may arise from several contributing factors. One possible explanation is spatially non-uniform mixing across the diffuse contact surface, which could introduce line-of-sight-dependent variations in CN number density. In addition, quenching of the CN(A) state within the contact region or finite excitation time immediately behind the shock would invalidate the assumption of rovibronic equilibrium implicit in the stimulated emission correction term in equation 4, leading to bias in the inferred ground-state population. A small timing offset between the two laser scans may also contribute, since the 1128 nm measurements are acquired slightly earlier than those at 926 nm during periods of rapidly increasing CN concentration.

Overall, while the rotational temperature fit provides a useful consistency check, for these experiments that use multiple lines of sight it is most reliable near equilibrium. For this reason, the Doppler-derived translational temperature, combined with number-density inference via equation 4, is adopted as the primary method for the results presented later in this work. Since the source of divergence between lines of sight is unknown, all datasets presented in this paper are truncated prior to this divergence.

B. Model Comparison

Following Chang et al. [19], Fagnani et al. [20], and Brandis et al. [31], the Data Parallel Line Relaxation (DPLRv4.05) code provides the baseline simulation of the shock chemistry in the EAST facility. It uses the reduced order chemical reaction mechanism presented by Gokcen [32] and corrected by Johnston et al. [9], as well as the

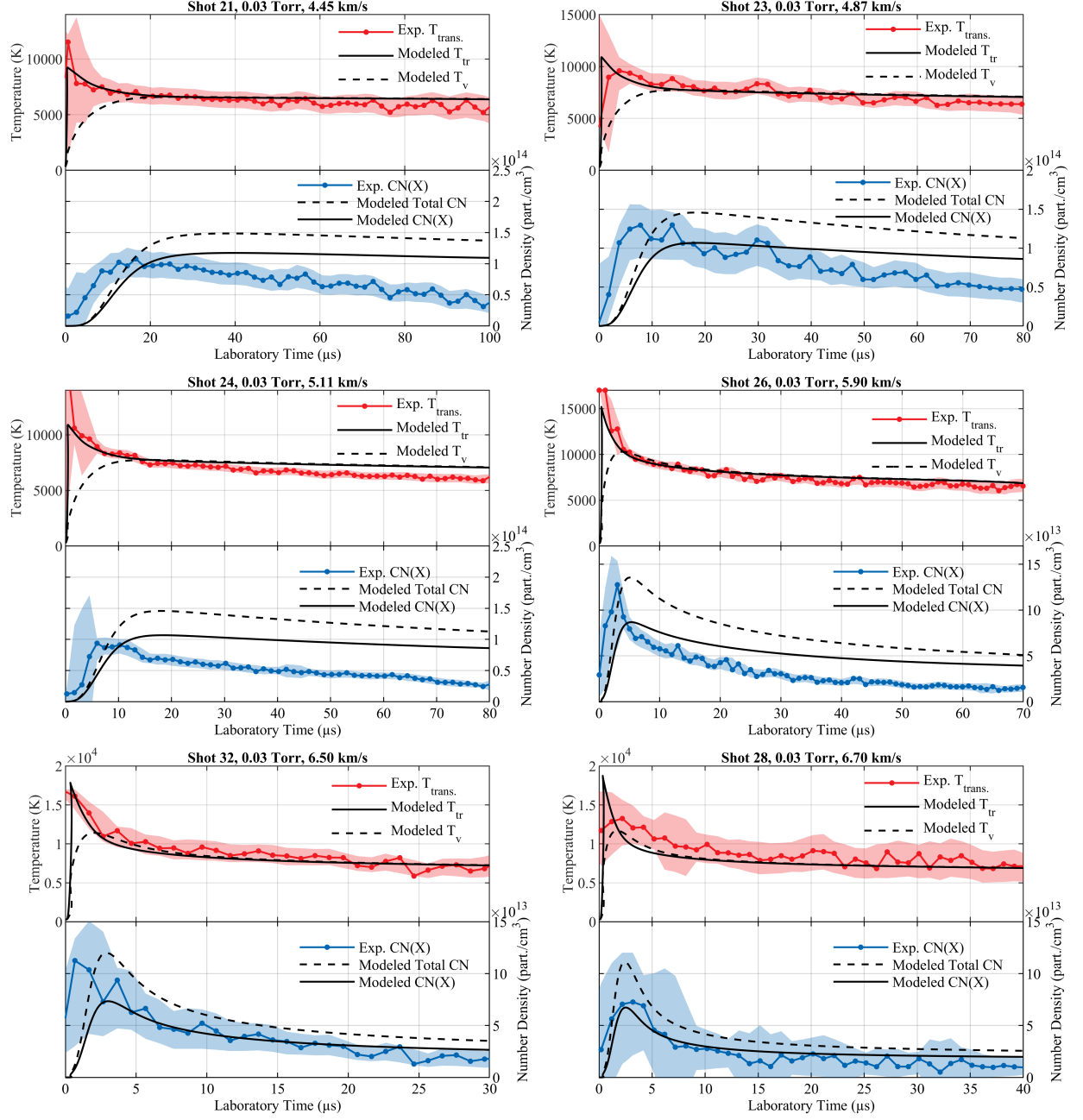


Fig. 6 Experimental translational temperature and CN(X) number densities for selected shots with 0.03 Torr fill pressures, and comparisons to those modeled using DPLR.

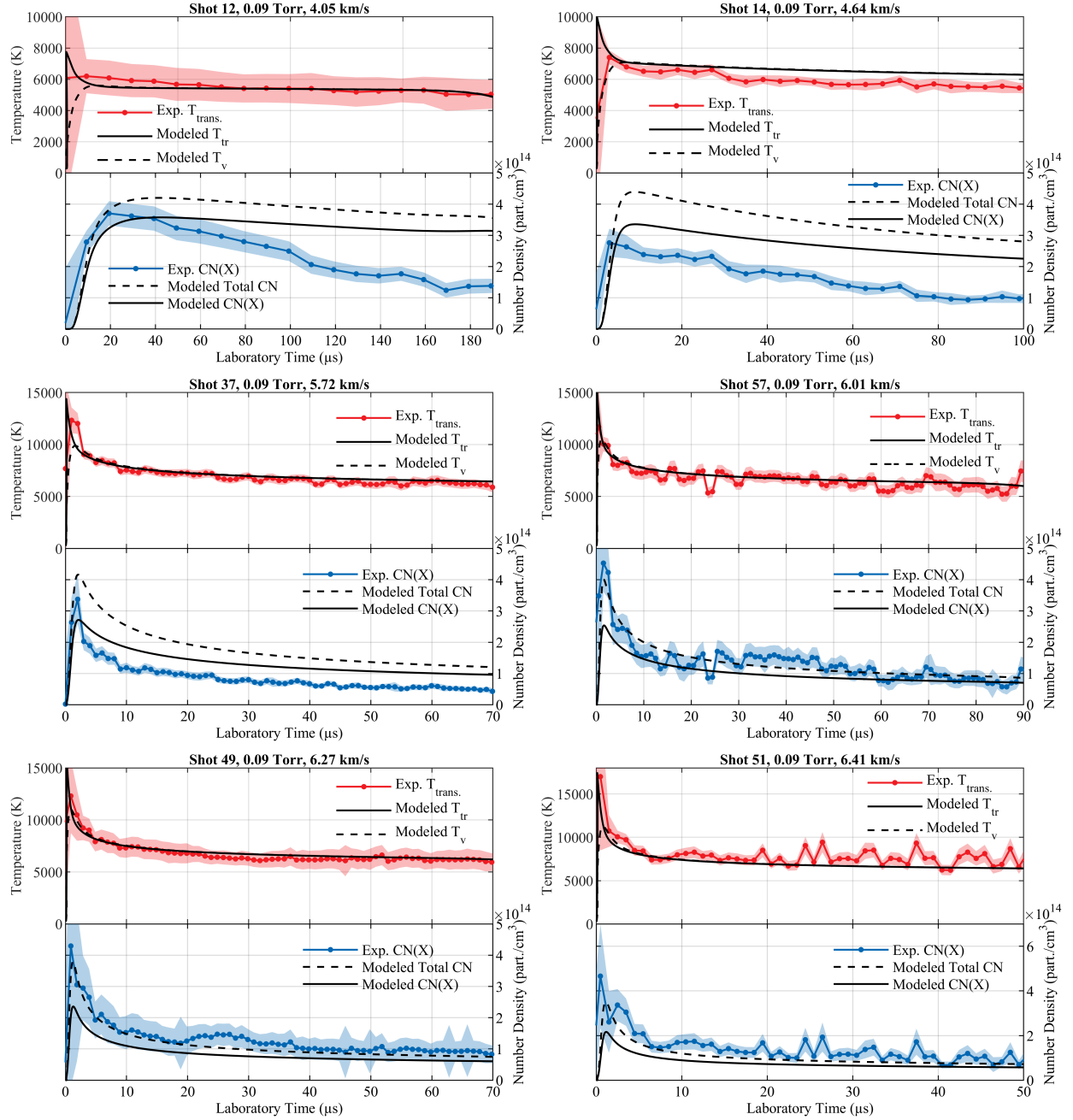


Fig. 7 Experimental translational temperature and CN(X) number densities for selected shots with 0.09 Torr fill pressures, and comparisons to those modeled using DPLR.

Bethe-Teller [33] relation and Milliken and White [34] correlation for vibrational relaxation of N_2 to compute time histories for translational and N_2 vibrational temperature, pressure, and species mole fractions. Comparisons between this model and the data assume similarity between the centerline flow of the shock tube and the stagnation line behind a bow shock over a blunt body. Typically a sphere with radius 3 m is used as the blunt body in order to create a large enough shock standoff distance to recreate the shock tube test slug. This approach is chosen because CFD can account for diffusive fluxes behind the shock wave, which helps better reproduce the non-equilibrium regime behind the shock. Further details for simulation are discussed by Fagnani et al. [20].

For processes that require fast model iteration, such as sensitivity analysis and rate fitting, a secondary model was constructed that assumes the accuracy of the translational and vibrational temperatures and the pressures output by DPLR. Since the test mixture is composed of 97.8% N_2 , these time histories are assumed to be dominated by nitrogen dissociation and vibrational relaxation, and are therefore largely indifferent to perturbations in other rates. This model uses Cantera to perform a 0D simulation of the Gokcen model with Johnston correction over time, at each time step setting the translational temperature and pressure of the simulation to that interpolated from the DPLR output. The model used a logarithmic time vector with number of points chosen with enough resolution to match the initial DPLR species time histories within 1%. Following the two-temperature modeling precedence of Park [35], dissociation reactions are presumed governed by $T_a = T_{tr}^{0.5} T_v^{0.5}$, recombination and exchange reactions are governed by T_{tr} , and the ionization reactions are governed by T_e which is assumed equal to T_v . This is implemented in Cantera through a corrective reaction rate multiplier applied at each time step to both the forward and reverse reactions. In order to do this, forward reactions are implemented as unidirectional reactions, while reverse rates are least squares fit to the non-Arrhenius form between 4000 K and 18,000 K and implemented as separate unidirectional reactions.

Since the DPLR model tracks variables as a function of distance along a stagnation line, the output must be converted into the laboratory time of the shock tube experiment for a proper comparison. To this end the particle time of the DPLR simulation, t_{DPLR} , is first calculated from the output post-shock velocity, u_{DPLR} and distance, x_{DPLR} through

$$t_{DPLR} = \int_0^{x_{DPLR}} \frac{1}{u_{DPLR}(x_{DPLR})} dx. \quad (5)$$

Next, the velocity of the test gas behind the shock wave in the tube is assumed to follow Mirels' approximation for steady state boundary layers [23]. This gives the correlation for the velocity of the post shock flow, u , as a function of the distance from the shock, x ,

$$u(x) = \frac{\rho_\infty u_\infty}{\rho} \left(1 - \sqrt{\frac{x}{\Delta_m}} \right), \quad (6)$$

where ρ_∞ and u_∞ are the freestream density and velocity respectively, and Δ_m is a characteristic distance described by Mirels [23]. Given these relations and the shock velocity U , laboratory time t_{lab} satisfies

$$t_{DPLR} = U \int_0^{t_{lab}} \frac{1}{u(Ut)} dt, \quad (7)$$

Selected laboratory time histories of translational temperature and CN(X) number density are presented in Figs. 6 and 7 along with comparisons to the converted DPLR model. Figure 6 corresponds to experiments conducted at a fill pressure of 0.03 Torr, while Figure 7 shows results at 0.09 Torr. Both figures span a sweep of incident shock velocities covering the range tested in this campaign. At early times, the inferred temperatures exhibit large uncertainties due to the weakness of the observed transitions; when CN concentration is low, the absorption features are shallow and difficult to resolve above detector noise, leading to poor constraints on the Doppler width. The shaded temperature bounds in each plot reflect the 2-sigma uncertainty of the least-squares fit to the Doppler-broadening component of the Voigt profile. For number density, the shaded bounds represent a worst-case envelope generated by combining the upper or lower limits of the transition integrated areas with the corresponding bounds on temperature in equation 4.

Variation in uncertainty between experiments arises in part from the differing CN concentrations produced under each condition, with higher CN levels providing stronger absorption features and reduced uncertainty. Additional variability resulted from gradual window fouling, as soot deposition on the optical windows attenuated laser power and reduced the signal-to-noise ratio. Periodic cleaning was required, but the process disrupted the double- and triple-pass optical configurations and the time-intensive realignment was not always possible between successive shots.

A notable feature in the data is that the initial peak of the experimentally inferred CN(X) number density often exceeds the Boltzmann-based ground-state prediction and, in many cases, aligns more closely with the total CN prediction from

the model. This behavior is consistent with the finite excitation times of CN electronic states - if the higher states have not had time to excite, the ground state will be overpopulated compared to the equilibrium Boltzmann fraction. The translational temperature generally matches, within uncertainty, the initial decay of the modeled temperature and tracks its evolution throughout the test time. Exceptions are observed for shots 24 and 14, where the experimental temperature falls below the modeled temperature at later times. This depressed temperature may contribute to the decay of CN for these experiments in addition to the chemical reactions.

Despite these localized deviations, the overall agreement between experimental and modeled temperature lends confidence to the comparison of experimental and simulated CN number densities. Across the full data set, the modeled CN(X) population shows the best agreement with experiment at higher shock velocities for both fill pressures. For both the 0.03 Torr and 0.09 Torr cases, however, the model tends to overpredict at late test times and this discrepancy is exacerbated with decreasing shock speed. This may indicate the presence of a CN removal reaction that becomes important at lower temperatures but is not adequately captured in the current model. Additionally, for the 0.03 Torr cases, the initial CN production occurs faster and with less of an induction time than the model predicts. This time period corresponds to the post-shock vibrational non-equilibrium zone, as evidenced by the divergence of T_{tr} and T_v . This large amount of non-equilibrium time after the shock is unique to these lowest pressure experiments since the collisional frequency is low at these conditions, and is increased with the lower temperatures of lower shock speeds. This indicates that vibrational non-equilibrium at these low pressures may have a more apparent effect on the CN production reactions than is currently modeled.

VI. Conclusions

Tunable diode laser absorption spectroscopy was applied in the EAST Low Density Shock Tube to produce time-resolved measurements of CN(X) population and translational temperature under the low-pressure, oblique-shock-relevant conditions of Test Series 65B. The rapid tuning rates, multi-pass configurations and added spectral content enabled resolution of CN formation and relaxation dynamics across a broad sweep of shock velocities and fill pressures. Comparison of multiple inference strategies demonstrated that Doppler-based temperature extraction, coupled with line-area-based number-density fitting, provides the most reliable characterization of the flow during periods of thermal equilibrium and uniform post-shock conditions. Analysis of the two optical paths further identified a potential criterion for determining the kinetically meaningful test time.

Across the dataset, measured temperatures generally follow the modeled temperature decay, supporting the use of DPLR-derived thermodynamic histories for subsequent kinetic evaluation. However, systematic discrepancies in CN(X) population were observed, particularly at lower shock velocities and lower fill pressures. The model commonly overpredicts late-time CN(X) population and underpredicts the rapid onset of CN(X) formation at the lowest pressures, suggesting missing or inaccurately parameterized CN removal pathways and an underrepresentation of vibrational non-equilibrium effects during the extended low-pressure relaxation period. These findings reinforce earlier indications from Test Series 65A that refinement of the reduced-order Titan kinetic mechanism is needed to accurately capture CN chemistry over the full range of entry-relevant shock conditions.

The measurements presented here provide a new benchmark for evaluating and improving nonequilibrium CN kinetics under the lowest-density conditions central to Dragonfly aftbody radiative-heating predictions at high altitude. Ongoing work will integrate these results with complementary OES measurements and sensitivity analyses to guide targeted updates to the kinetic model and to improve confidence in radiative-heating estimates for Titan entry.

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