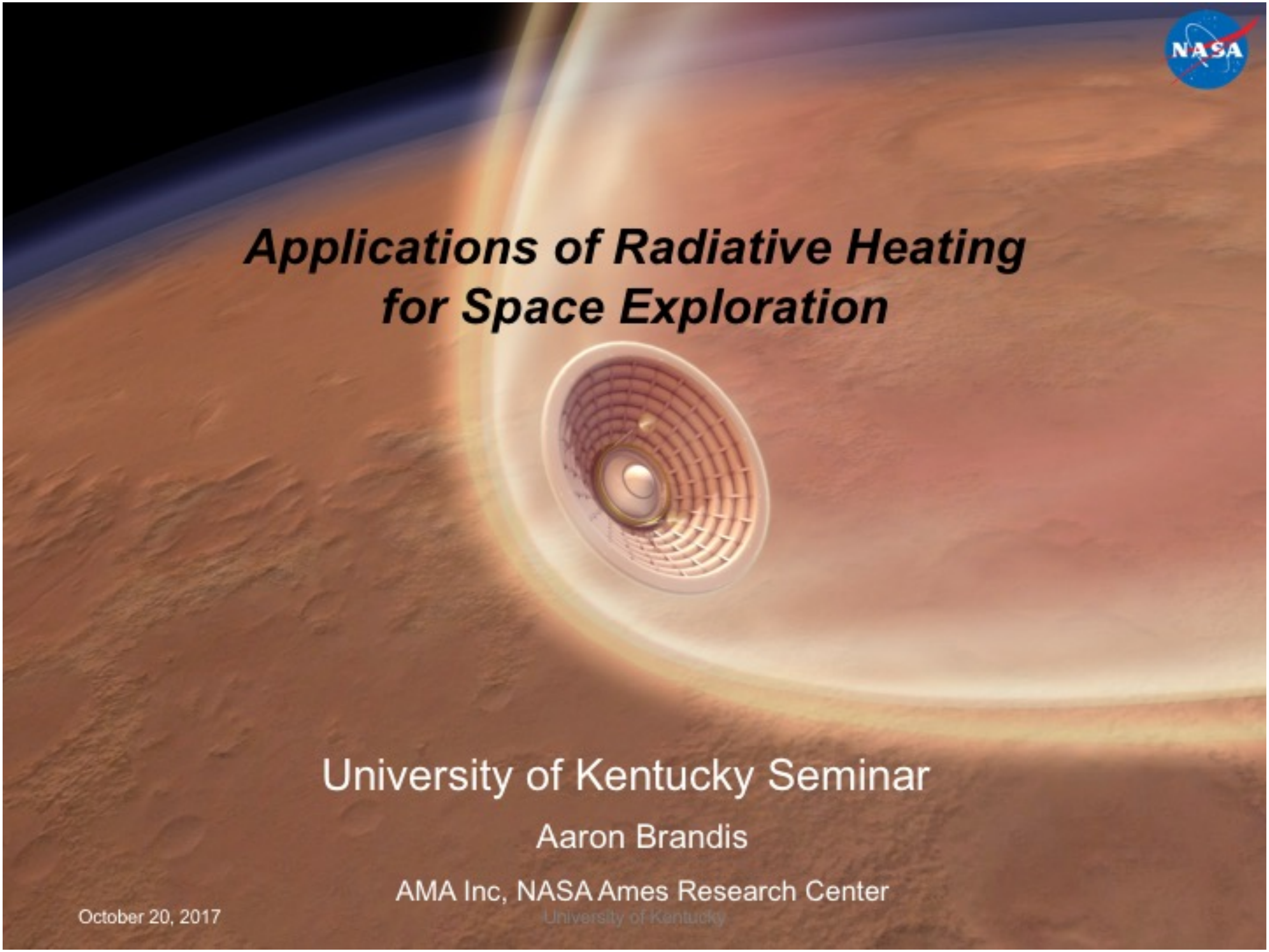


Applications of Radiative Heating for Space Exploration

University of Kentucky Seminar

Aaron Brandis

AMA Inc, NASA Ames Research Center

What is radiative heating?

- When the gas in front of the vehicle gets shocked to a high temperature, it will radiate energy resulting in heating of all surfaces.

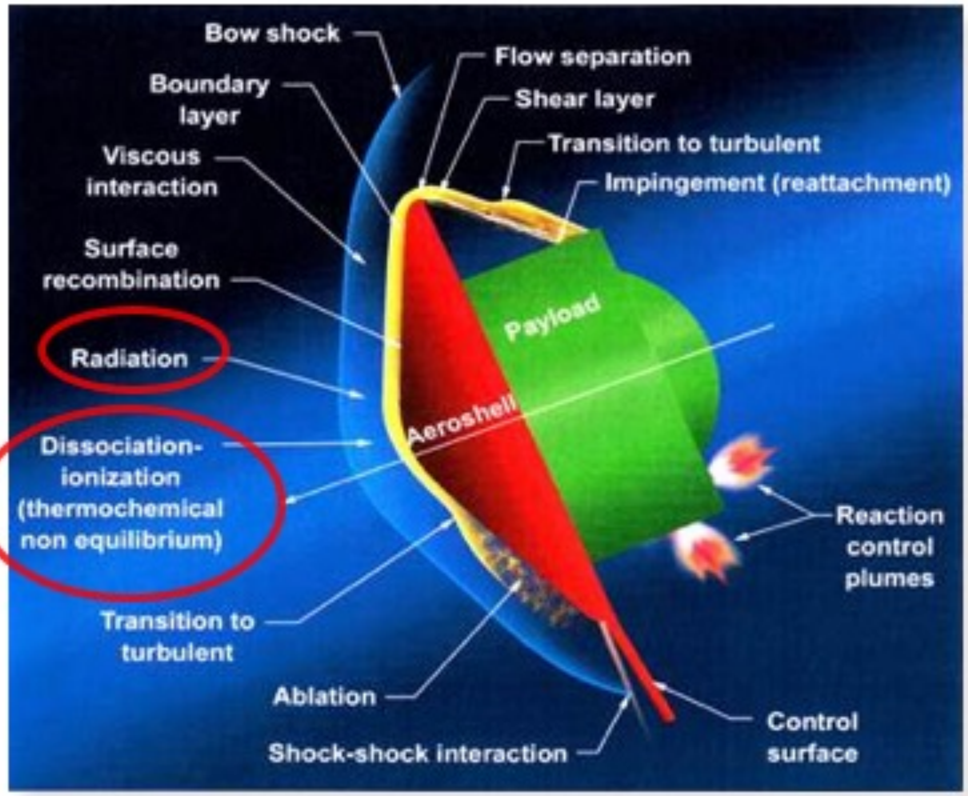
When is radiative heating most relevant to flight?

- When vehicles are larger, entering at faster speeds, radiative heating increases exponentially

Why do we care about radiative heating?

- Understanding radiative heating is critical for designing the heat shield and Thermal Protection System to ensure that the vehicle does not burn up and the mission is successful

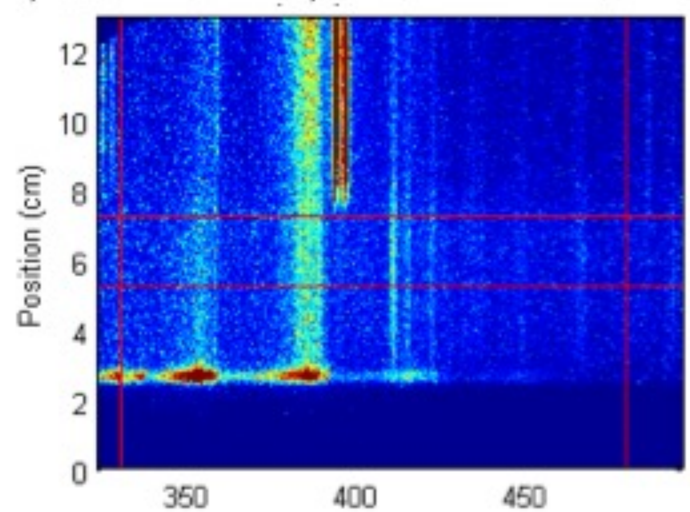
Complex Aerothermal Environments



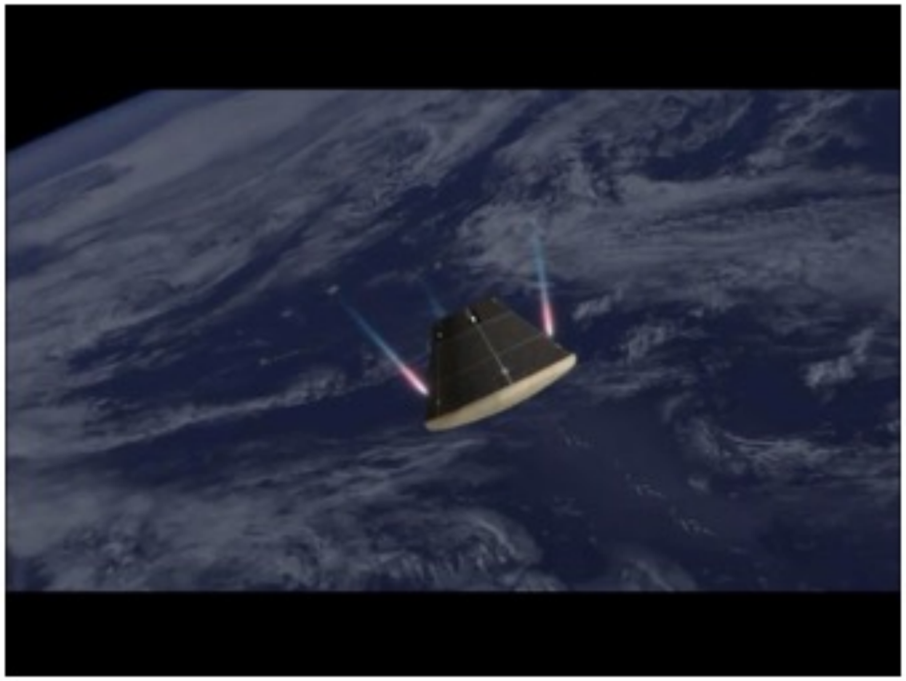
- Complicated multi-physics problem to be solved with time and length scales that vary by many orders of magnitude
- Successful spacecraft design relies on many research groups working together across inter-connected disciplines

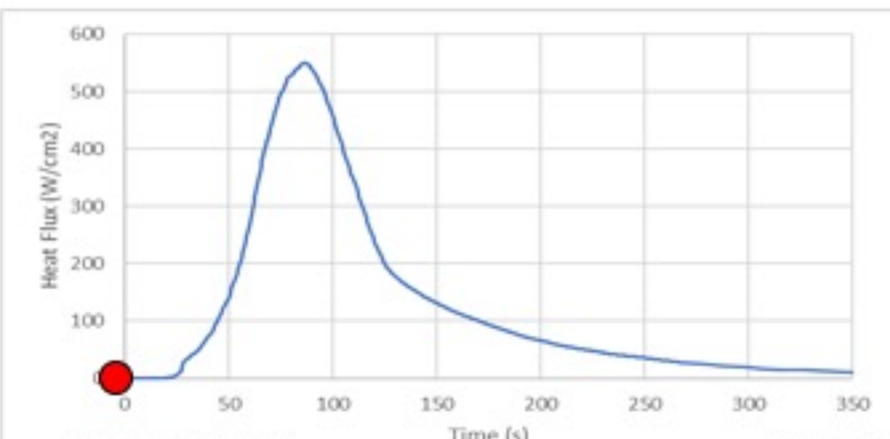
Shock Layer Radiation at NASA Ames

- Background: Complex aerothermal and thermochemical phenomena of planetary entry define convective and radiative heating. A spacecraft's TPS mitigates heat transfer to substructure. Successful TPS design relies on verifiable characterization of these phenomena in the anticipated flight environment.
- Approach: EAST simulates high-enthalpy, real-gas phenomena encountered by hypersonic vehicles entering planetary atmospheres by spectrally imaging a the flow behind a moving shock wave.
- Goal: Validate aerothermal models (DPLR & NEQAIR), inform model improvements, reduce uncertainty and quantify design uncertainties.
- Recent Relevant Projects: MSL & Mars 2020, InSight, OSIRIS-REx, Orion EFT-1 & EM-1 and New Frontiers



Re-entry Vehicles





Lunar Return : 11 km/s at Entry Interface

Peak Heating : 10.6 km/s, 60 km altitude
Mach ~30

Enthalpy, $h = \frac{1}{2} v^2 = 56$ MJ/kg

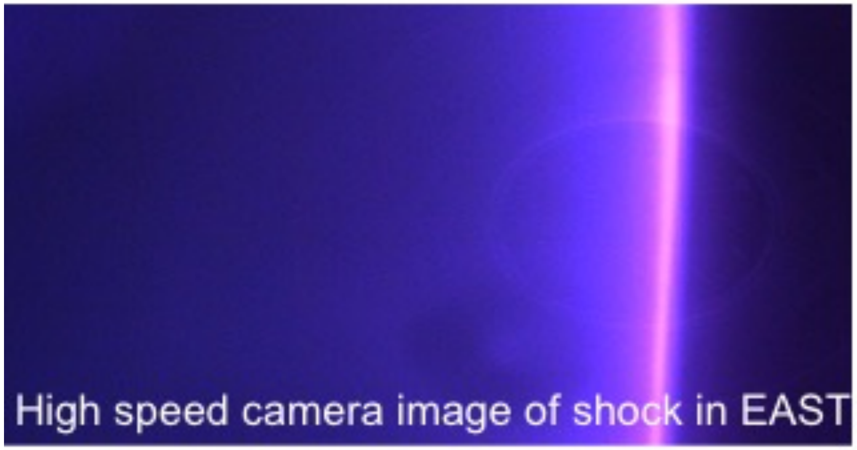
At 56 MJ/kg:
Equilibrium Temperature ~11,000K
Dissociation >99%
Ionization ~ 7%

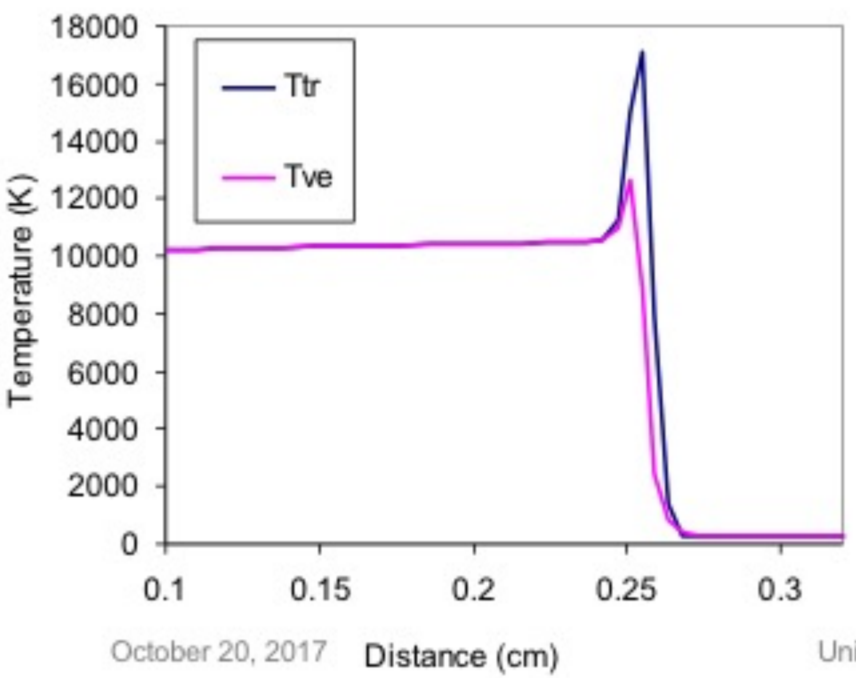
The plasma emits radiation

- Enthalpy, $h \sim v^2$
- Temperature $T \sim h \sim v^2$
- Radiation $q \sim T^4 \sim v^8$ (often higher power)

Up to half of heat flux at Lunar Return

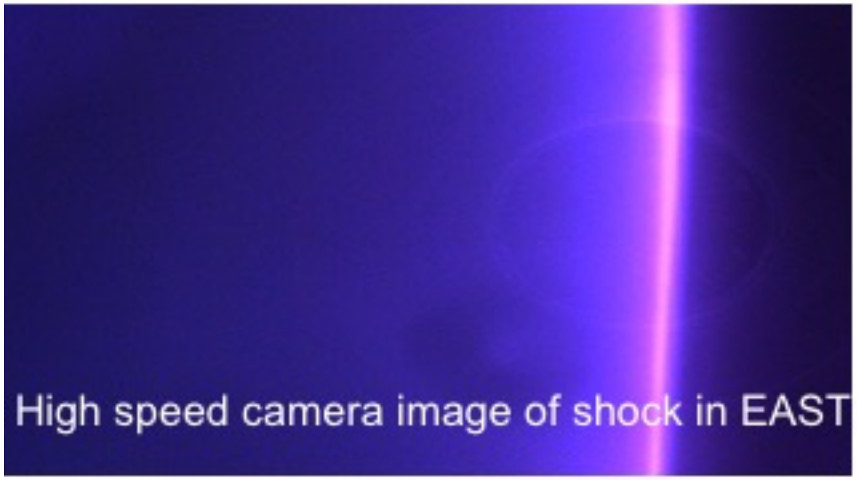
Thermal Non-equilibrium

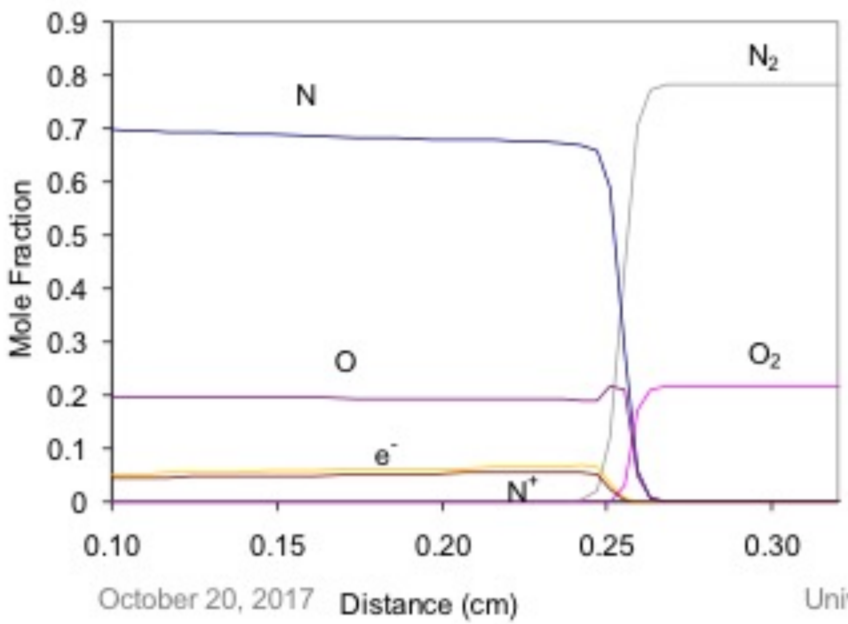




- Gas is not described by a single temperature (T)
- Usual approach is to assume two temperatures:
  - $T_r = T_t = T$
  - $T_v = T_e = T_{electron}$
- Lumping temperatures in this way makes for a more computational tractable problem
  - However, can be source of discrepancies for non-equilibrium radiation

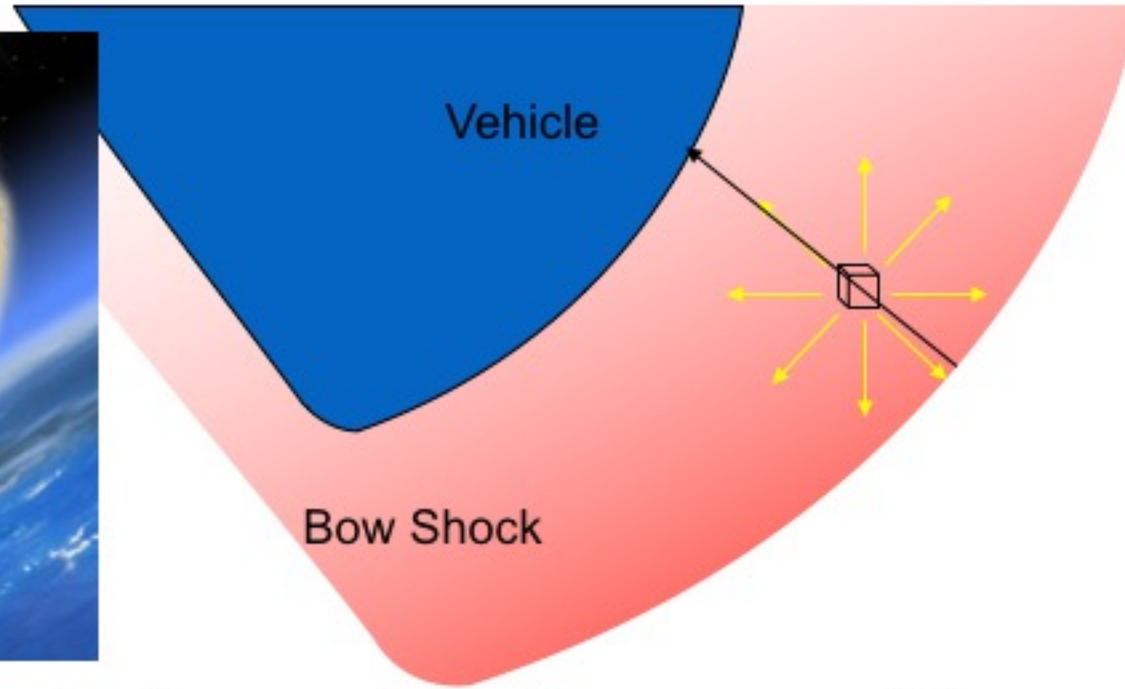
Chemical Non-equilibrium





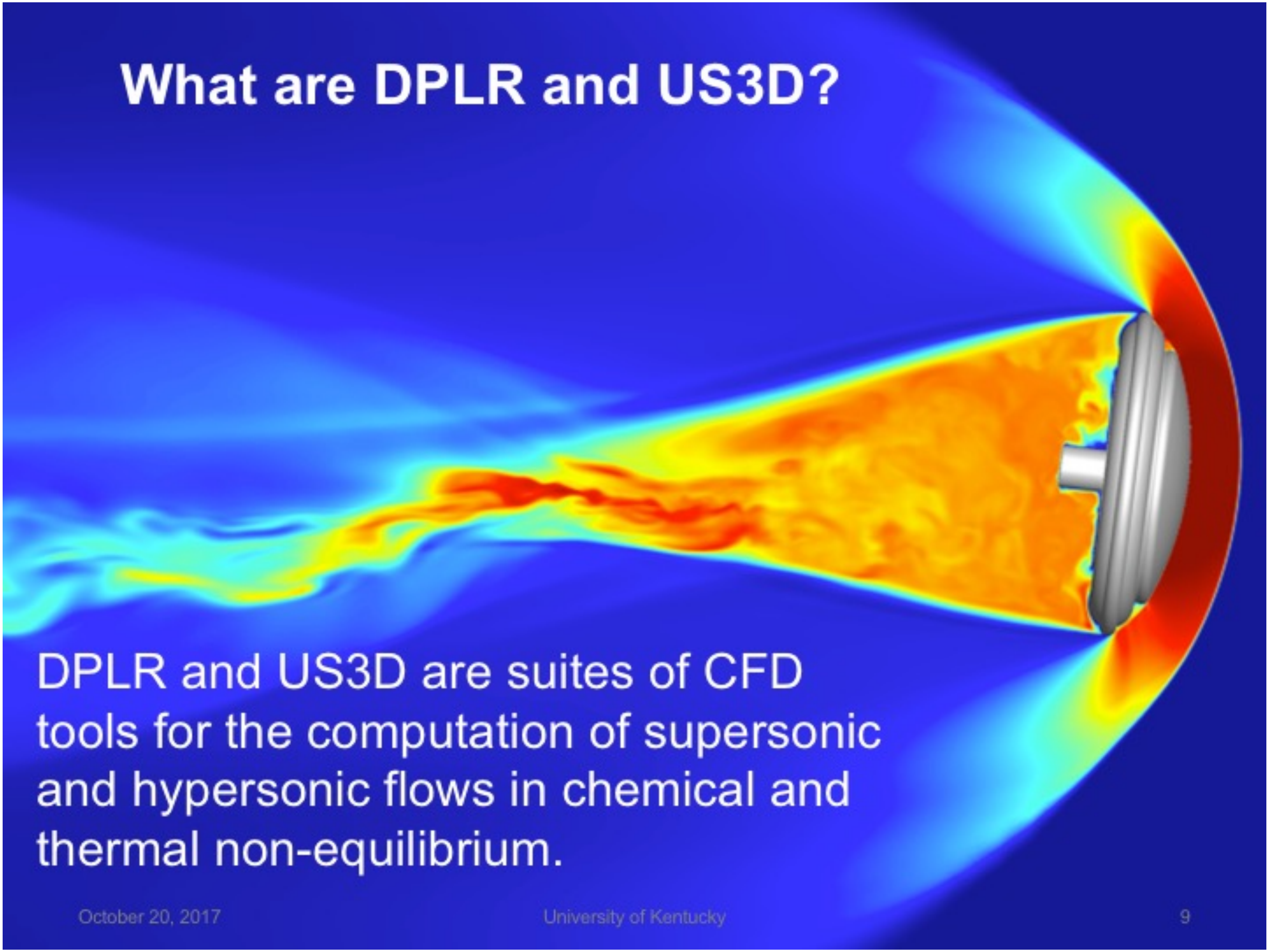
- Molecules decompose more slowly than the shock heats up
  - Molecules are present in the non-equilibrium region
- Ionization typically follows dissociation
- Reactions in the shock convert thermal energy into chemical energy
  - Causes temperature to decrease as system approaches equilibrium (endothermic)

Entry Vehicles and Radiation



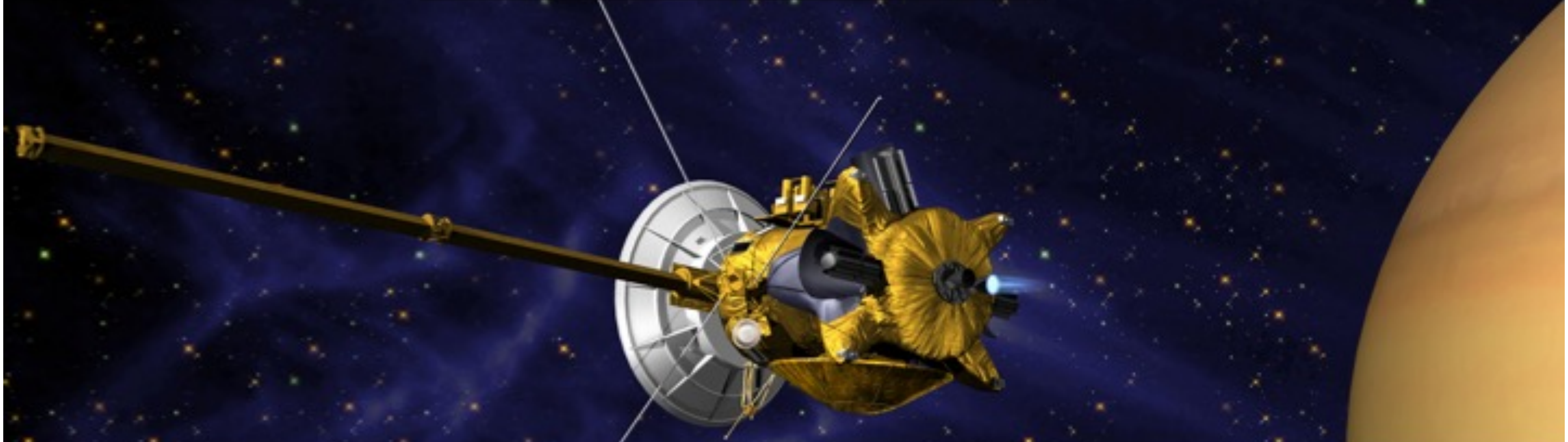
- How do we calculate radiative heating experienced by a space craft?
  - Hot gas (plasma) in the bow shock radiates in all directions
  - Radiation incident upon the surface of a vehicle is realized as a heat flux
  - Radiative spectrum depends on temperature, species number density of the flowfield
  - Prediction of radiation requires knowledge of the radiative spectrum
- At Ames, DPLR or US3D is used to simulate flowfields and NEQAIR is used to calculate radiation.

What are DPLR and US3D?



DPLR and US3D are suites of CFD tools for the computation of supersonic and hypersonic flows in chemical and thermal non-equilibrium.

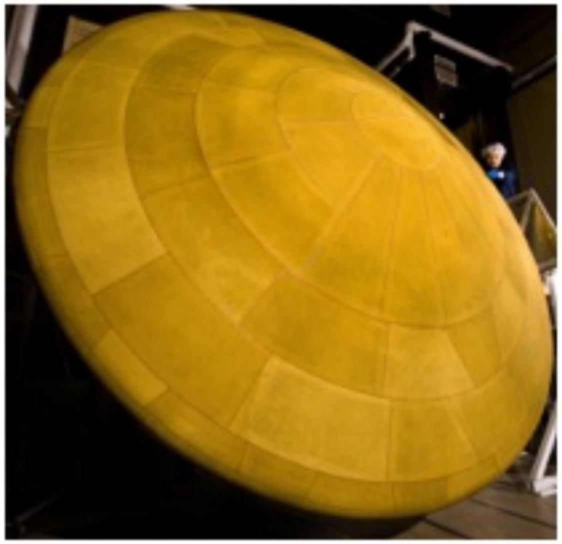
What is NEQAIR?

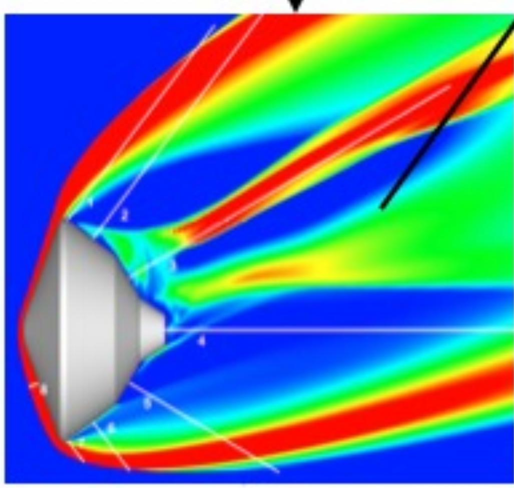


NEQAIR was NASA's first radiative heating code and has been the go-to-tool for 30 years

NEQAIR computes spectra and radiative heating based on a given flow-field

How Does NEQAIR Work?





NEQAIR

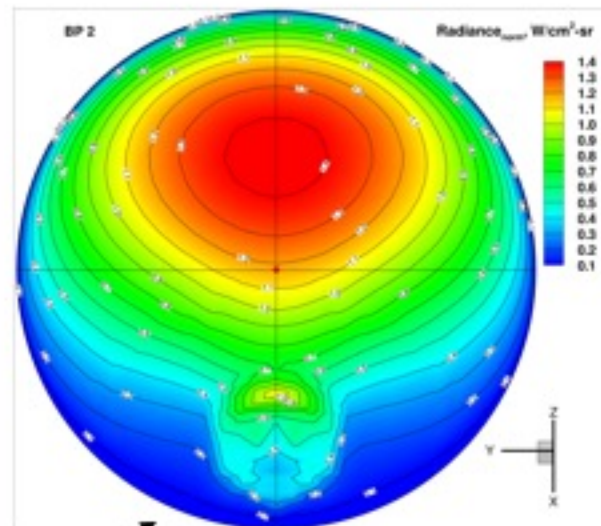
Calculate Emission & Absorption

↓

Radiative Transport

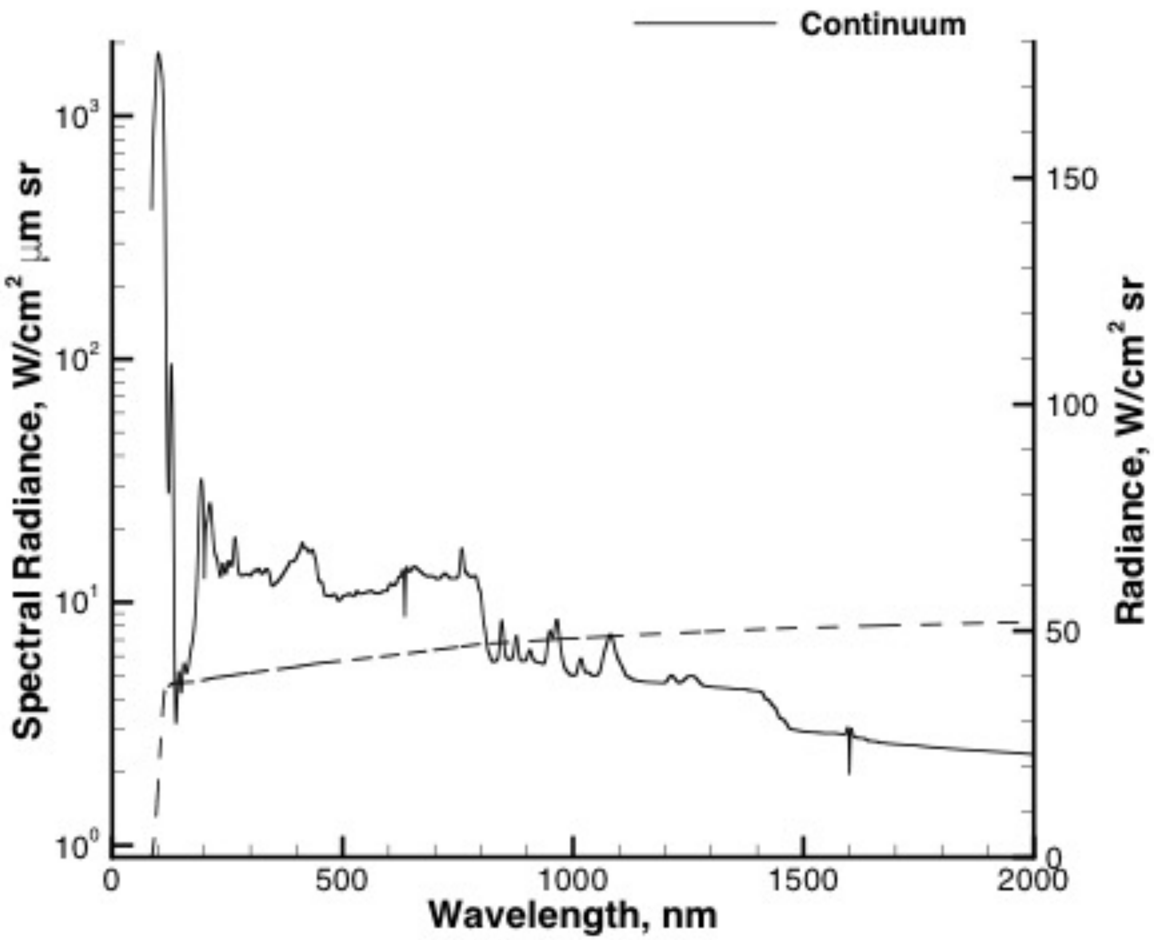
↓

Evaluate Radiative Heating



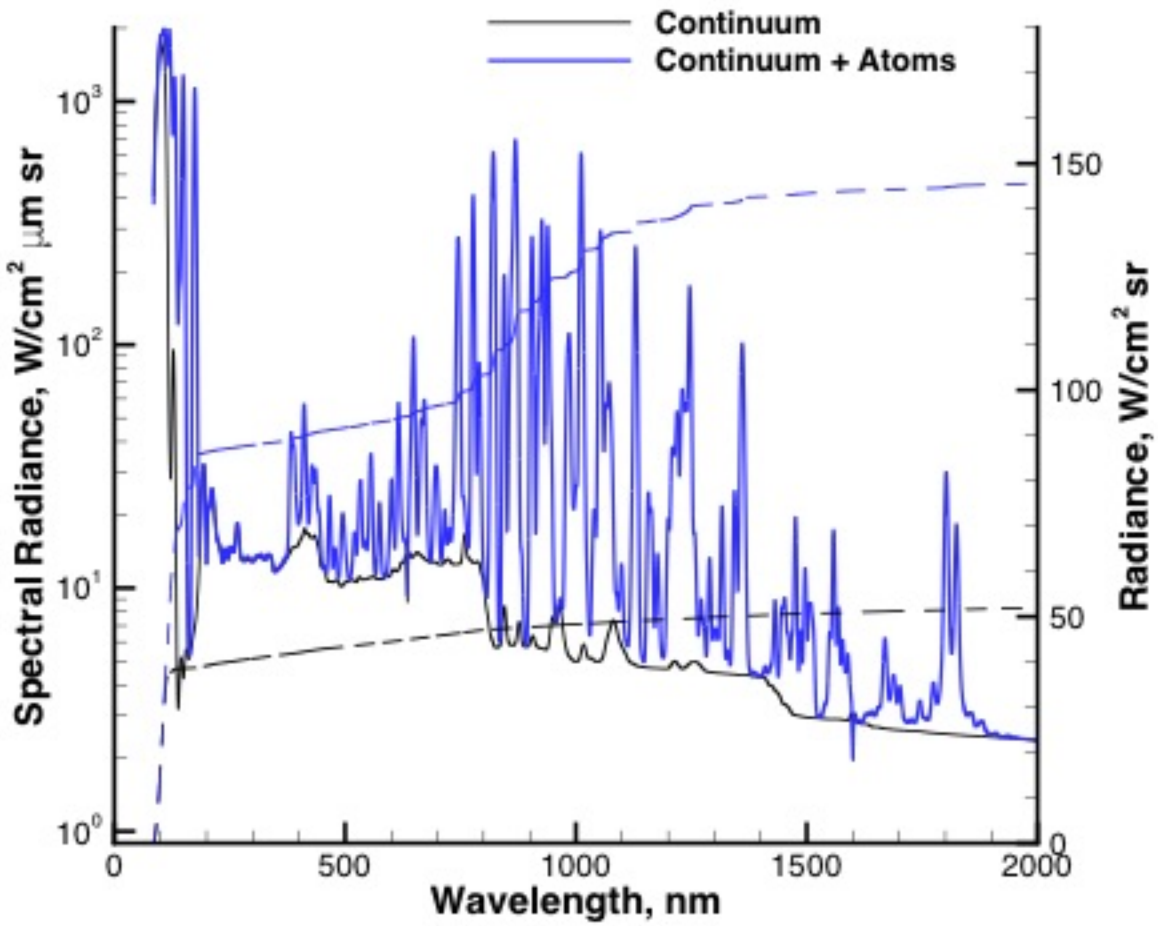
Building a Spectrum

FIRE II Test Case



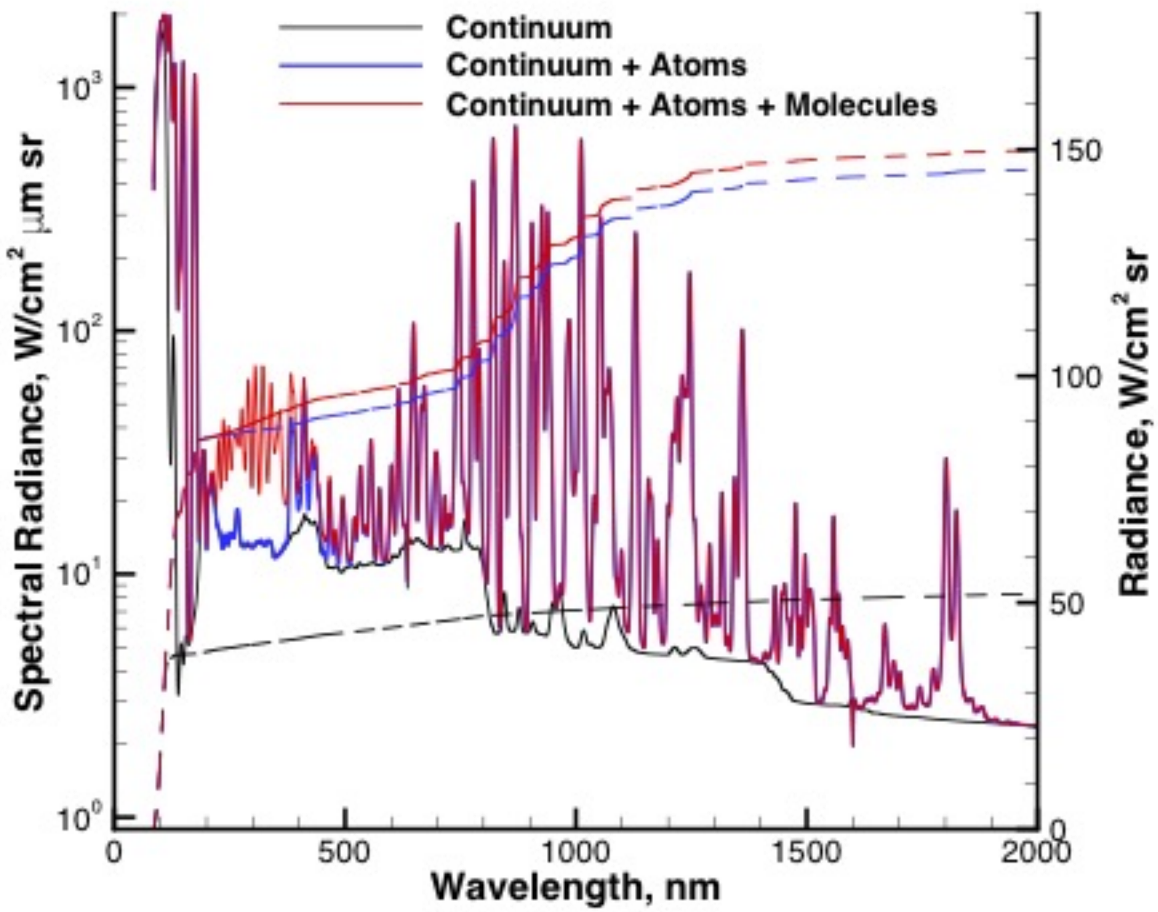
Building a Spectrum

FIRE II Test Case



Building a Spectrum

FIRE II Test Case



Radiative Heating For Flight Missions

- Radiative heating plays two main roles relevant to mission design:
  1) Calculating the radiative heat flux incident on the surface of an entry vehicle.
  2) Validating these results within quantified uncertainty bounds with experimental data to help evaluate margin policies.
- Subsequently, there are two principal modes for running NEQAIR:
  1) As a radiative heat flux prediction tool for flight projects (also has been used to simulate the radiance measured on previous flight missions).
  2) As a tool for creating synthetic spectra of any desired resolution (including convolution with a specified instrument/slit function). This mode is typically used in simulating/interpreting spectroscopic measurements of different sources (e.g. shock tube data, plasma torches, etc.).

Broad Applications

Flight

Hypersonic/
Supersonic Vehicles

Robotic Missions

Human Missions

Astrophysics

Solar Physics

Astronomy

Meteor Entry

Experimental Validation

Shock Tubes

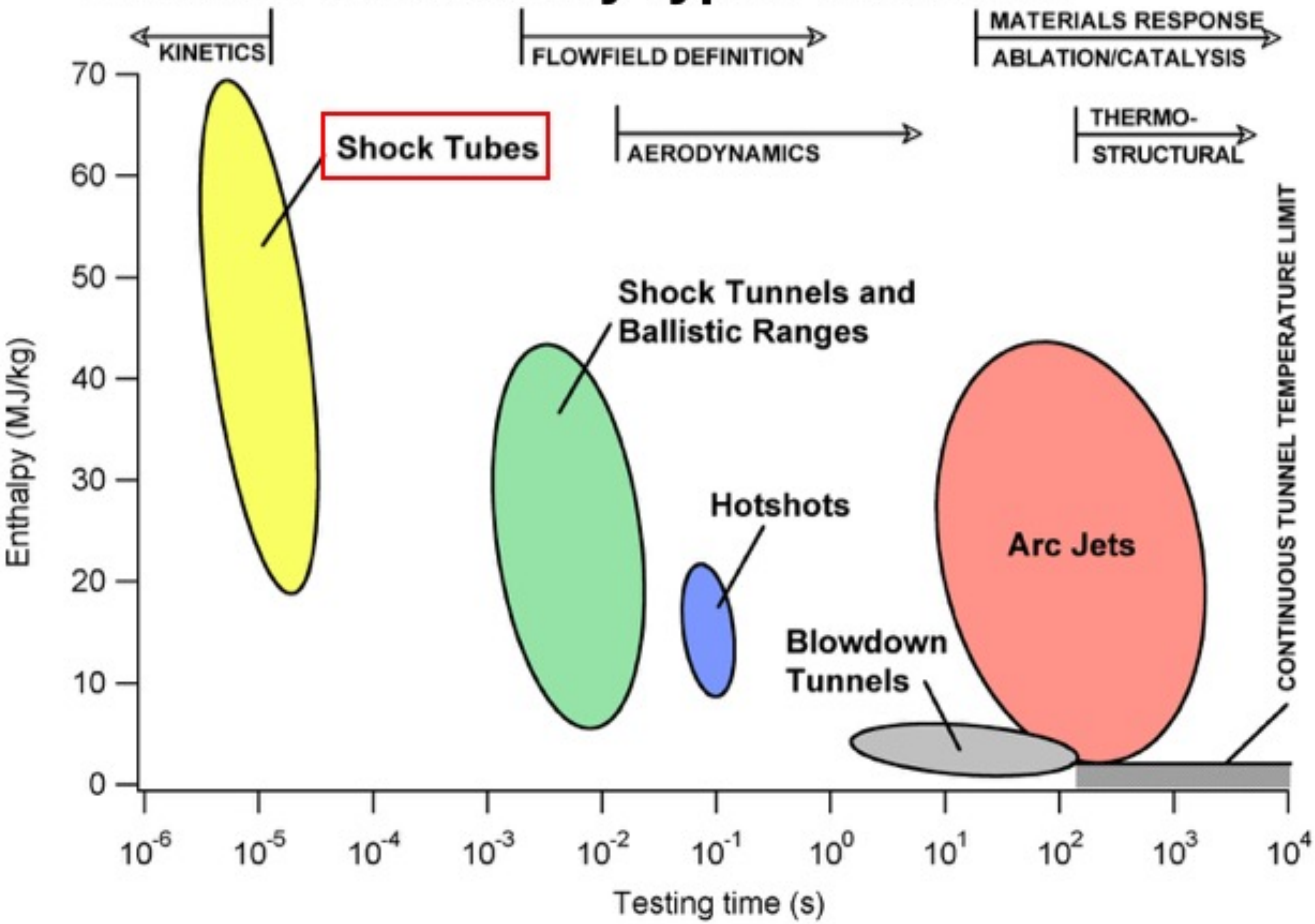
Plasma Discharge

Combustion

Arc Jets

How do we validate radiation models?

Ground test facility types and uses

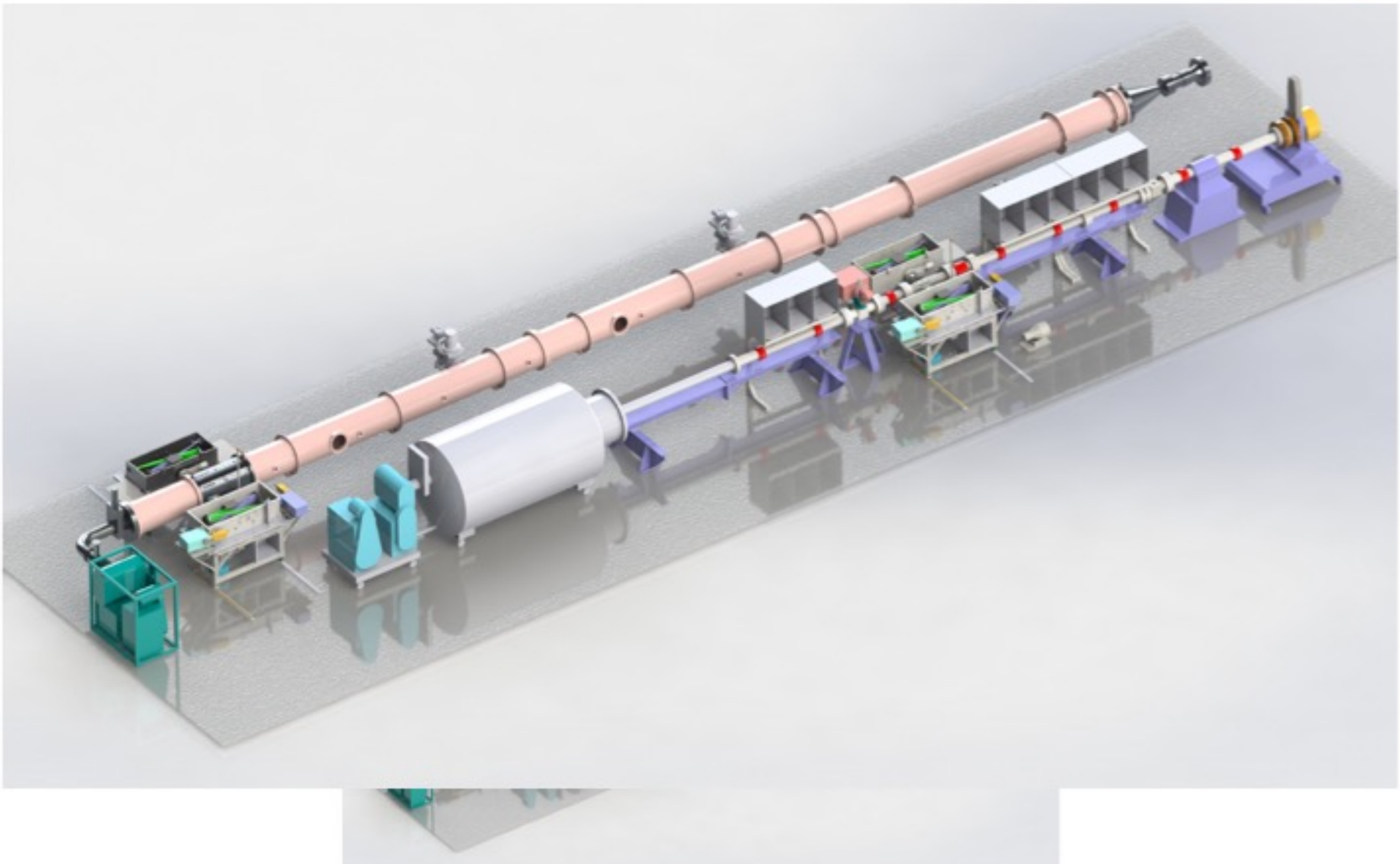


Radiance in Shock Tubes

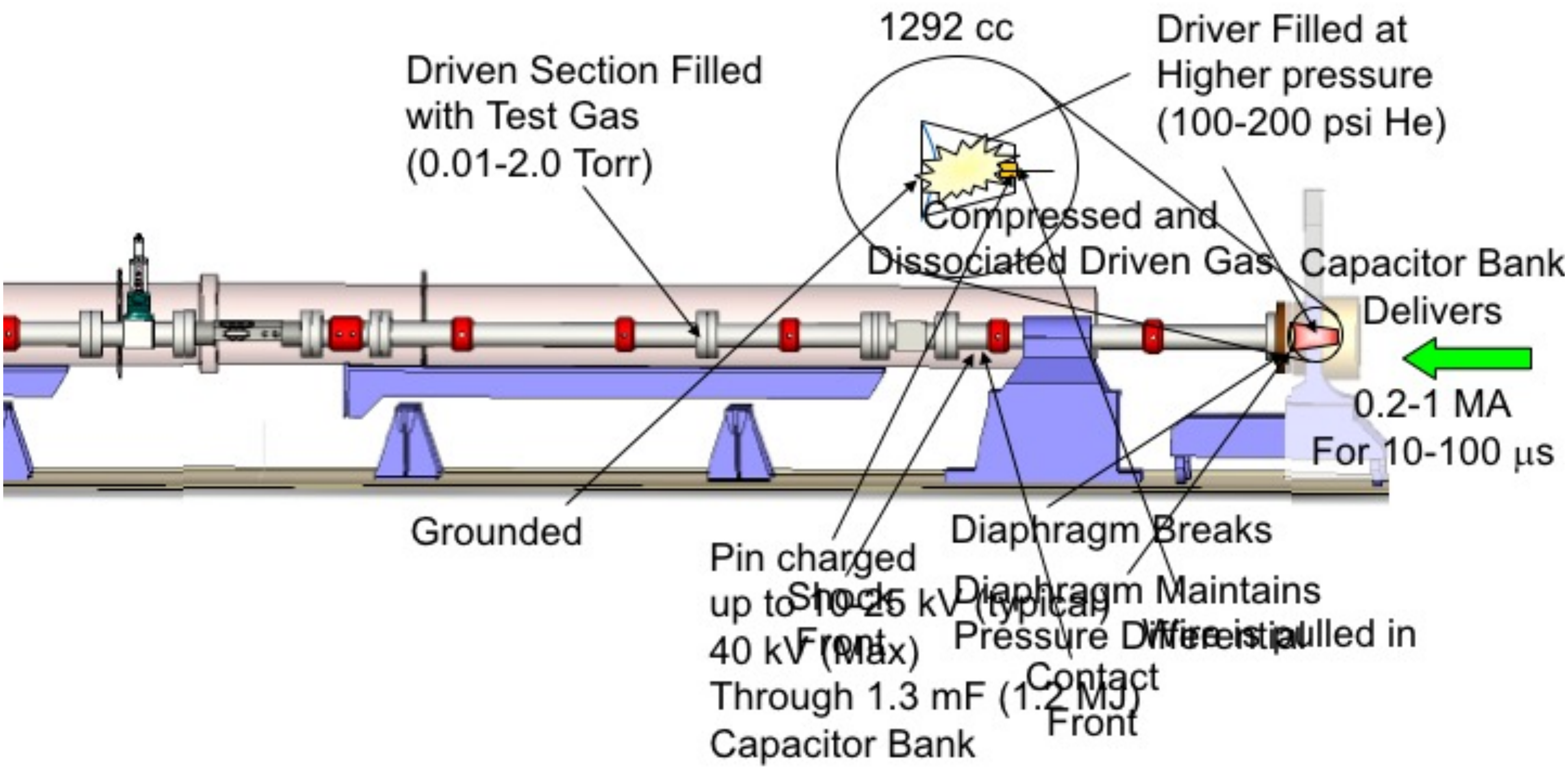
- Driver Gas in the shock tube compresses the gas in front of it, much like a blunt-body (entry vehicle) does on entry
- 1D flow in front of driver gas has similarity to entry stagnation line if shock velocity and freestream density are matched
- Measurements obtain radiance normal to the flow direction:
  - Data informs both spectroscopic and reacting flow (kinetic) models

First arc-driven shock tube at Ames (1962)

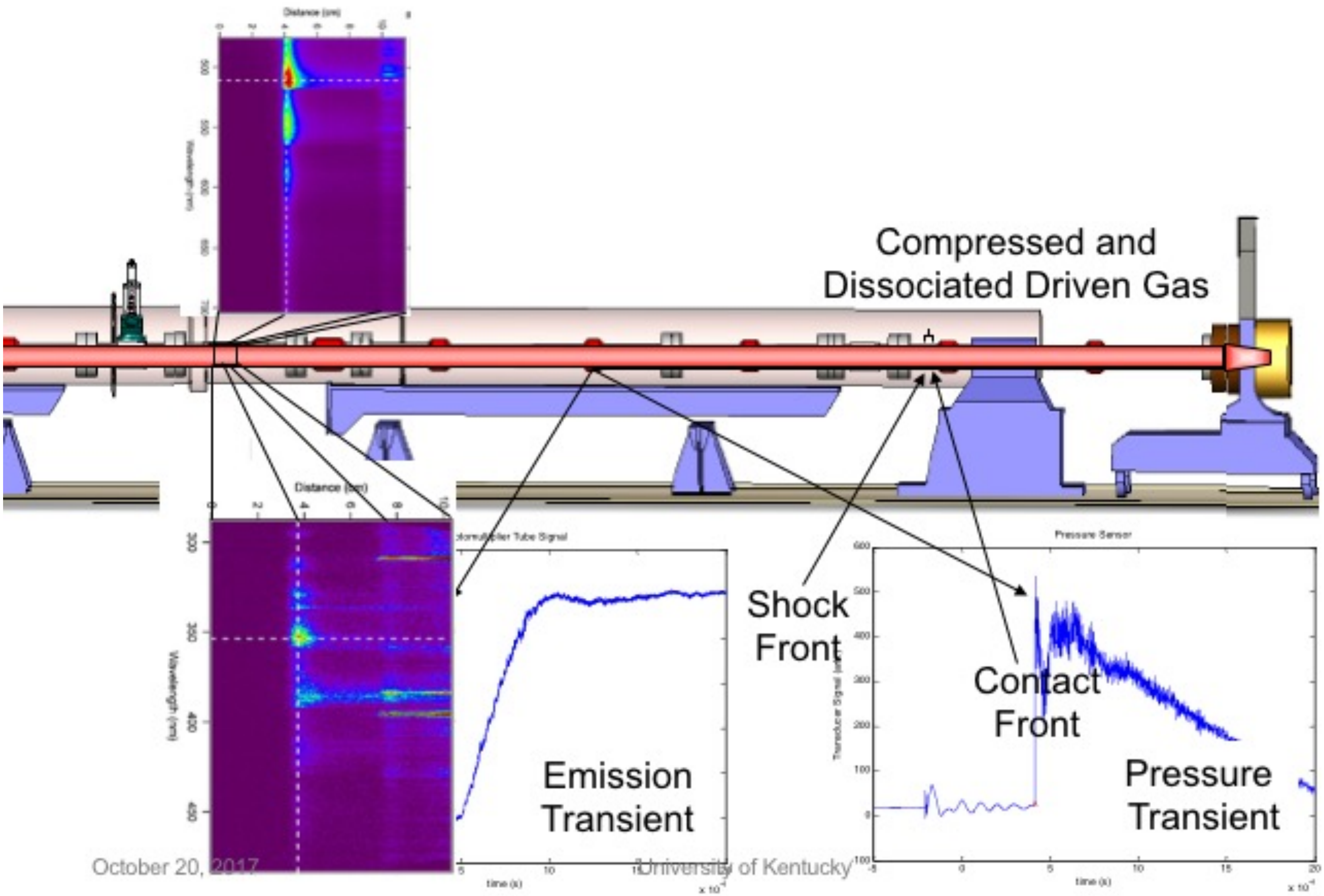
Present Day EAST



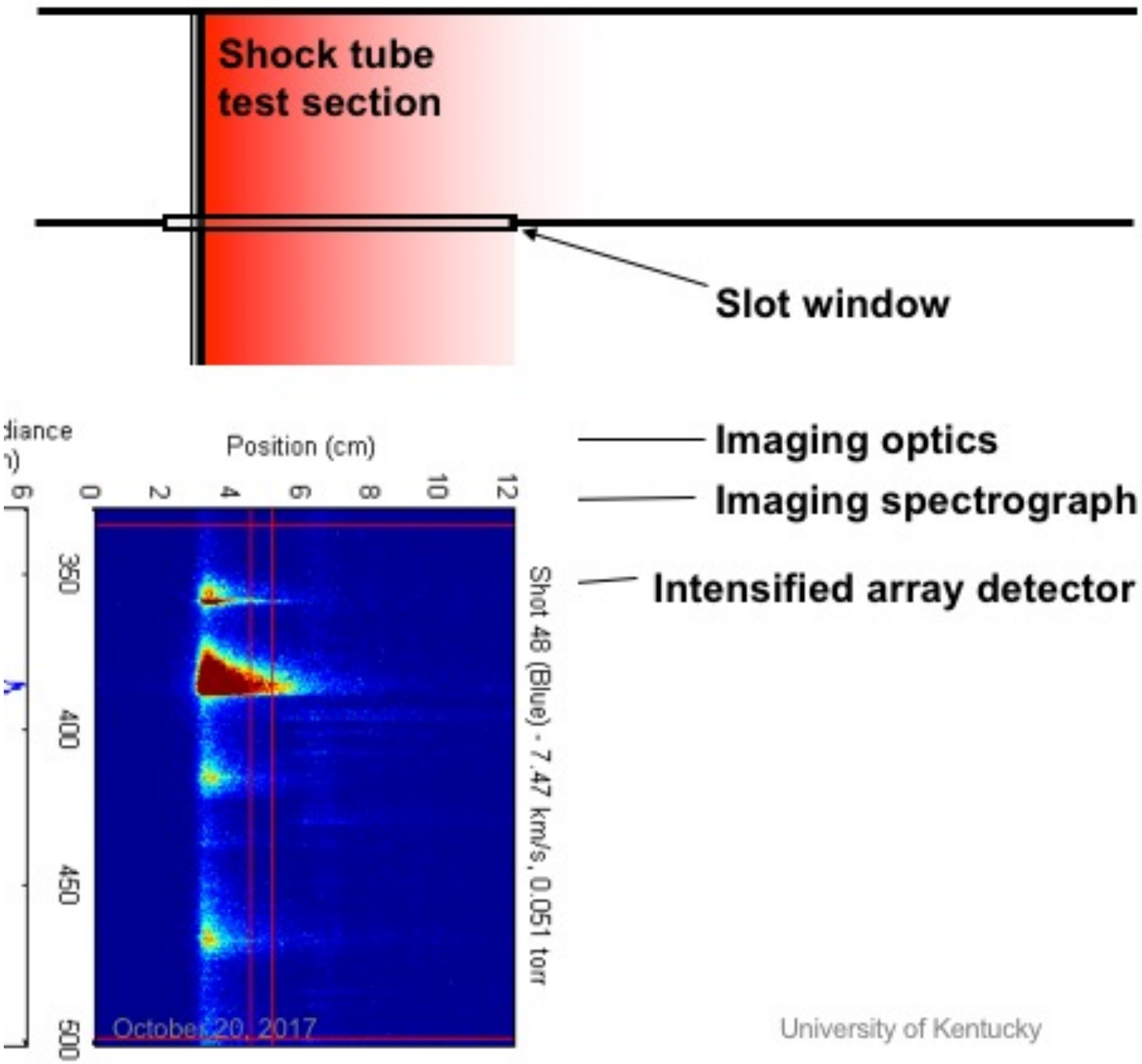
Shock Wave Generation



Shock Wave Generation

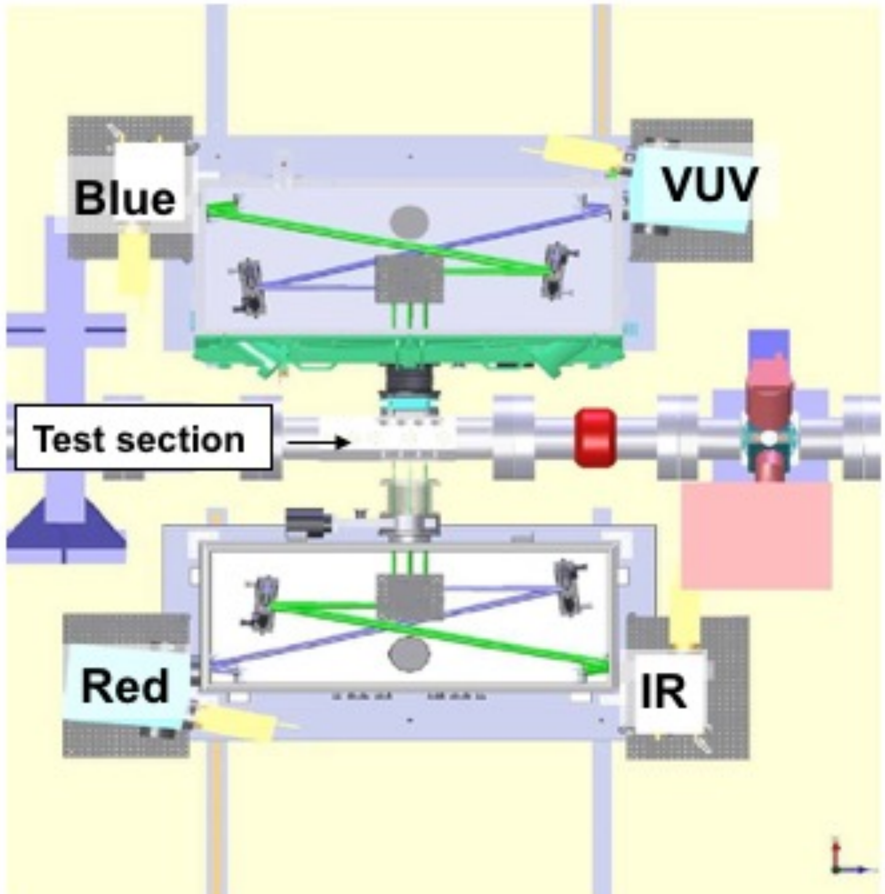


Radiance Measurement



- Image of shock is captured as it crosses the test section
  - Shock is smeared from 0.1-1 μs by exposure time

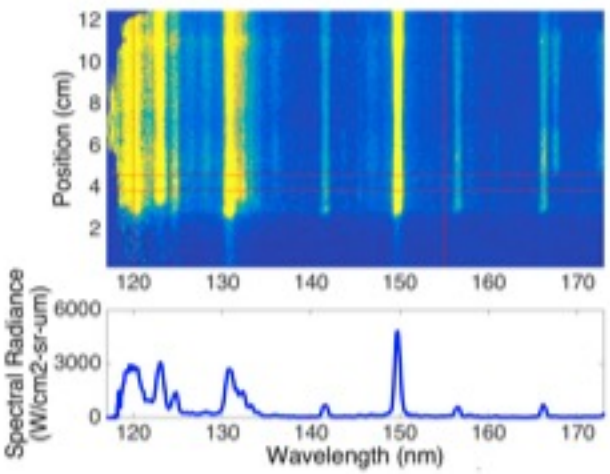
Spectroscopy Instrumentation



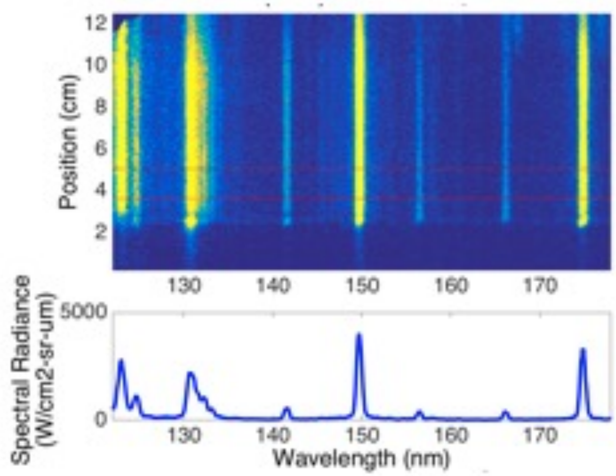
- Entire optical path under high vacuum for imaging down to 120 nm
- Four spectrometers cover VUV through NIR regions

Radiance Obtained in Different Spectral Regions

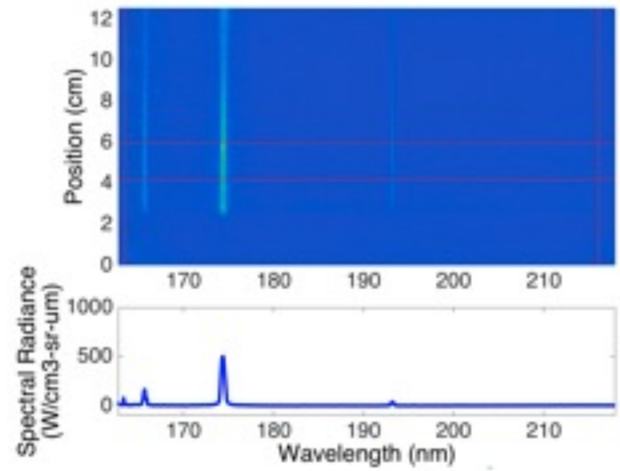
Deeper VUV



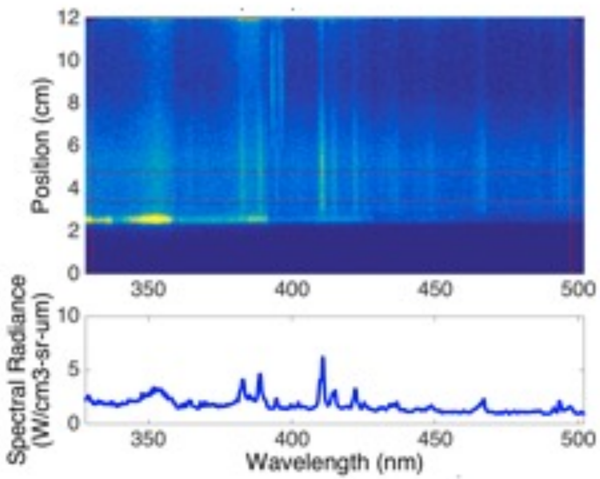
VUV



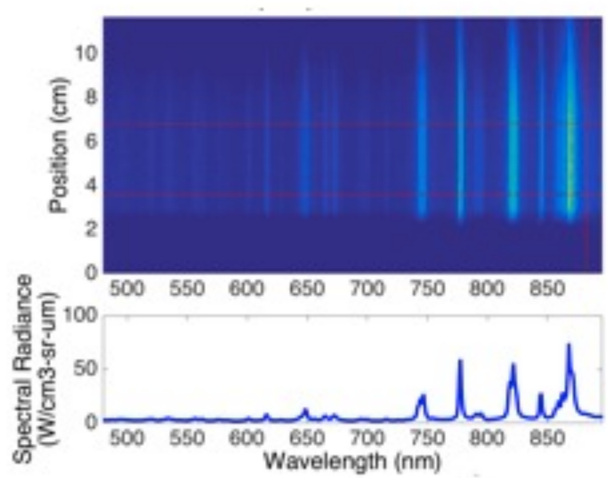
VUV/UV



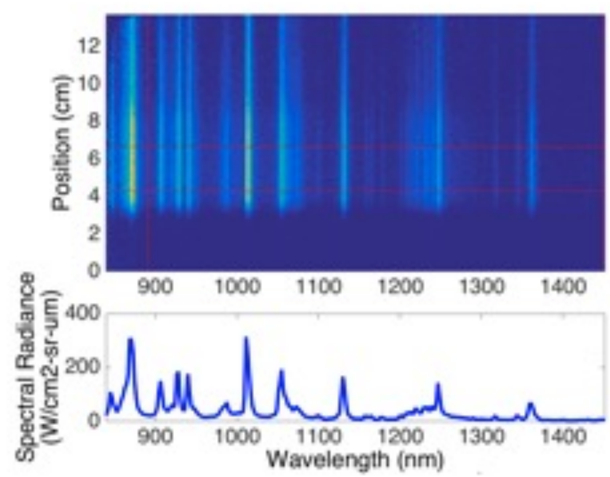
UV/Vis



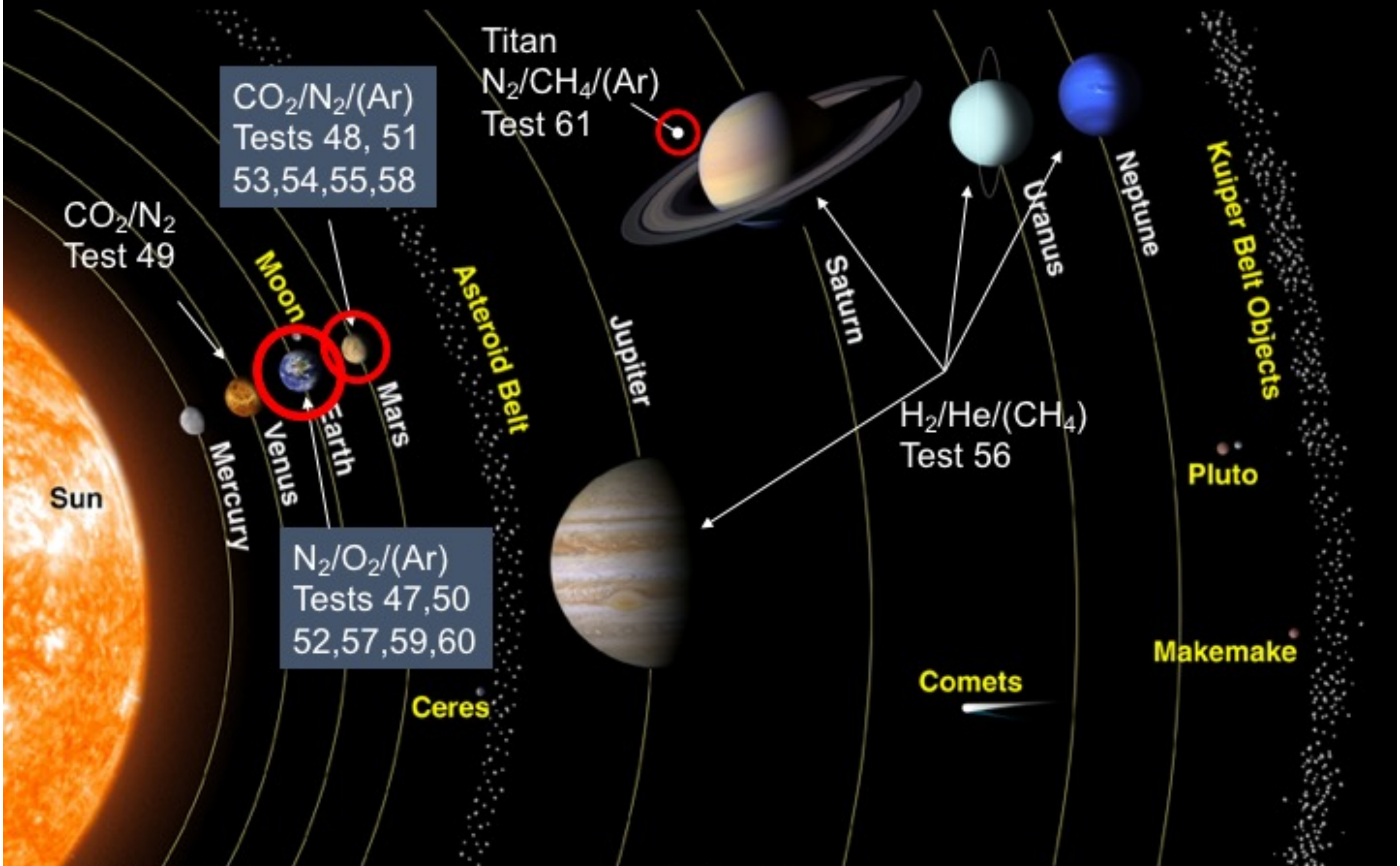
Vis/NIR



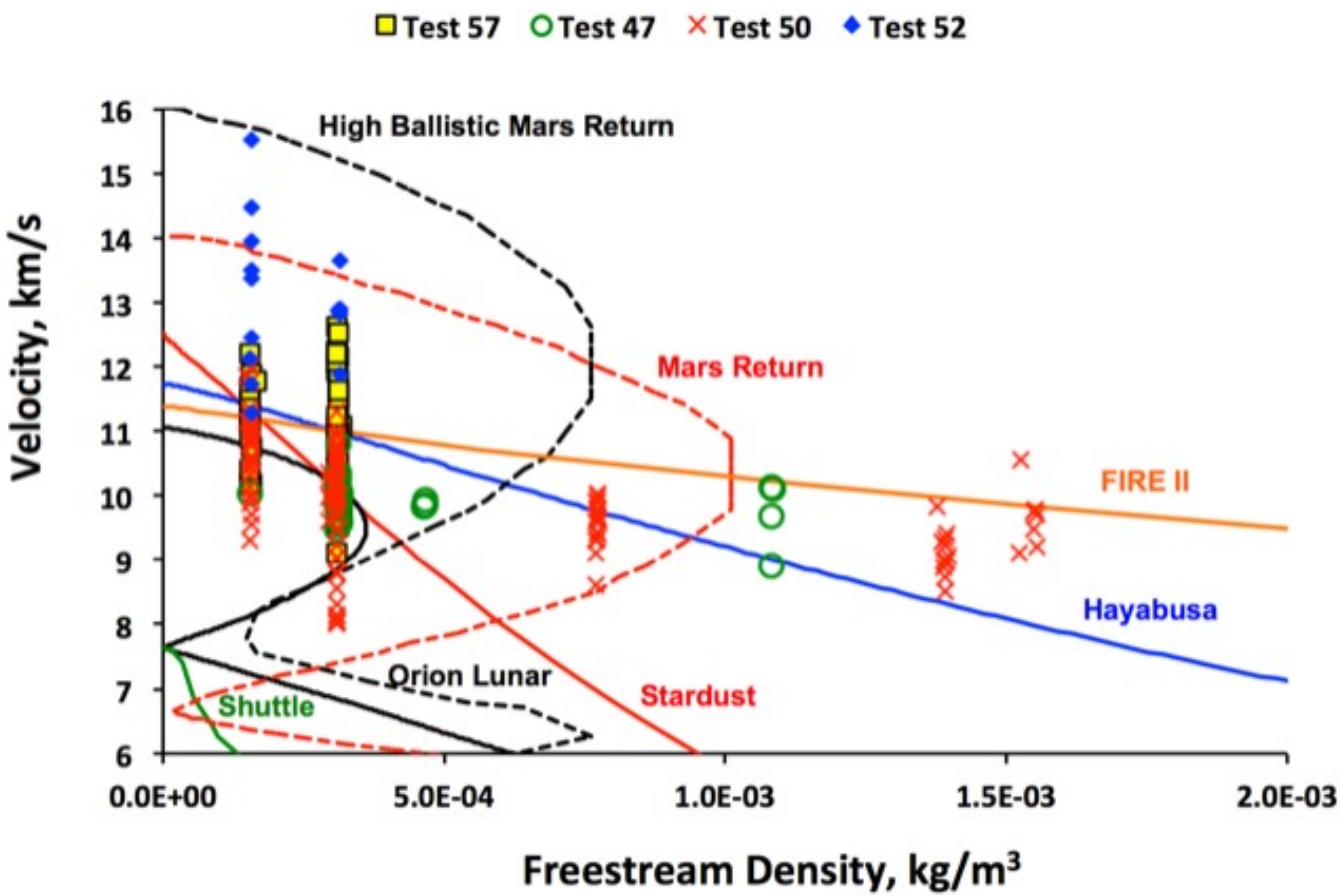
NIR/IR



Planetary Atmospheres



Recent EAST Earth Testing Conditions



Recent Significant Achievements

- **Margin Policies**
  - Rigorous approach to radiation margin developed for Earth re-entry **Orion: EM1**
  - Similar approach applied for to Mars entry **Mars 2020**
- **FT1 Radiometer Discrepancy**
  - Significant under-prediction of FT1 radiation with baseline simulations
  - EAST testing allowed for the construction of a new model **Orion: FT1, EM1**
  - Model updates show good agreement with FT1 data
- **Titan Radiation Discrepancy** **New Frontiers: Dragonfly**
  - Radiation predictions for Titan entry have historically greatly over-predicted shock tube measurements
  - Newly measured radiation is substantially larger compared to literature
  - Good agreement with simulations observed for peak radiance, while discrepancy in decay rate is still present
- **New Validation Data for Martian Entries** **Future Mars missions**
  - TDLAS measurement provides new avenues for understanding Martian reaction kinetics
- **Backshell Radiation** **Mars 2020, Orion, InSight**
  - ESM research implementing and validating backshell radiation for both Mars/Venus and Earth entries has directly influence mission design

Recent EAST testing has driven significant model improvements and multiple infusions with flight projects

Updating Orion Aerothermal Margin

Introduction

- Re-entry missions involving larger vehicles and higher entry velocities motivate improved simulation of radiative heating and associated uncertainties, e.g. EM-1

Brief Overview of Missions

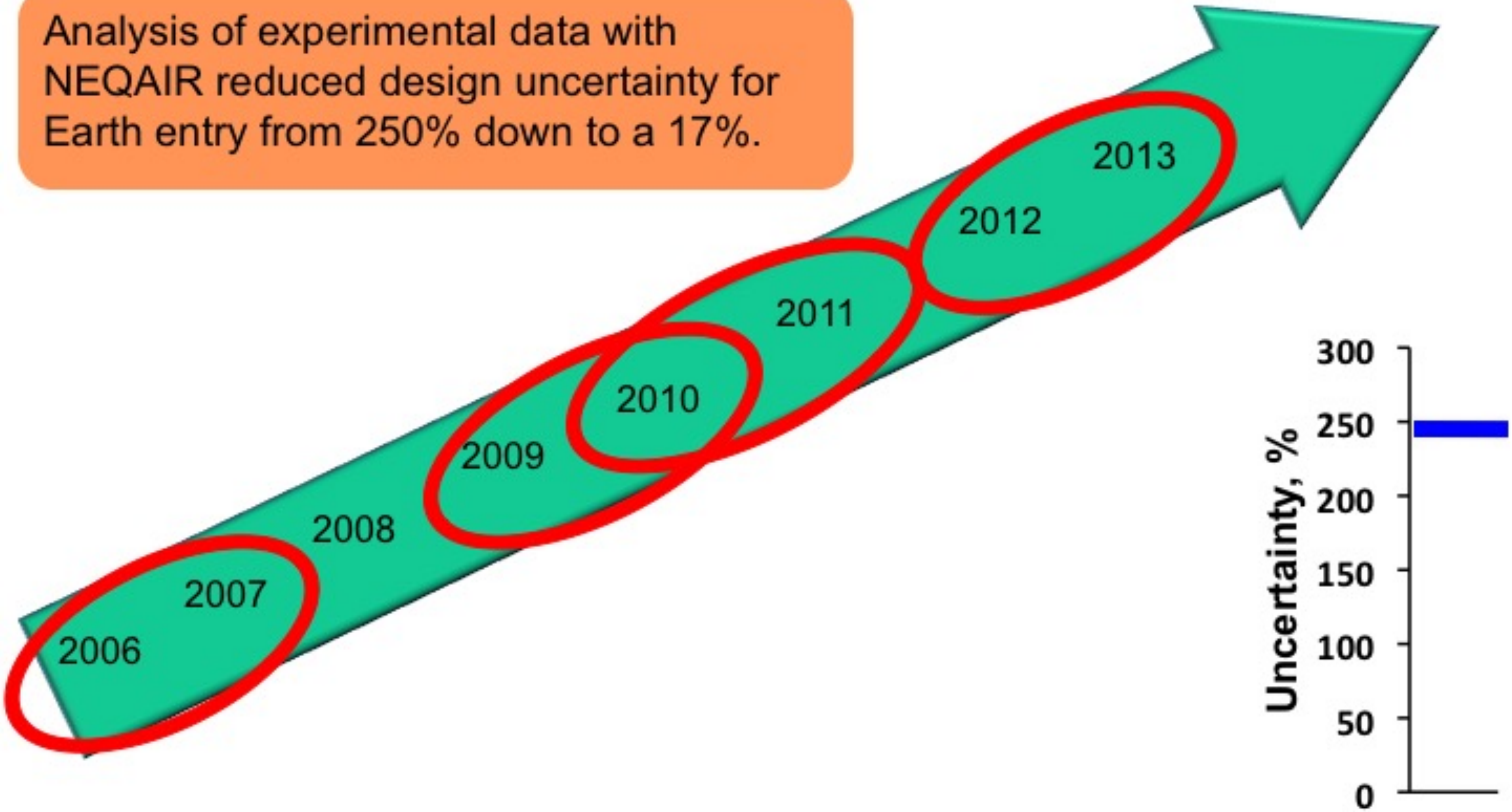
EFT-1: First Orion flight test; entered Earth's atmosphere from a highly elliptical orbit in December of 2014

EM-1: the next Orion flight will undertake a lunar return trajectory (radiation will be significant)

- Using shock tube data to validate non-equilibrium should only be attempted if equilibrium is well understood
- Previous analyses have conducted extensive comparisons between EAST and radiation calculations at equilibrium

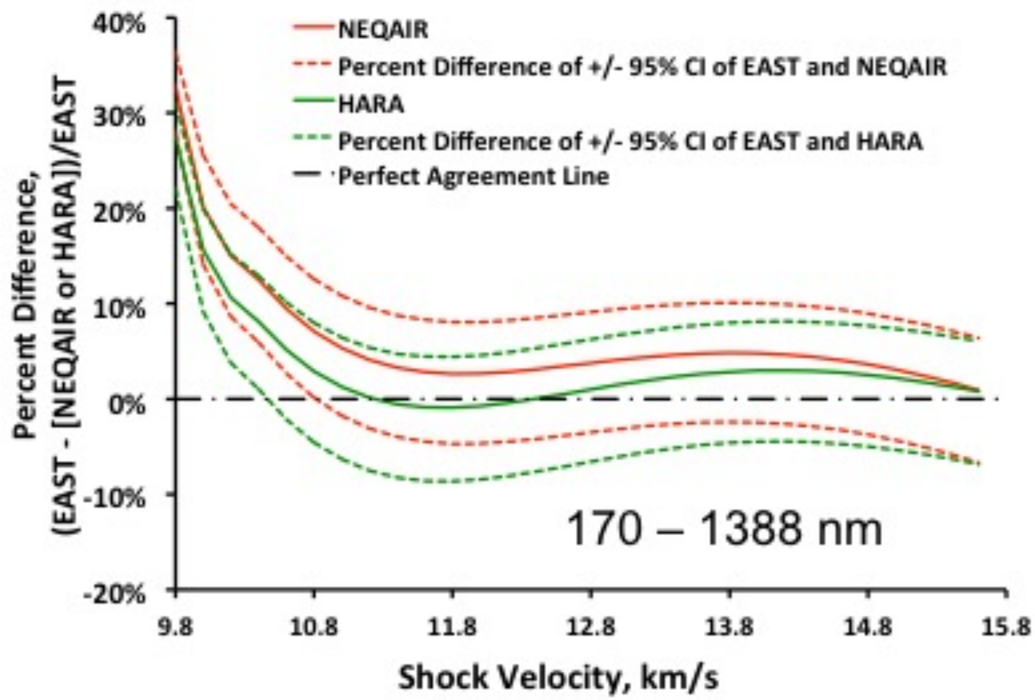
Improvement of Uncertainty for Earth Equilibrium Radiation

Analysis of experimental data with NEQAIR reduced design uncertainty for Earth entry from 250% down to a 17%.



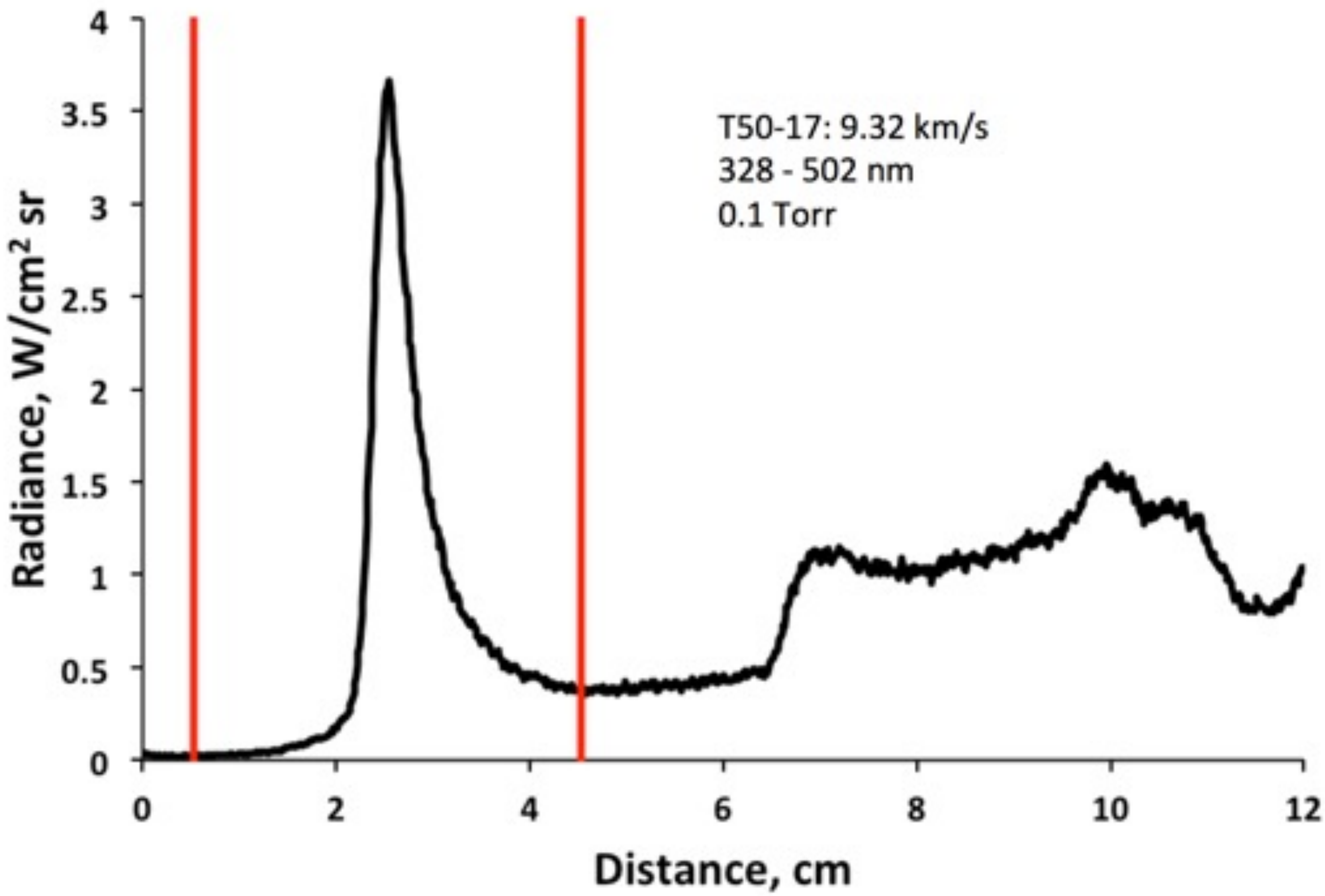
Equilibrium Summary

- Uncertainty for model predictions of EAST as a function of velocity for Earth entry up to 15.5 km/s.
- 1 Standard deviation in scatter of EAST: 17%.
- Disagreement of models w.r.t. to mean EAST result from 11 – 15.5 km/s on average [9.0%, -6.3%].



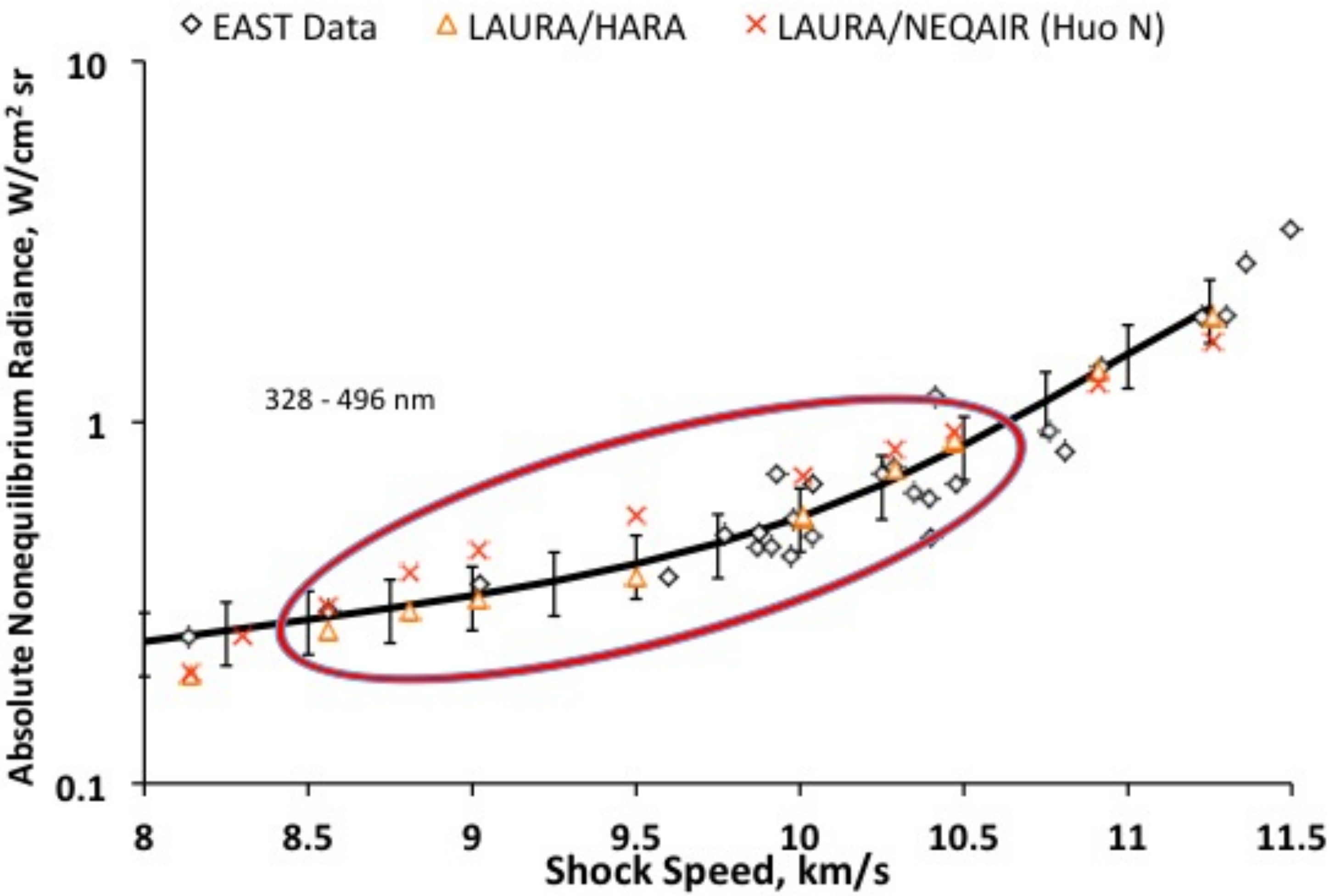
Non-equilibrium Metric

Absolute Non-Equilibrium Radiance



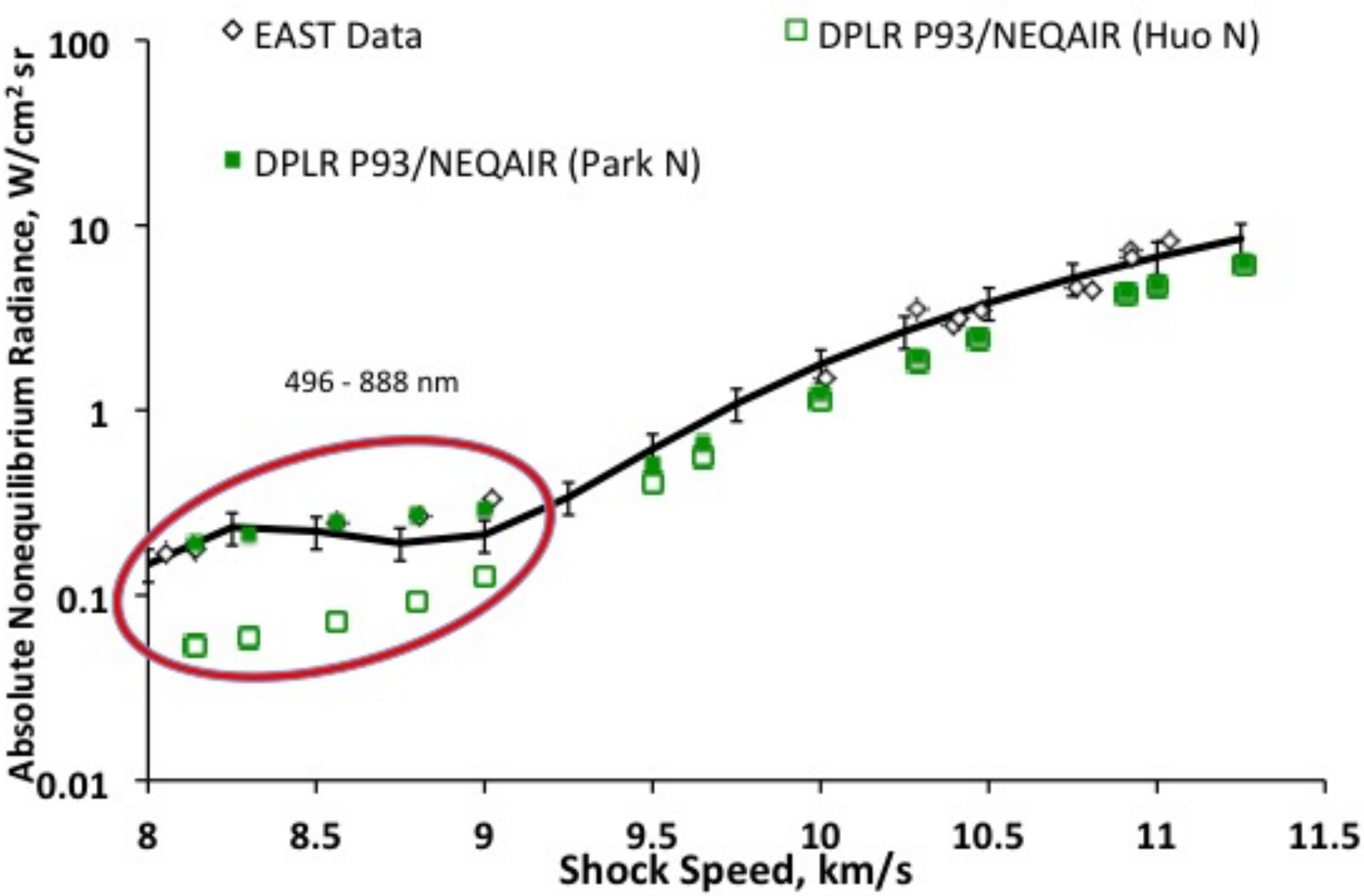
Integrate radiance ±2cm either side of shock front.
Normalized by shock tube diameter

Simulations vs EAST: UV



- In the UV, NEQAIR and HARA show a difference between 8.5 and 10.5 km/s when based on the same (LAURA) flowfield

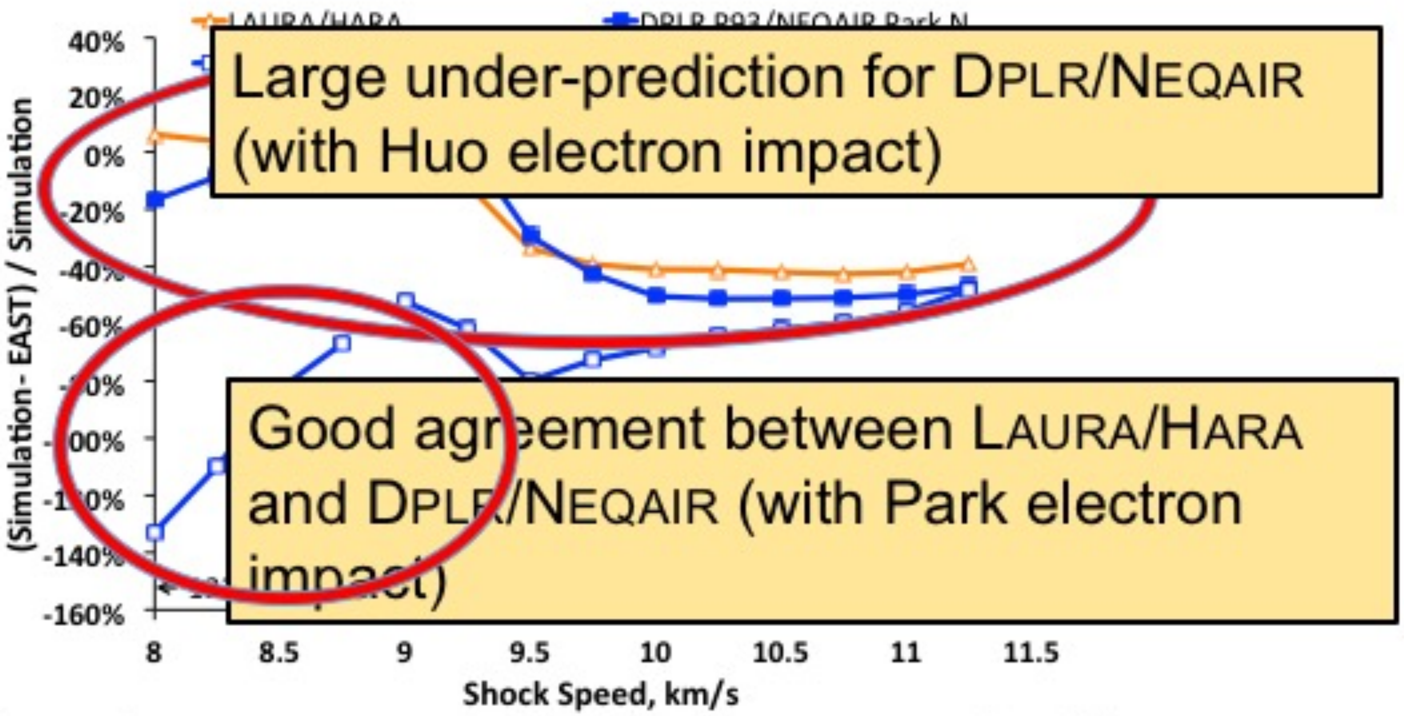
Simulations vs EAST: Vis/NIR



- In the Vis/NIR, the nitrogen electronic impact excitation rates from Park match well with EAST, while there is an under-prediction with those from Huo

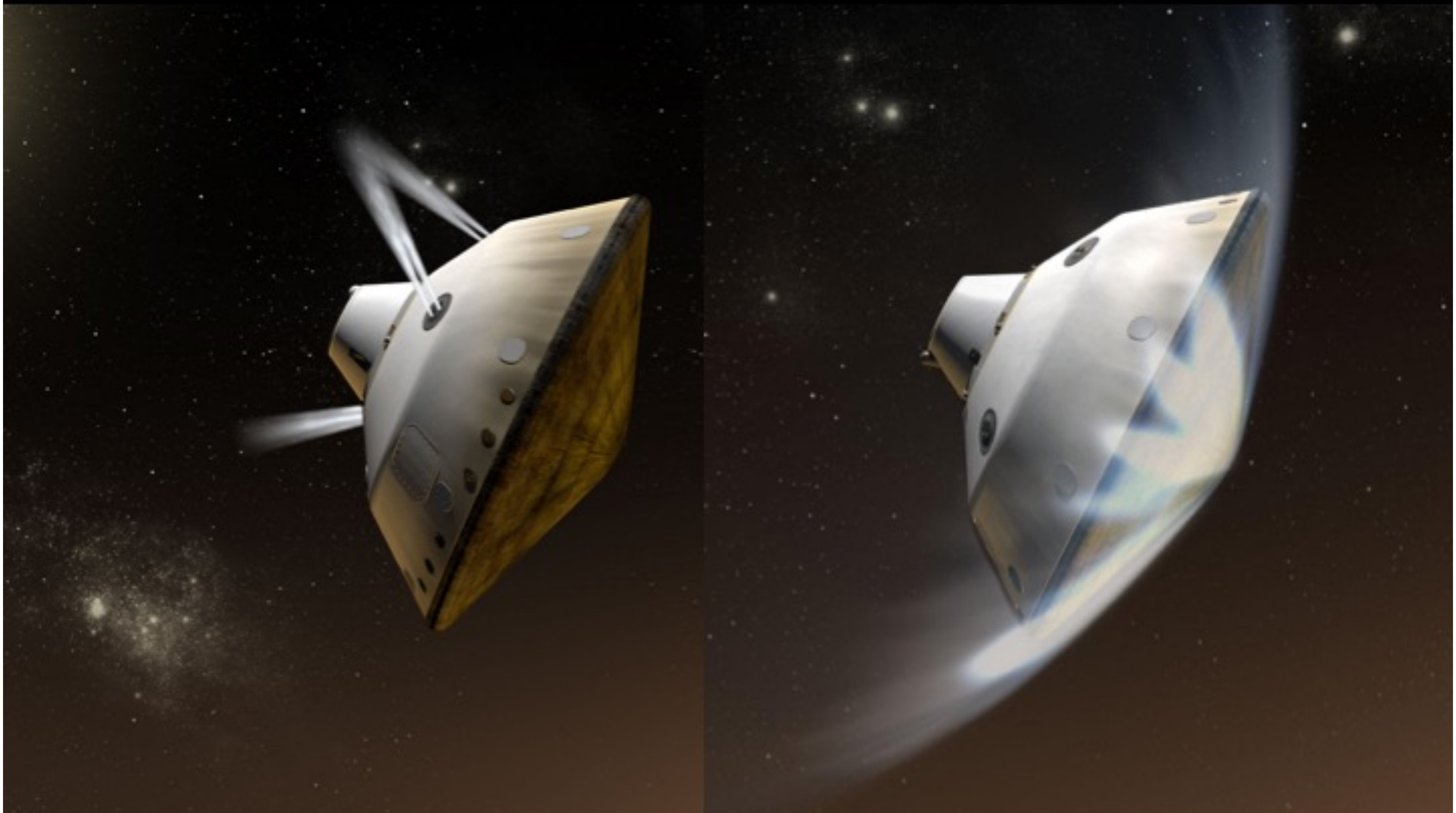
Overall Summation

- The summation of the weighted discrepancies (overall difference) is shown below.

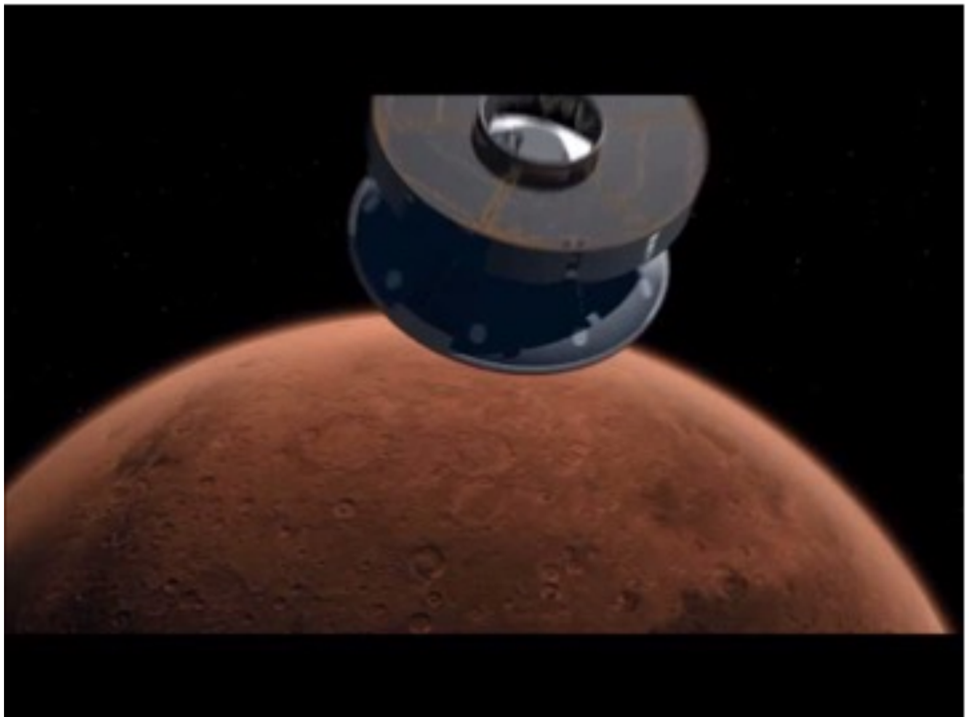


- Lower speeds, where non-equilibrium is more significant, there are large differences.
- Improving agreement between the codes as shock speed is increased.

Radiative Heating for Mars Exploration



Mars Science Laboratory (MSL)



Mars Science Laboratory (Curiosity)

Landed on Surface of Mars, August 2012

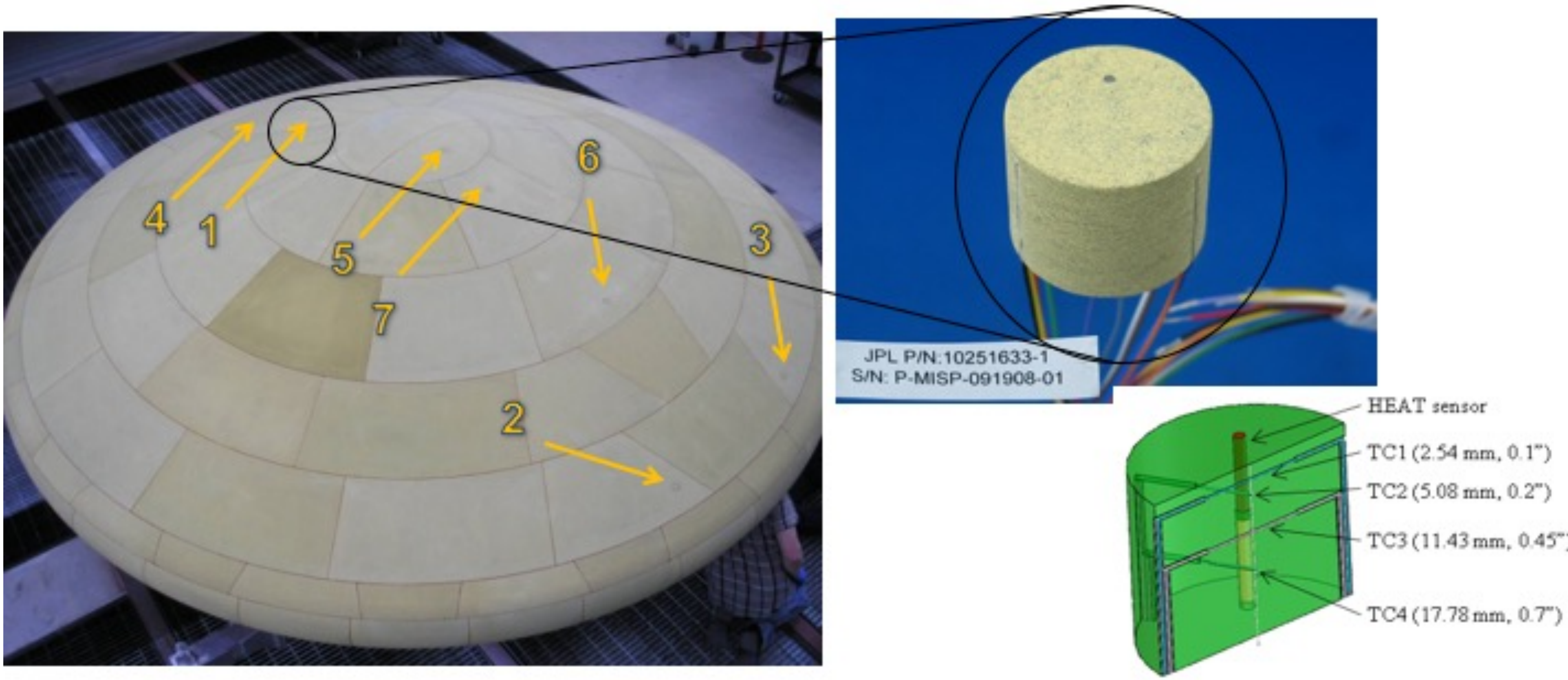
Entry Velocity : 5.9 km/s

Entry Mass : 3200 kg

Heat Shield Diameter : 4.5 m

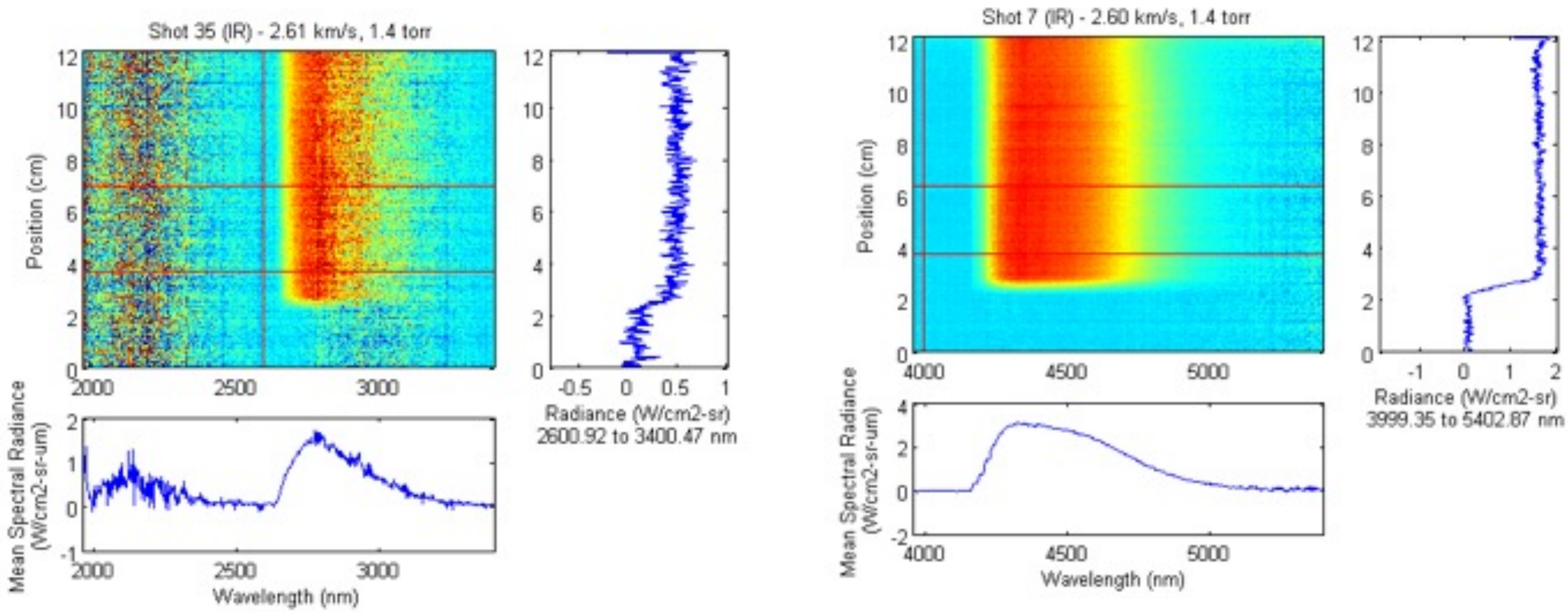
Heat Shield had instrumentation to measure heat flux

MSL Entry Descent and Landing Instrumentation (MEDLI)



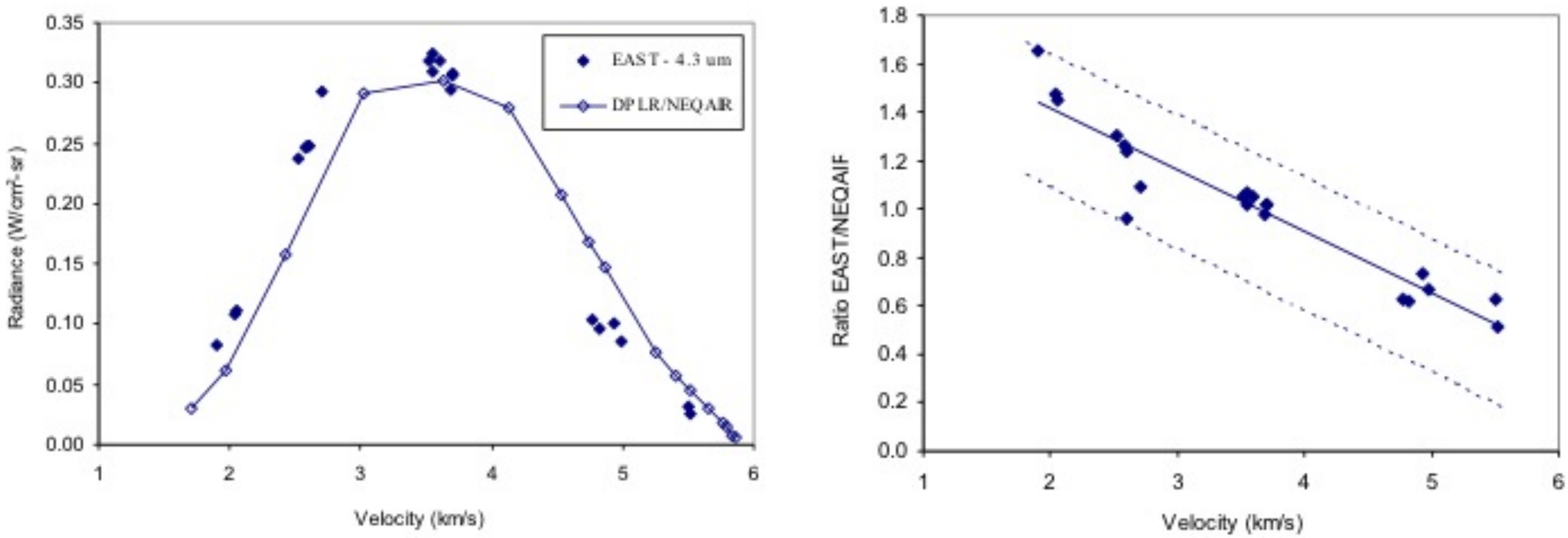
- The MSL heat shield was instrument with MEDLI sensor plugs (labeled in photo)
- The MEDLI sensor plugs measure heat shield temperatures at depths ranging from 0.10-0.70"
- Can be used to back out heat flux via inverse analysis

EAST Experiments – Later Trajectory

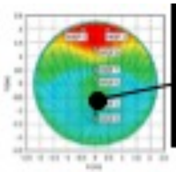


- Condition of 2.6 km/s and 1.4 Torr corresponds to t = 95.2s point of MSL Entry
- In this condition
  - No non-equilibrium zone observed
  - No radiation observed in UV/VUV. Visible is weak
  - Both 2.7 μm and 4.7 μm bands of CO_2 are observed

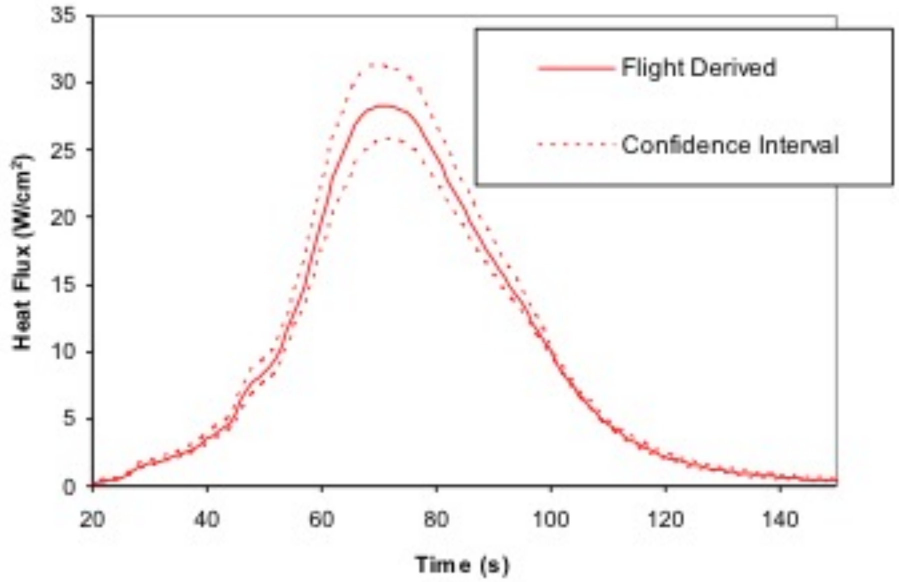
Validation – 4.3 μm

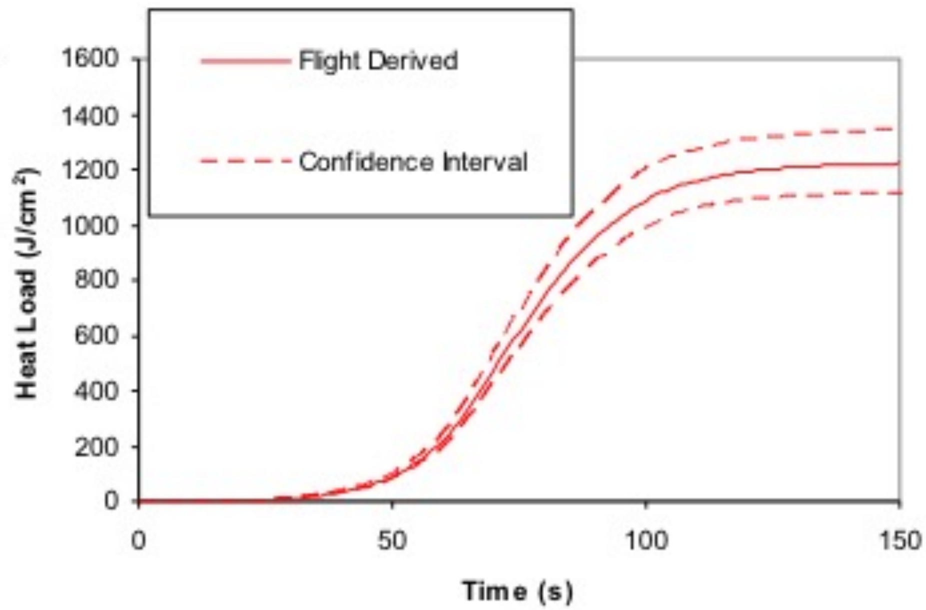


- The 4.3 μm band is matched, but appears shifted by ~0.2 km/s
  - This shift is larger than facility velocity uncertainties
  - We speculate that it may be related to uncertainties in the chemical kinetic model
- Corresponding mean uncertainty:
  - +50% at low velocity, -50% at high velocity
  - Almost zero at peak radiation



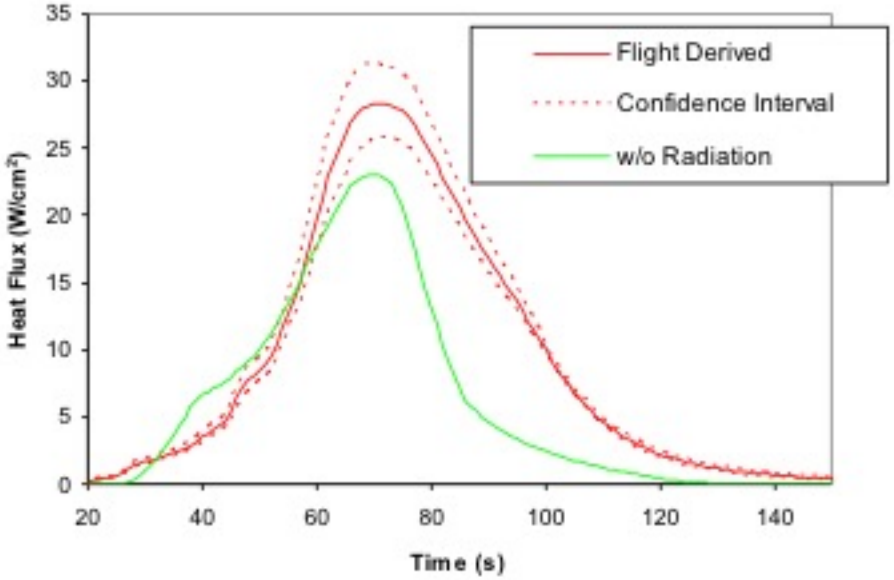
Flight Derived Heating

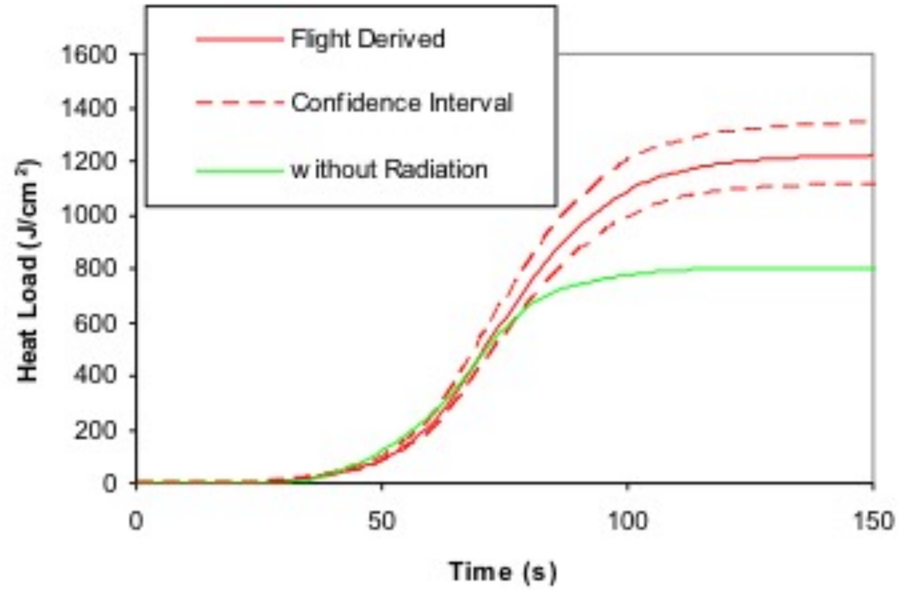




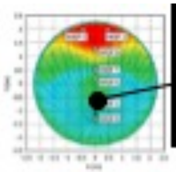
- Confidence intervals are based on using a Monte Carlo analysis
- Heat load can be more relevant for heat shield sizing

Comparison to Flight Data

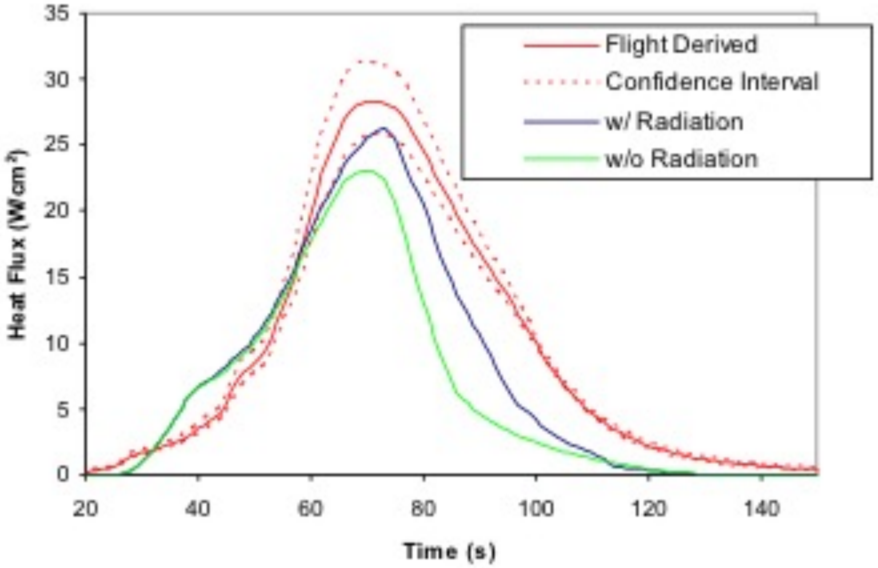


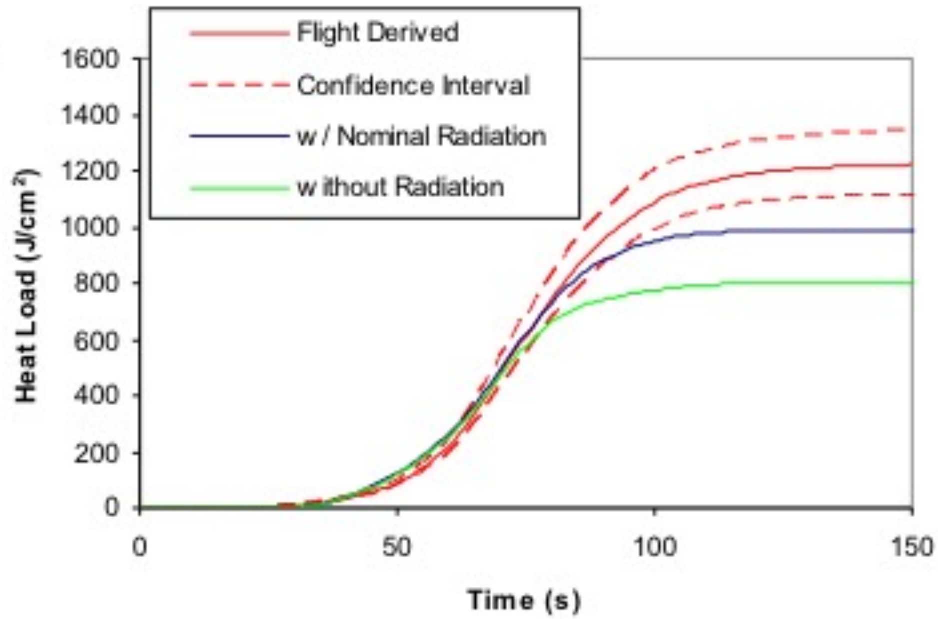


- Confidence intervals are based on using a Monte Carlo analysis
- Heat load can be more relevant for heat shield sizing
- Using convection only, the heat flux is under-predicted significantly
- Heat load is under-predicted by 400 J/cm^2, or 33%



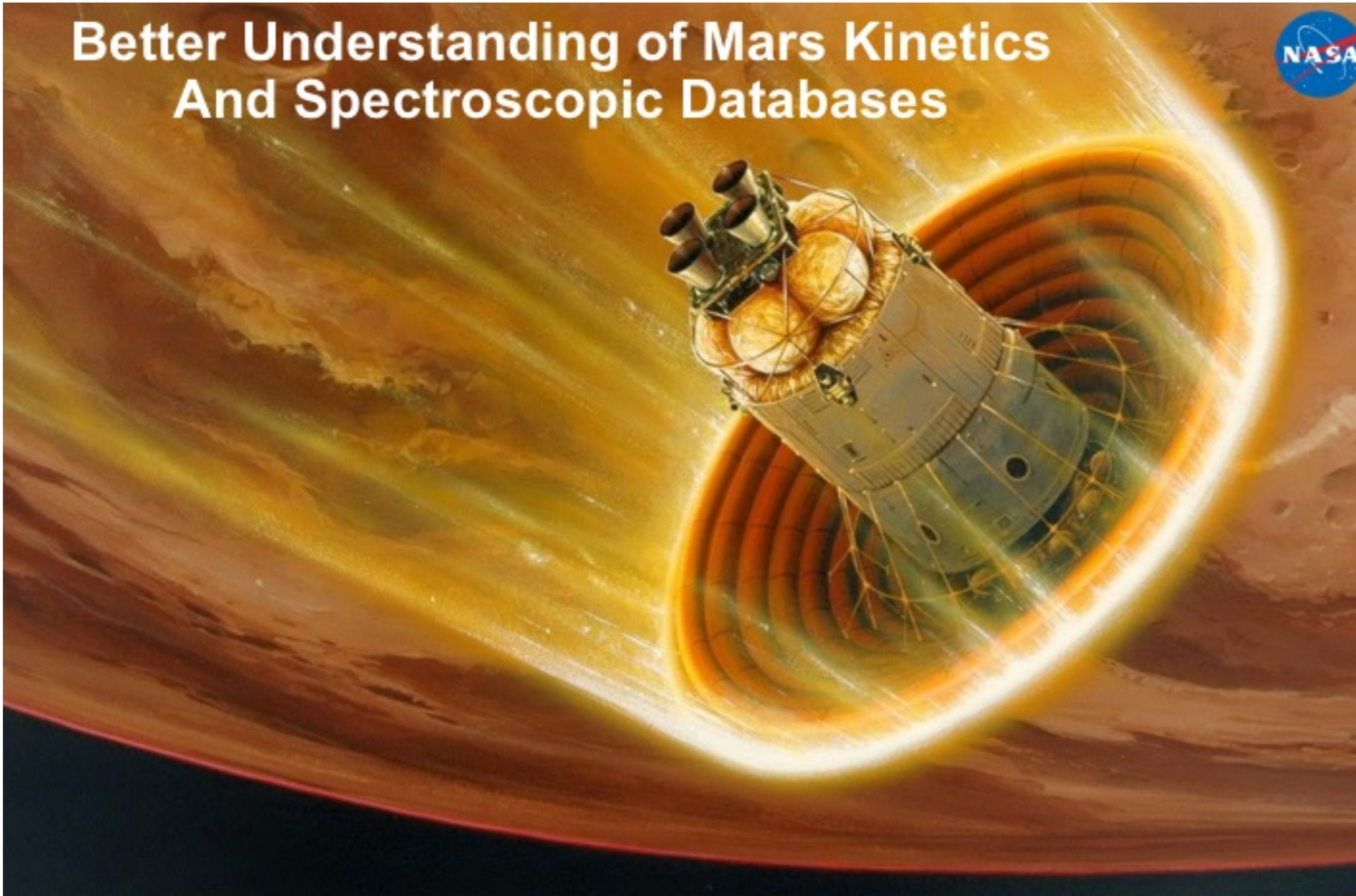
Impact of Radiation





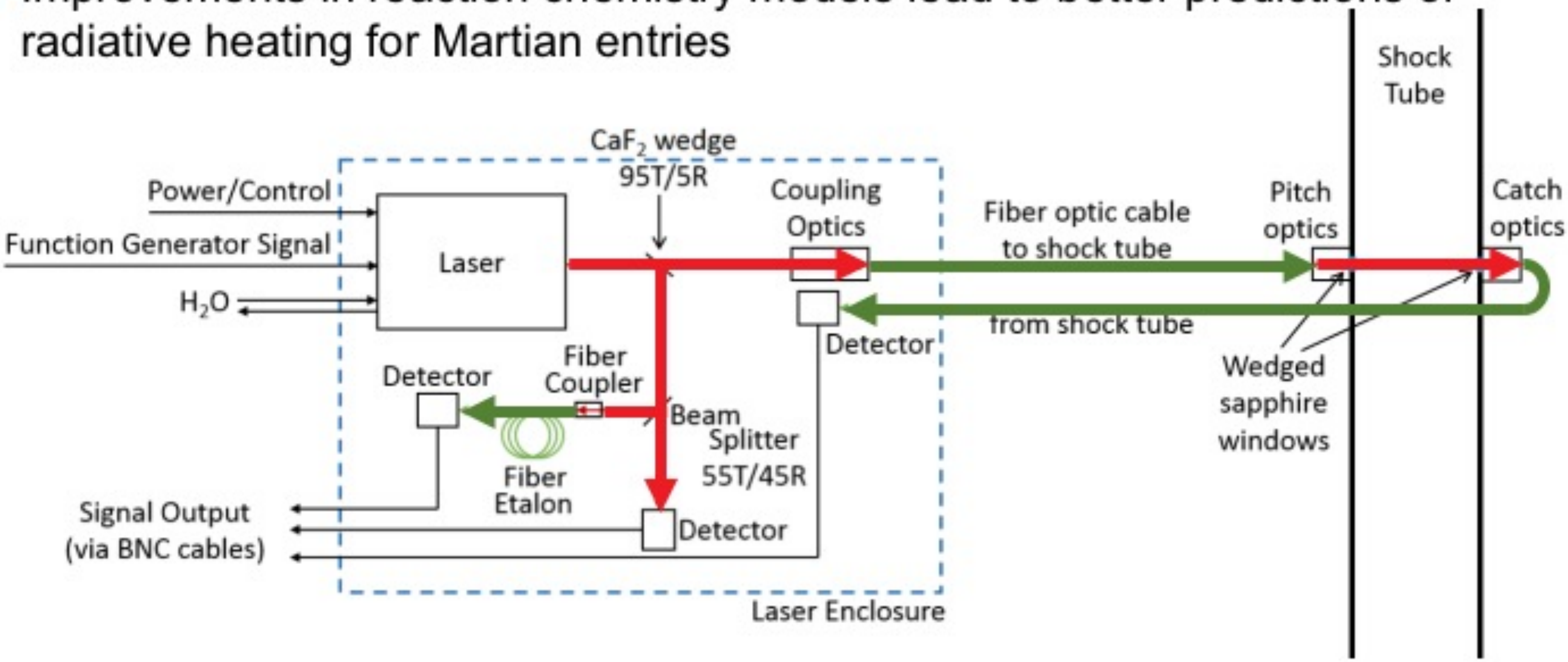
- Including radiation calculated by NEQAIR reduces heat flux discrepancy by approximately half
  - Heat load under-prediction reduced to 19%
- Peak heat flux is just within confidence interval at peak heating

Better Understanding of Mars Kinetics And Spectroscopic Databases



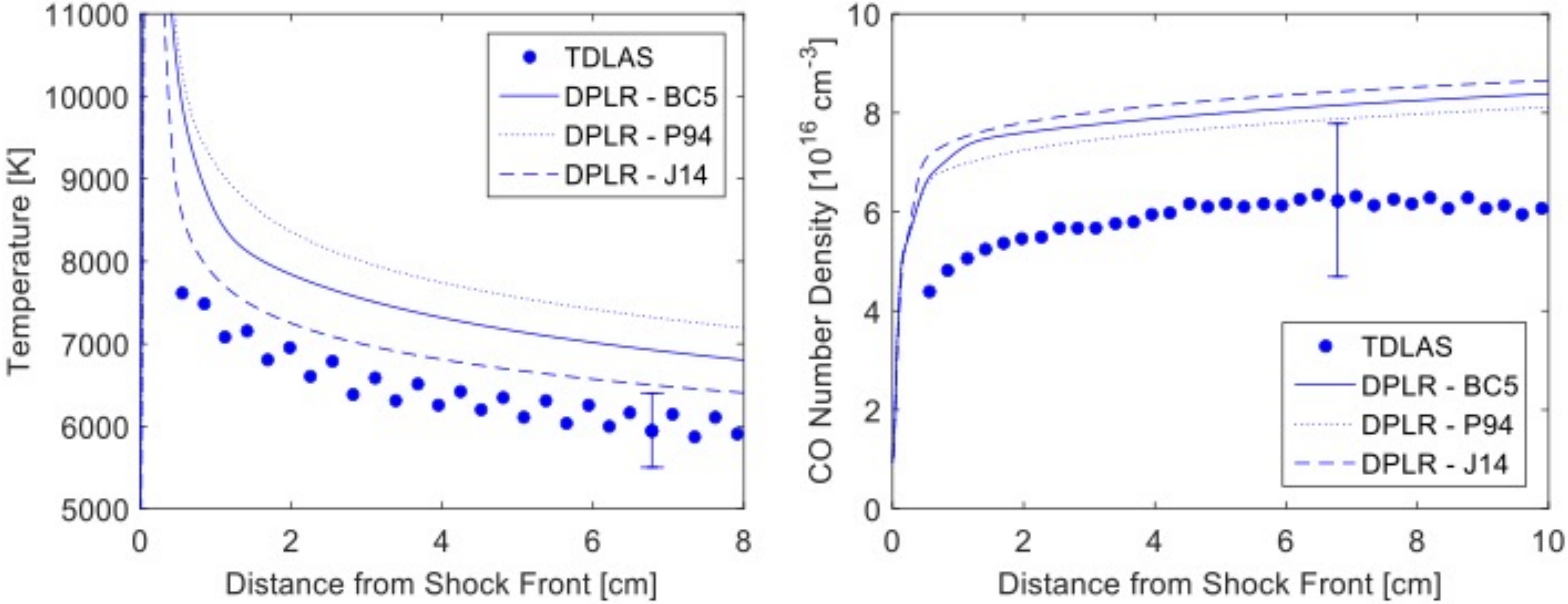
TDLAS Measurements in EAST

- Improve the understanding of the aerothermodynamics of Mars entries (predominantly CO_2 atmosphere)
- Aeroheating (convection + radiation) is dependent on reaction kinetics
- Absorption spectroscopy offers a measurement of CO number density
- Improvements in reaction chemistry models lead to better predictions of radiative heating for Martian entries



CO Comparison with Kinetic Mechanisms

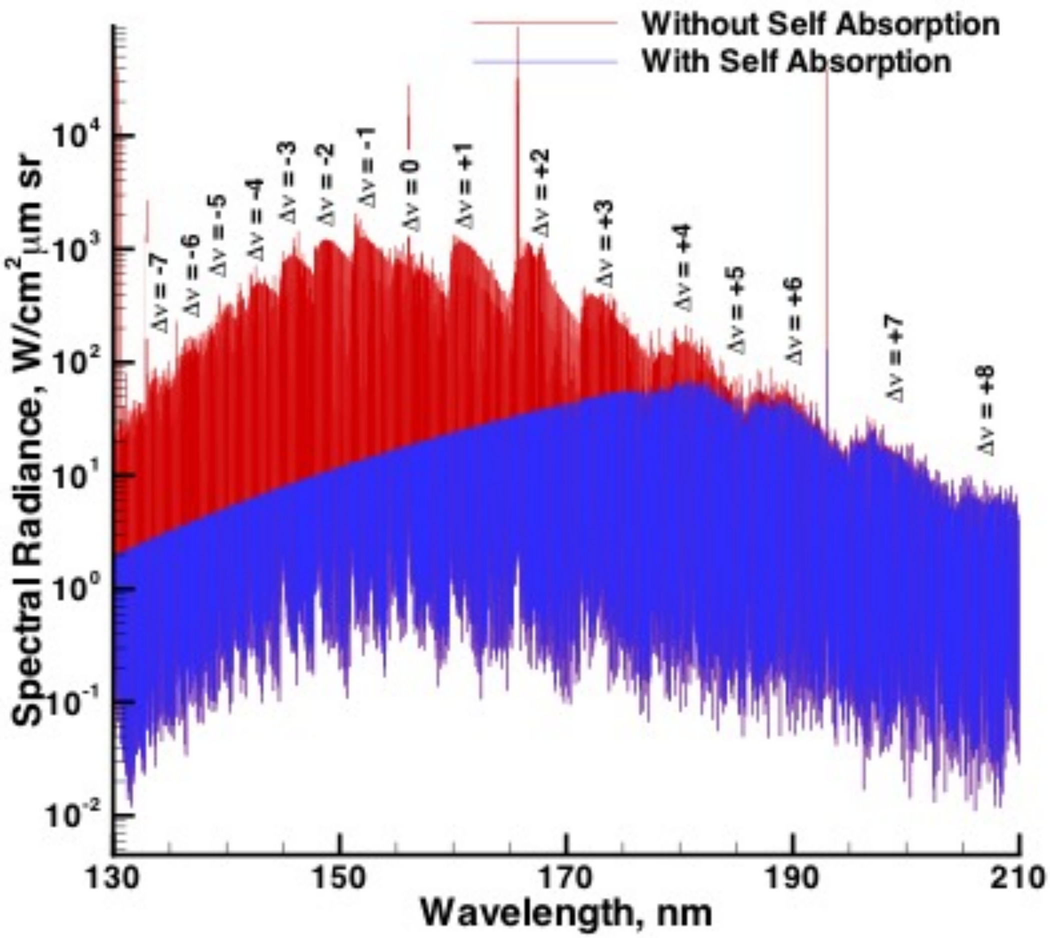
Pure CO, 33 Pa, 5.65 km/s



- Trends match for both temperature and number density
- Disagreement in number density due to uncertainty in line strength

Background – CO 4th Positive

- **CO 4th Positive significant component of radiative heating** (can be as high as 65 %) for high-speed Mars entries.
- Large portion of the **CO 4th Positive radiative intensity** is **black body limited**.



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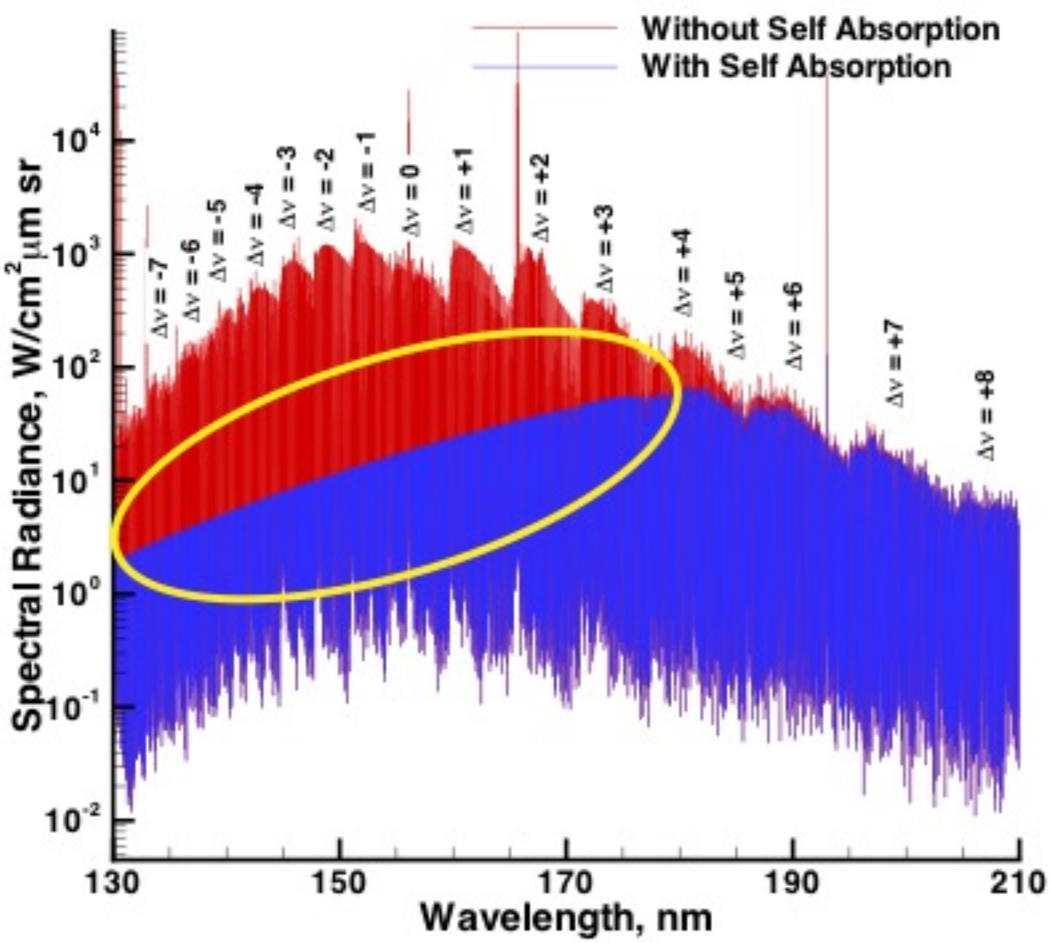
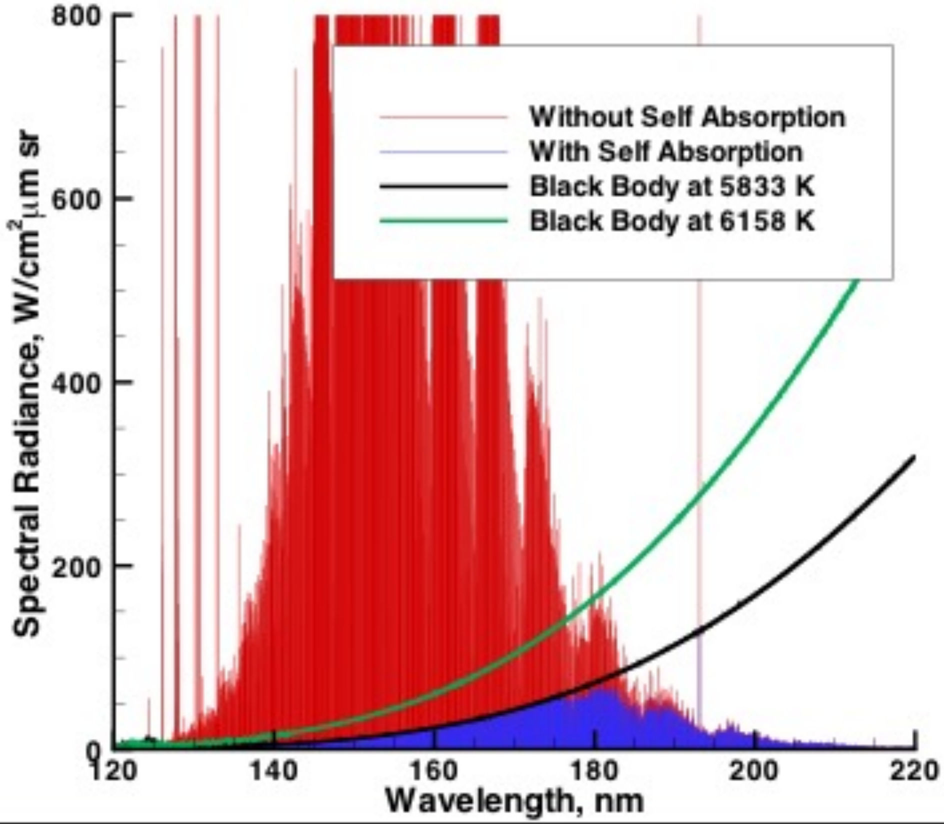


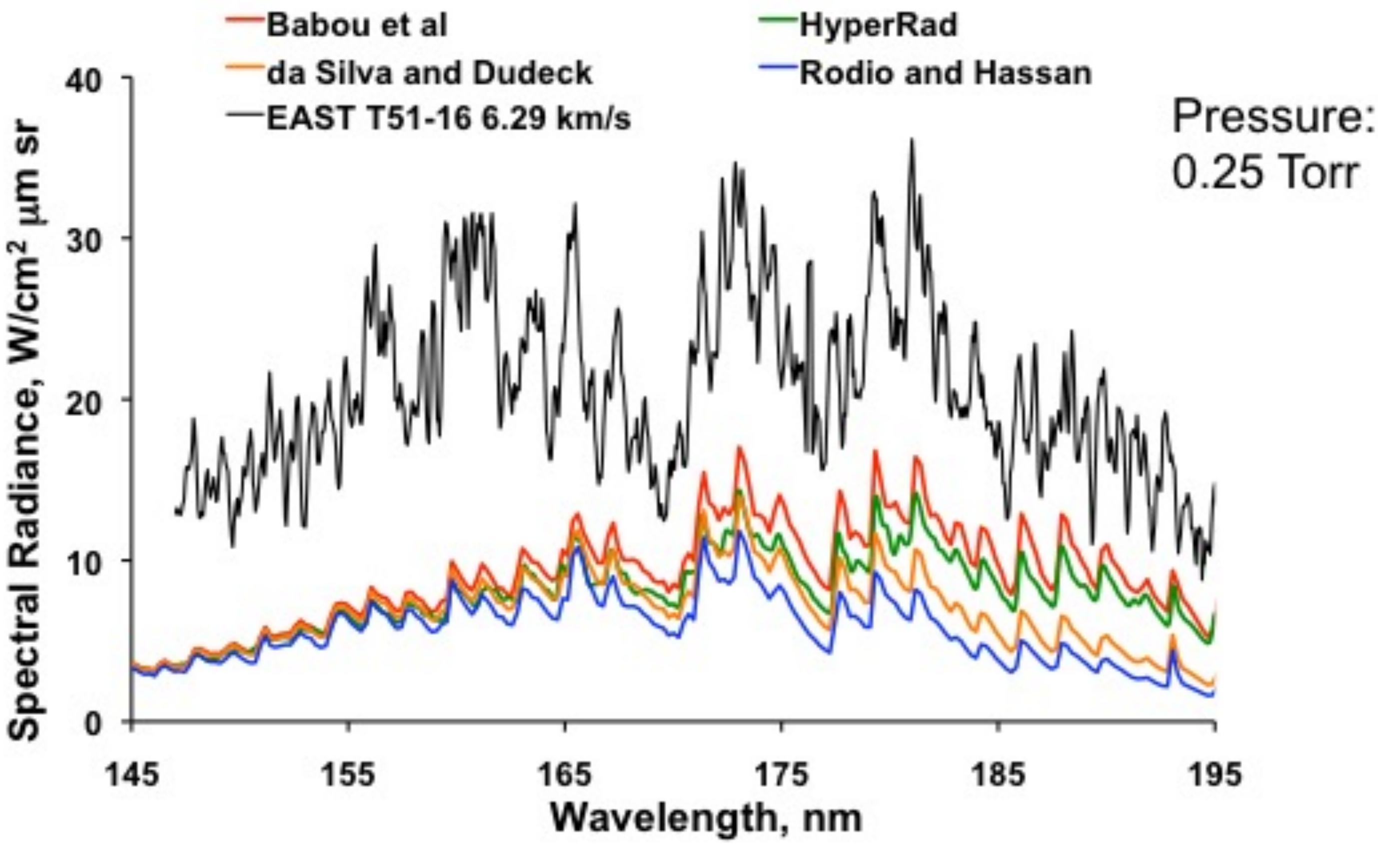
Background – Influence of Temperature

- **Intensity** of CO 4th Positive is **strongly dependent on the flow temperature**.



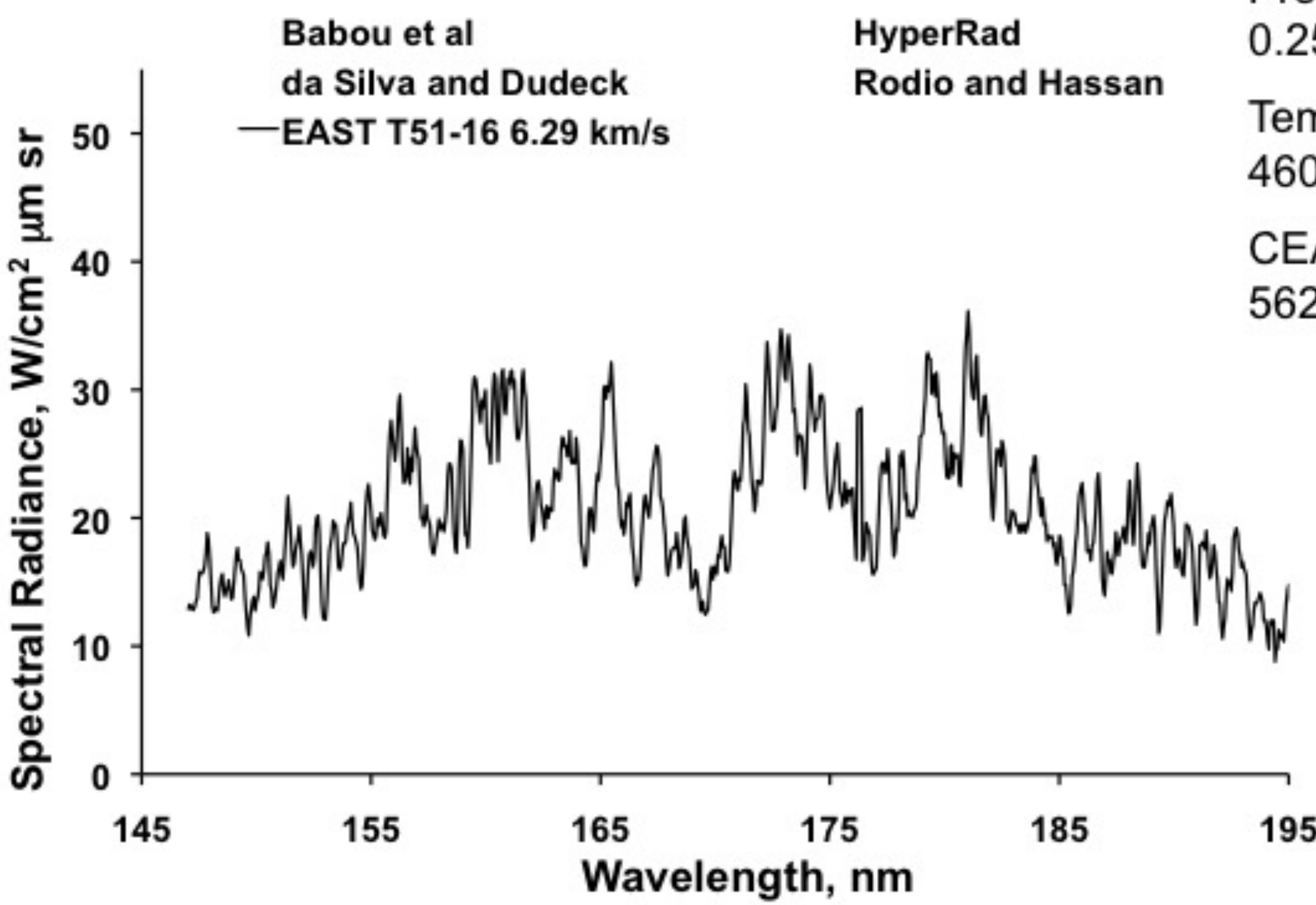
When temperature increases, the black body limit increases, allowing more radiation to be observed.

Analysis & Results - Equilibrium



All databases under-predict EAST using CEA equilibrium input

Analysis & Results – Black Body

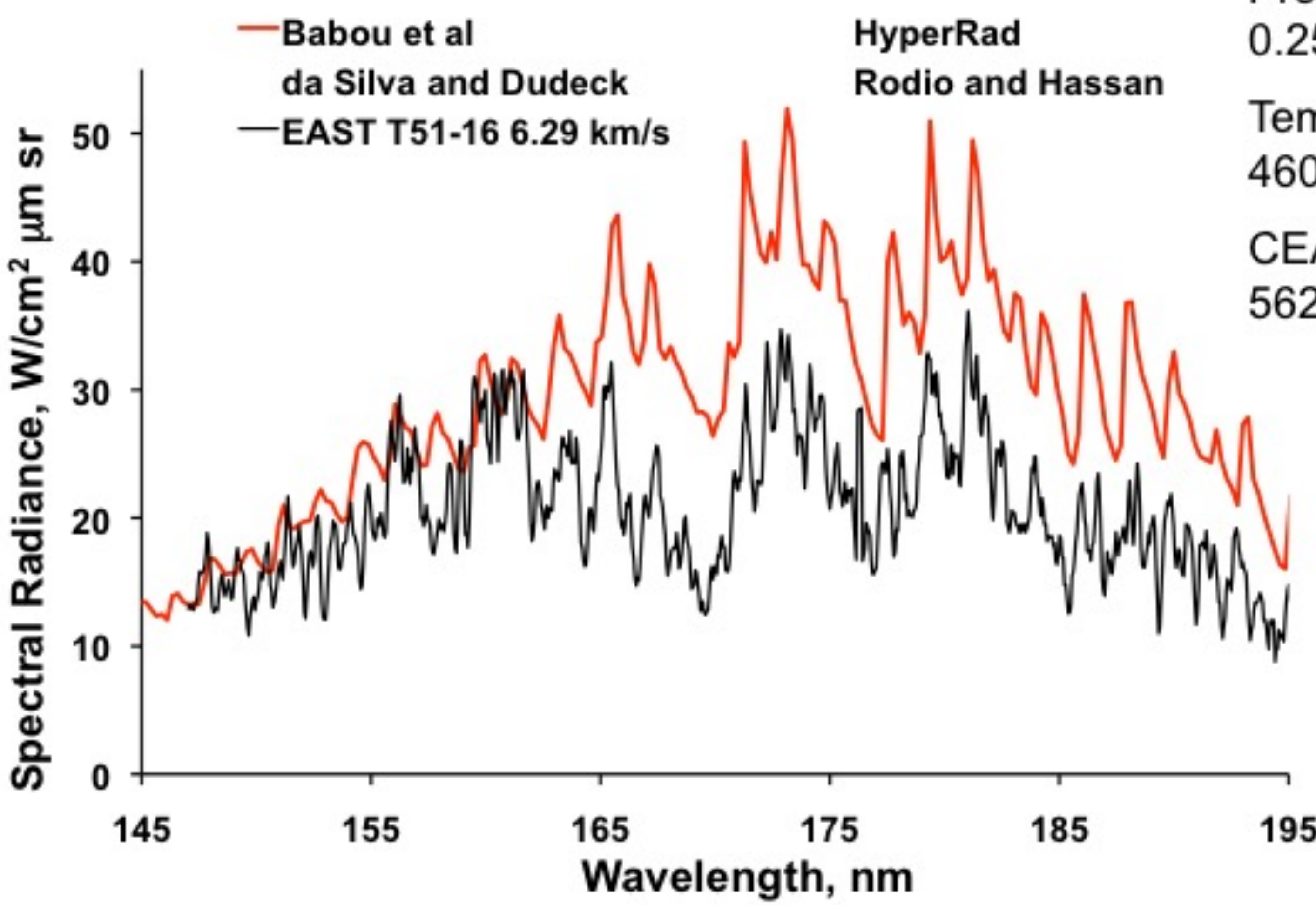


Pressure:
0.25 Torr

Temp Increase:
460 K

CEA Temp:
5625 K

Analysis & Results – Black Body



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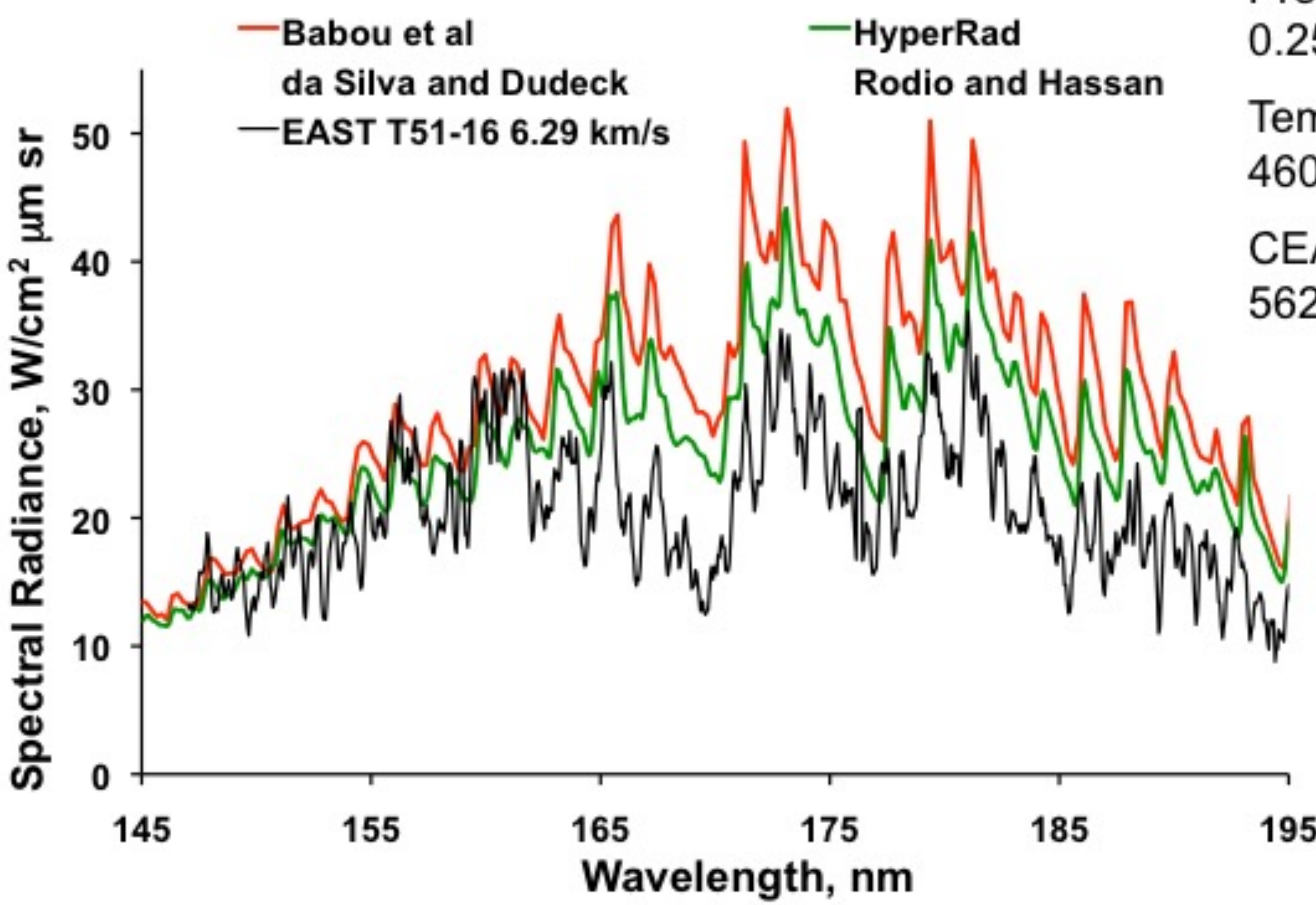

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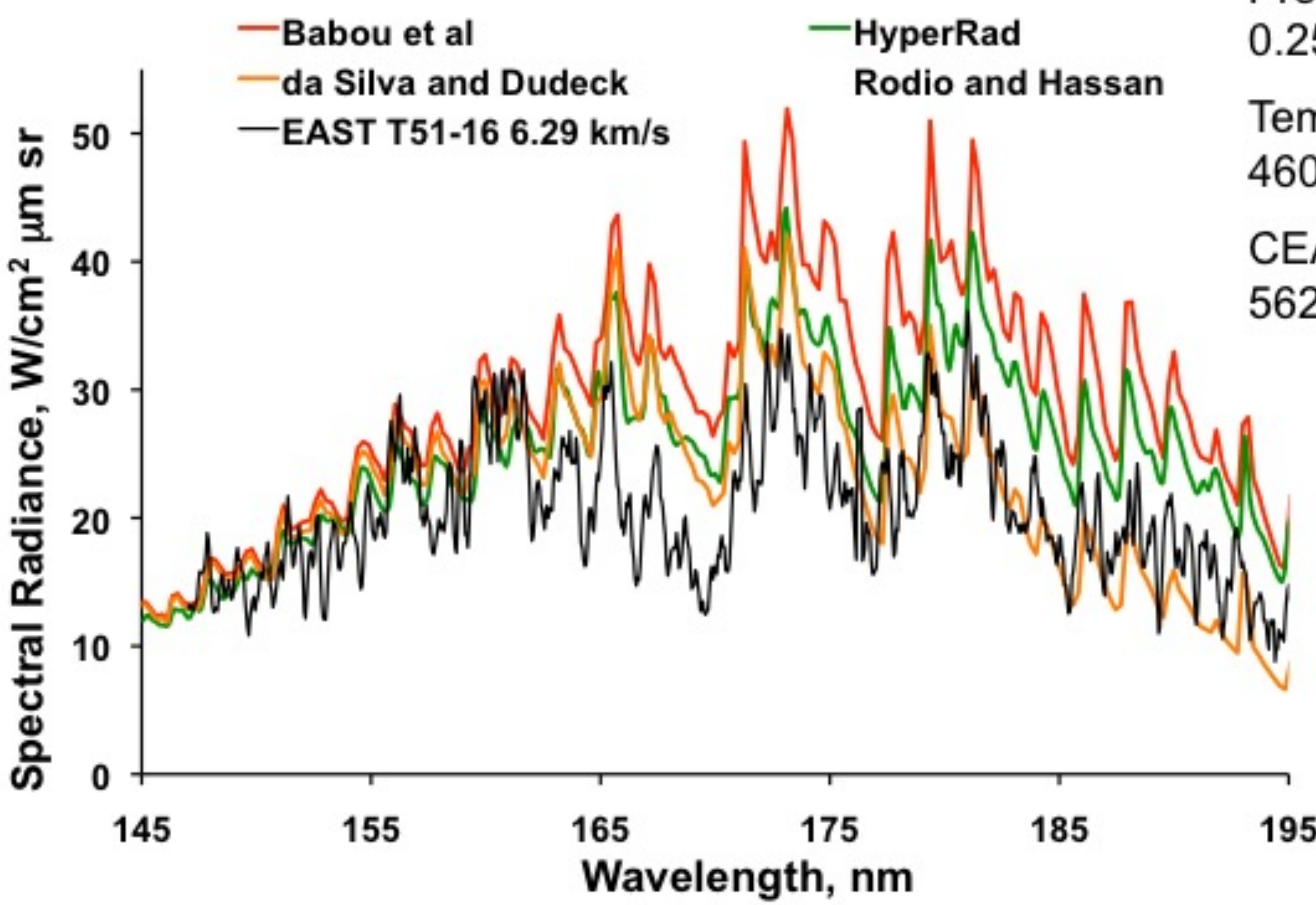

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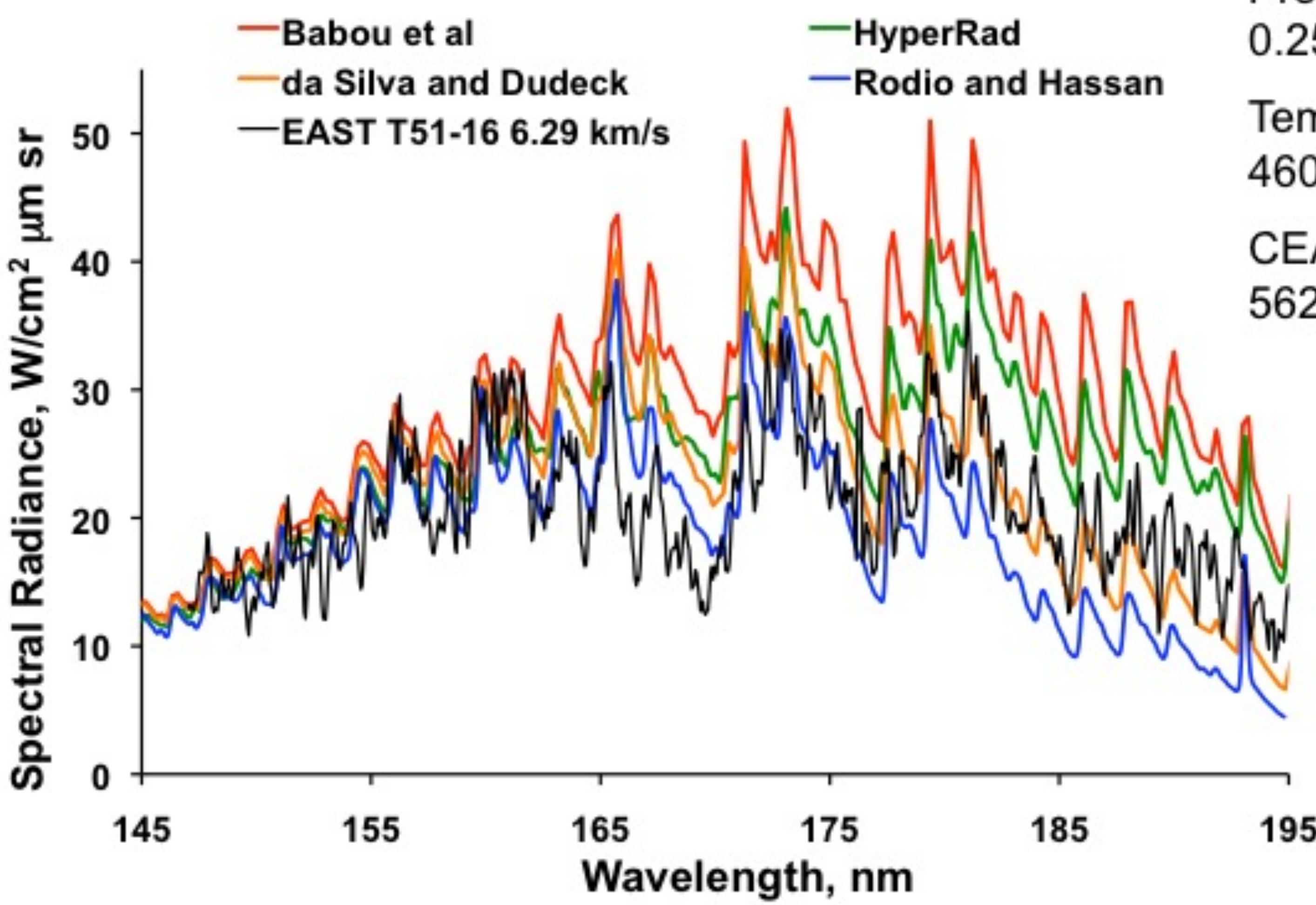
Analysis & Results – Black Body



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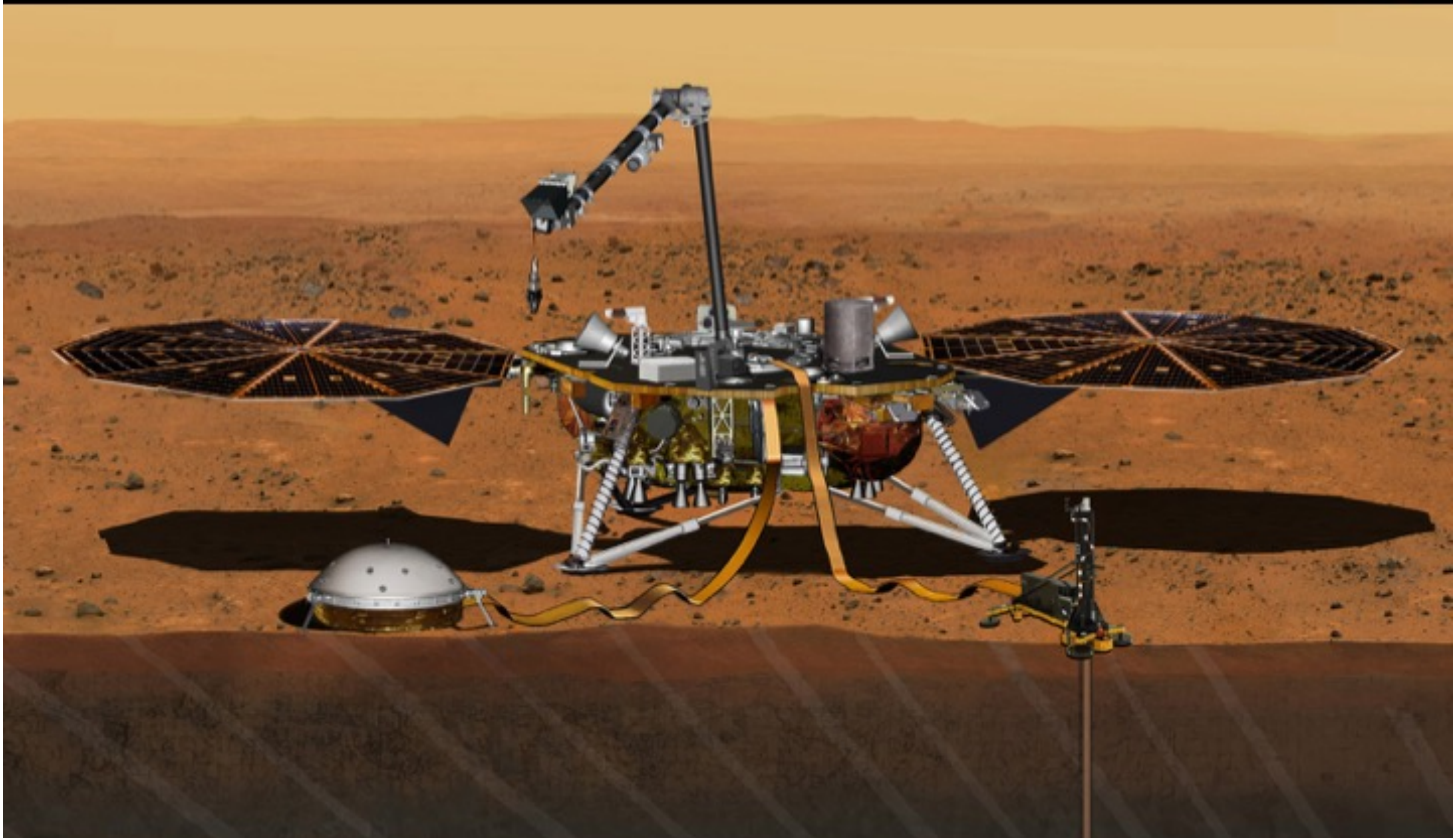
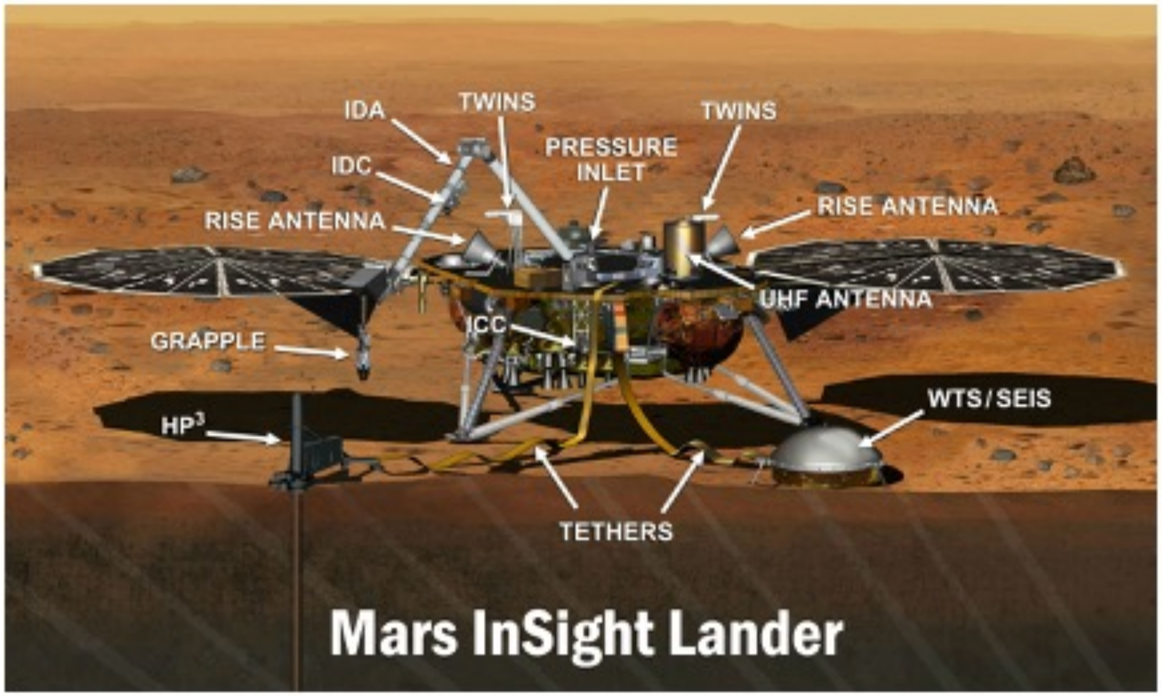
Mars InSight Lander



Influencing Mission Design



Mars InSight Mission

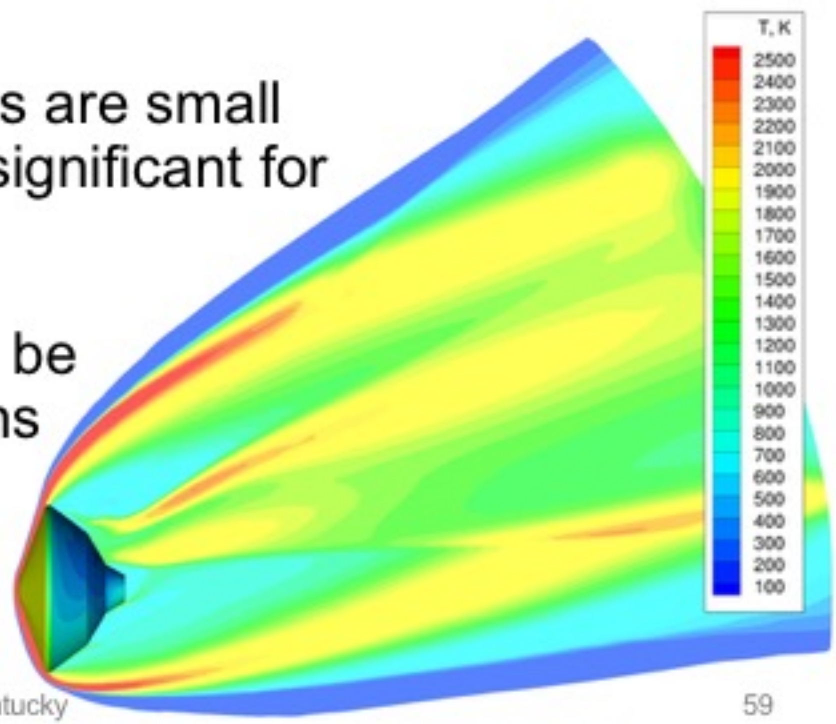
Scheduled to launch 5 May 2018

Vehicle based on the Mars Phoenix lander

Mission Objective: probe on the surface of Mars to study the planet's early geological evolution

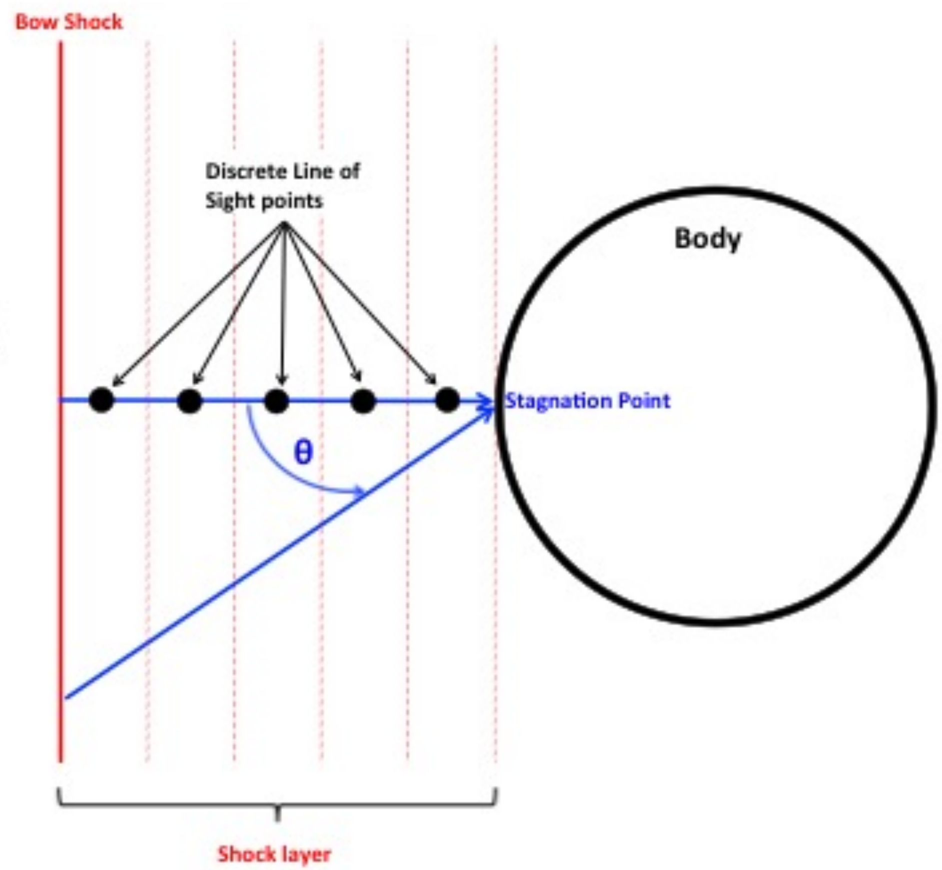
Mars Afterbody Radiation

- Radiative component of after-body heating has traditionally been neglected for Mars entry
- Recent theoretical analysis, simulations and experiments have highlighted the significance of Mid-Wave Infrared CO_2 radiation
- Radiative heating can substantially dominate convective heating on the after-body
- Even though absolute heat flux values are small compared to the fore-body, they are significant for back-shell TPS
- After-body radiative heating needs to be considered for all future Mars missions
- Significant analysis effort for both Mars 2020 and InSight



What is Tangent Slab?

- Tangent slab assumes that the properties are constant across an infinite slab parallel to the line of interest
- This approximation allows for a fast evaluation of the heat flux
- Typically assumed to be accurate (within 10%) for the majority of the fore-body

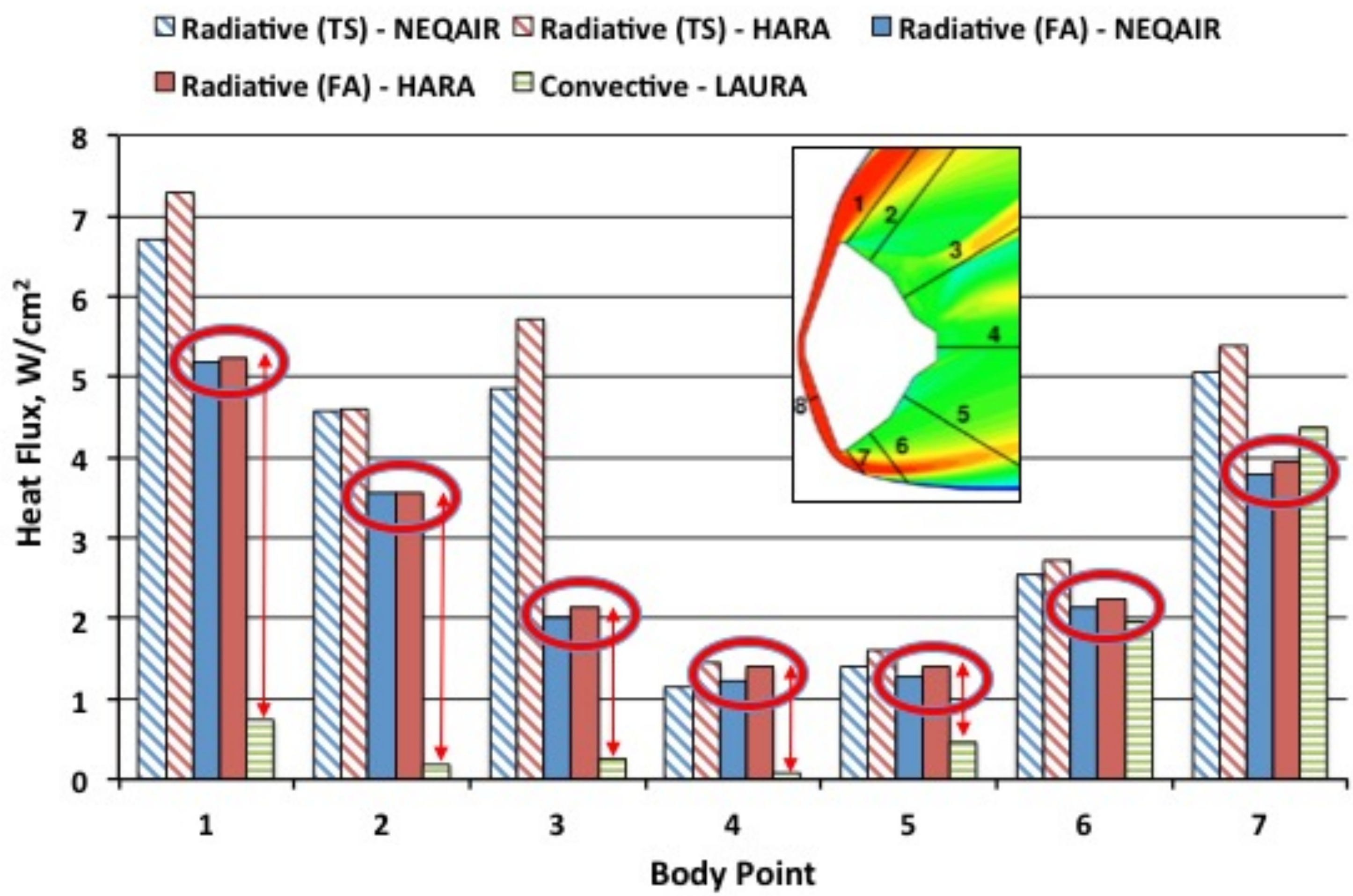


What is Full Angular Integration?

- A numerical integration over solid angle for a given body point
- A unit sphere is created which is centered at the body point and tangential to the surface
- Lines of sight are constructed from each body point extending to the outer grid boundary
- Each individual line of sight is calculated in 1-D
- The radiance from all lines is integrated over solid angle

Heat Flux for InSight

t = 87.5 s (Peak After-body Radiative)



- Excellent agreement between Ames (DPLR/NEQAIR) and Langley (LAURA/HARA) codes
- Radiation frequently dominates convective heating

Entry Systems and Technology Division
Ames Research Center

National Aeronautics and
Space Administration

Titan Atmospheric Entry Radiative Heating

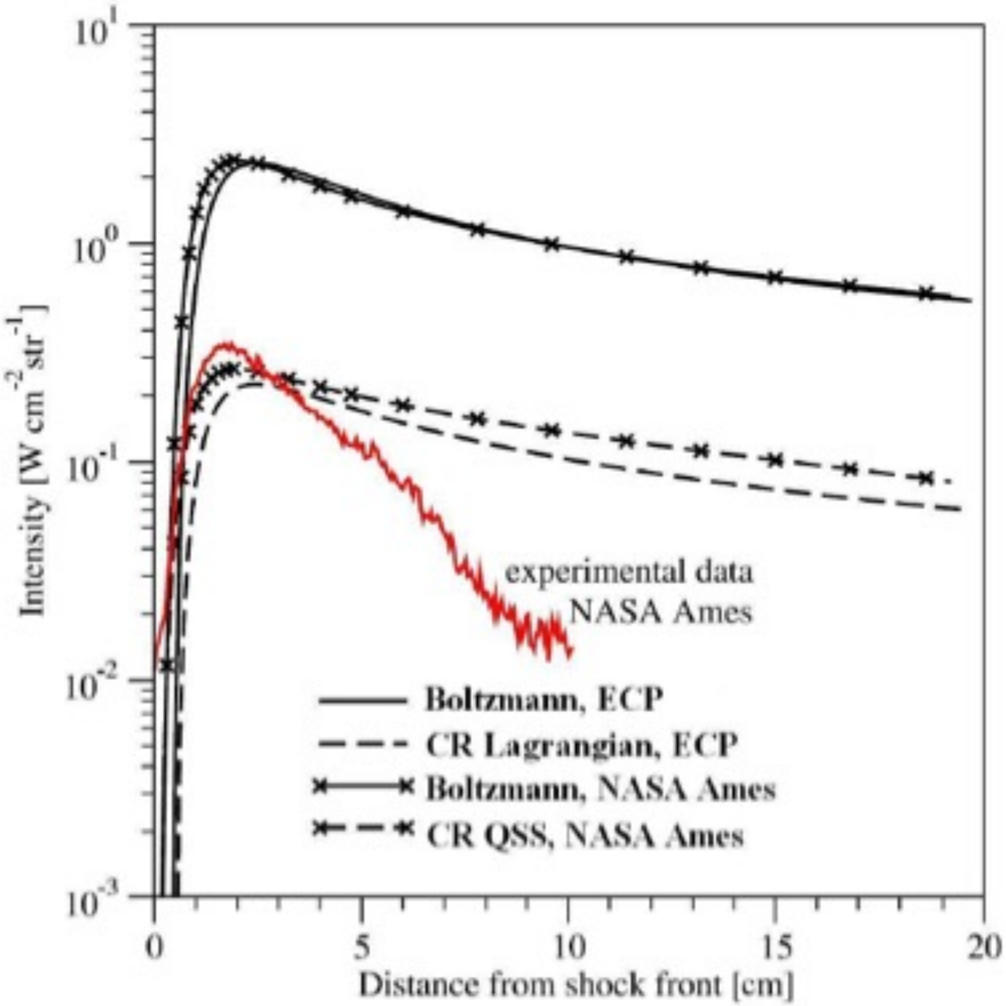
Previous Titan Radiation Studies

- The joint NASA/ESA Cassini/Huygens mission resulted in significant efforts to understand radiative heating for Titan.
- Post flight simulations were conducted assuming a Boltzmann distribution of CN excited states
  - If this were to be the case, Huygens may have burnt up during entry
- Consequently, experiments were performed in shock tubes and QSS/CR models developed.
- Reasons to believe there were issues with previously reported Titan (pre-upgrade) EAST data.
- Current interest in heading to Titan with two New Frontiers proposals
- Warranted to update published data due to improvements available with the current EAST set up

Previous Titan Radiation Studies

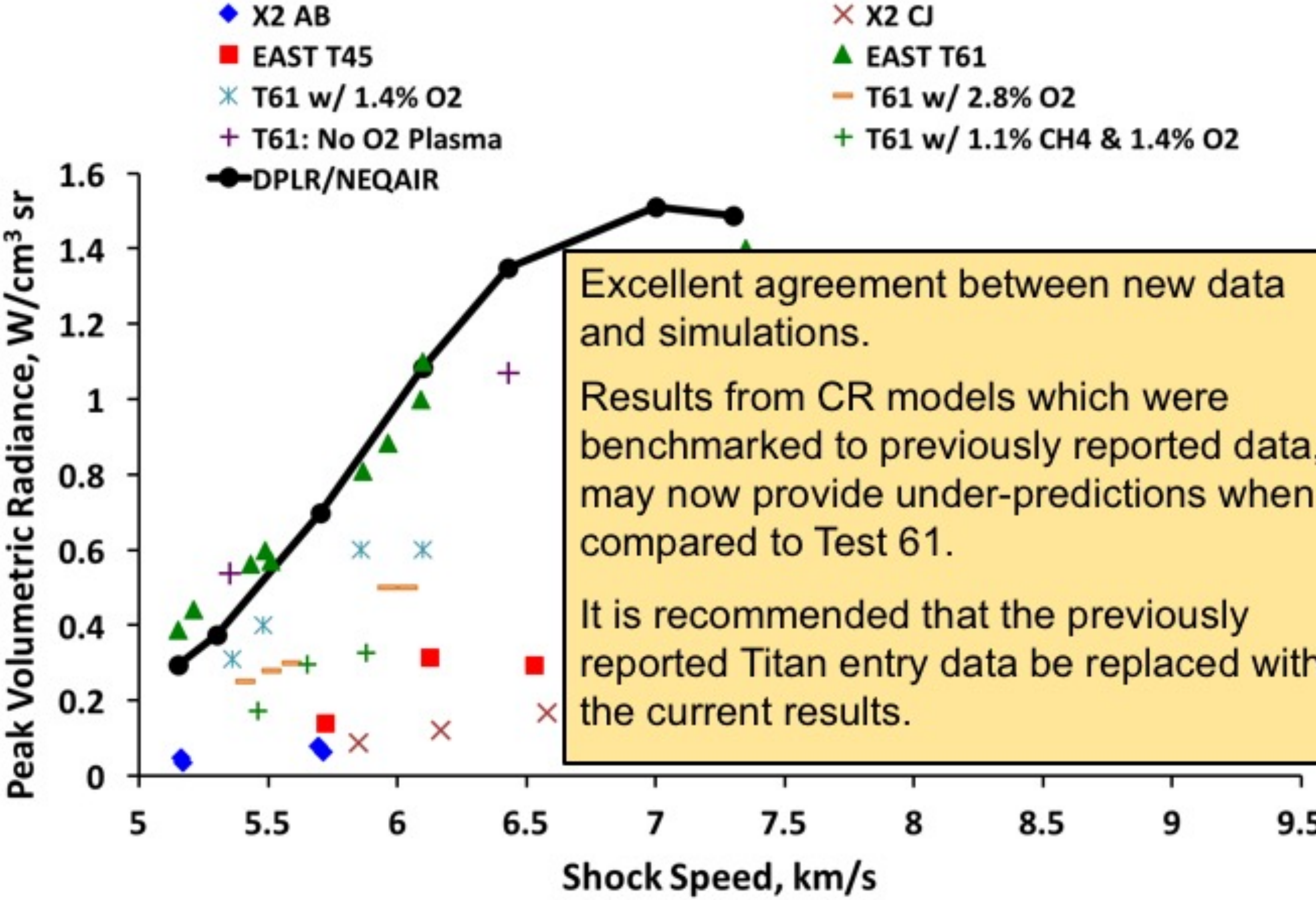
5.15 km/s, 98% N_2 : 2% CH_4, 0.1 Torr,

400 – 430nm. EAST T43-25



- Test 43 & 45 from EAST (2003 to 2005)
- Boltzmann predictions shown to substantially over-predict
- CR models deemed to adequately match peak (within a factor of ~2)
- Simulations showed slower decay rate than experiment
- X2 from Brandis & Jacobs

Comparisons To Previous Data: X2, Test 45



Excellent agreement between new data and simulations.

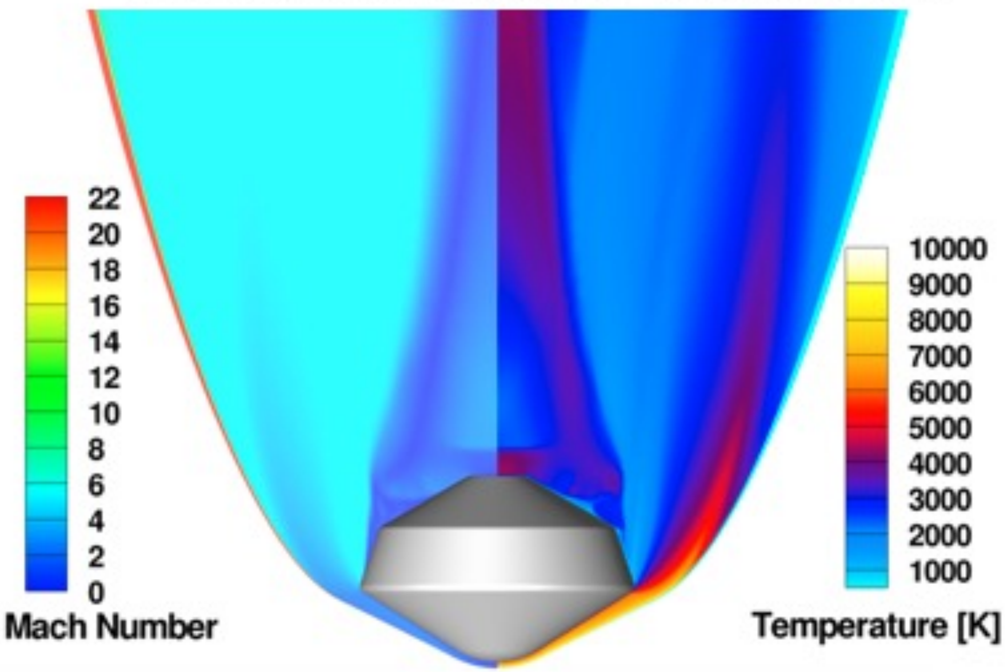
Results from CR models which were benchmarked to previously reported data, may now provide under-predictions when compared to Test 61.

It is recommended that the previously reported Titan entry data be replaced with the current results.

Exciting Opportunities…

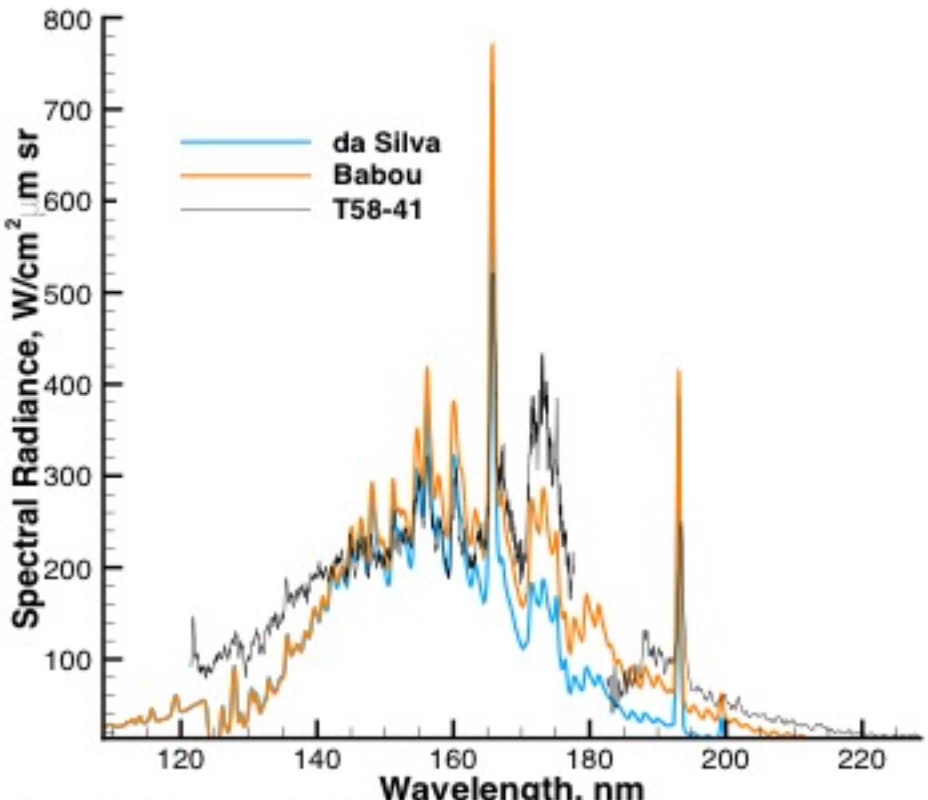
Exploring Titan with Dragonfly

- Dragonfly is a New Frontiers proposal by the Johns Hopkins Applied Physics Laboratory
- Send the first rotorcraft to another celestial body in order to study prebiotic chemistry and extraterrestrial habitability.
- Titan is unique in having complex and diverse carbon-rich chemistry on the surface, methane lakes and an interior ocean, making it a high-priority target for astrobiology.



Recent Testing – CO_2/Ar

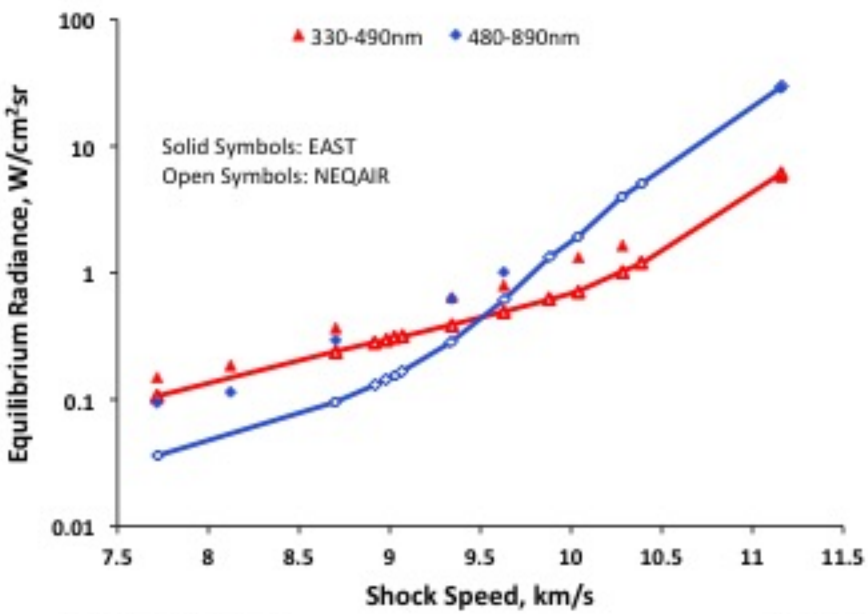
- Particular interest for Mars and Venus entries
- Several EAST tests have helped develop/confirm equilibrium radiation models and CO_2 reaction kinetics.
- However, results remain somewhat ambiguous
  - e.g. HARA and NEQAIR use two distinct CO 4th Positive models are used
  - Under different conditions or assumption one is observed to agree better than the other
  - The choice of spectroscopic database influences inferring reaction rates from EAST data

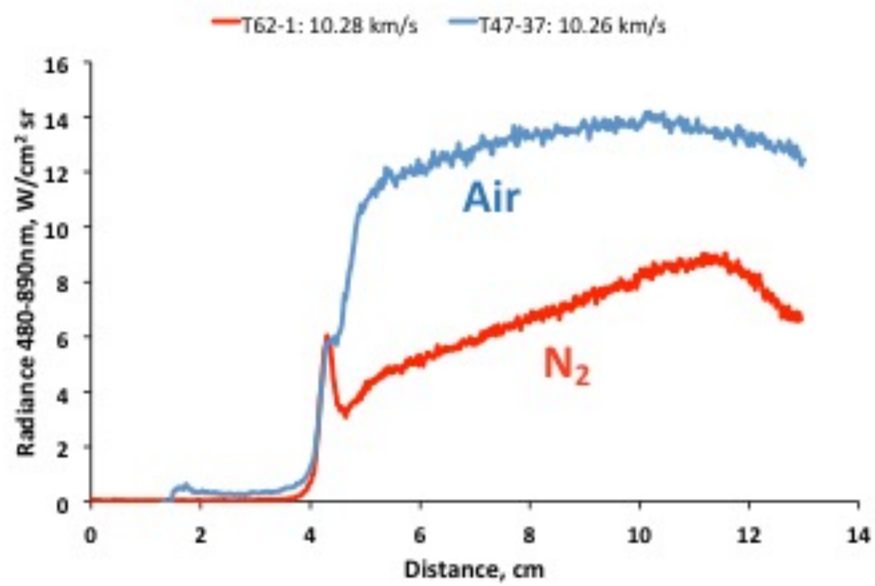


- Hybrid spectral database might provide better solution
- Possible test series to repeat with TDLAS and/or with 24" tube

Recent Testing –100% N_2

- Kinetic models for atmospheric entry involve many inter-connected reaction mechanisms
- Difficulties can arise when trying to validate specific rates.
- This test campaign provides data in a less complicated system, focusing on pure nitrogen, therefore no distractions



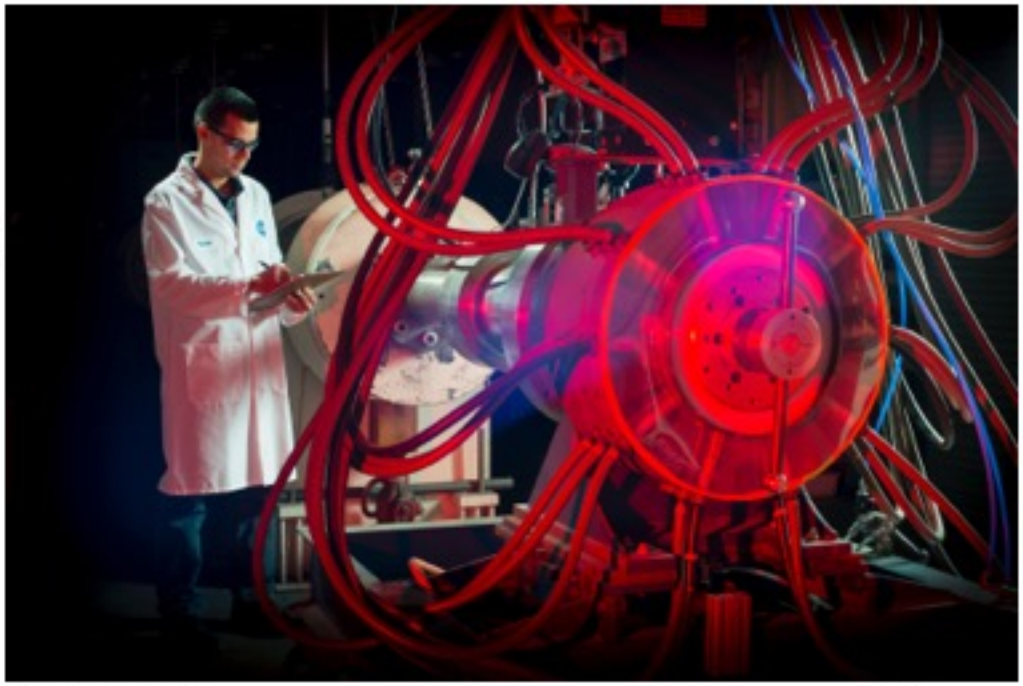


Benchmark EAST Earth Data

- Large number of EAST experiments
  - Great for statistical analysis, but problematic for identifying representative shots for detailed analysis
  - Provide more accessible data for future code validations and facility-to-facility comparisons
- Benchmark experiments are the ones in closest agreement to line of best fit and with the best experimental characteristics
- Data is reported in different formats for analysis, and all the information needed to simulate EAST is provided
- Data can be found at:
  - https://data.nasa.gov/docs/datasets/aerothermodynamics/EAST/index.html

Future EAST Plans

- What's in the pipeline for future EAST testing?
  - Using carbon/hydrogen based test gases (e.g. acetylene, C_2H_2) to mimic ablation species
  - At present, outer planets testing has been performed with just H/He, when in reality there is also some CH_4
    - This could drastically effect the formation of ions/electrons
  - Place a nozzle on to the EAST facility to expand the flow to mimic backshell radiation
  - More tests in the 24" tube facility with an aim to improve lower speed Earth and Mars tests
    - Focus on lower density regimes.



Acknowledgements

- EAST Facility Operations
  - Mark McGlaughlin, facility manager
  - Ramon Martinez
  - Rick Ryzinga
- NASA Radiation Group
  - Brett Cruden
  - Chris Johnston
- Project Management
  - Michael Wright/Michael Barnhardt, Entry Systems Modeling

Conclusions

- EAST Facility is a nation-unique facility capable of achieving flight-similar conditions for entry vehicles
- Analysis with NEQAIR and DPLR, combined with the data from EAST have been used to quantify the nature and magnitude of radiative heating for re-entry problems
  - Multi-purpose crewed vehicle/Orion, MSL, Mars 2020, New Frontiers proposals
  - Informs accuracy of predictive models
  - Allowed reduction of aerothermal margin for radiative heating
- Benchmark datasets from recent EAST Earth re-entry test campaigns have been identified.
  - Data can be found at:
    - https://data.nasa.gov/docs/datasets/aerothermodynamics/EAST/index.html

Challenging Missions for Radiative Heating

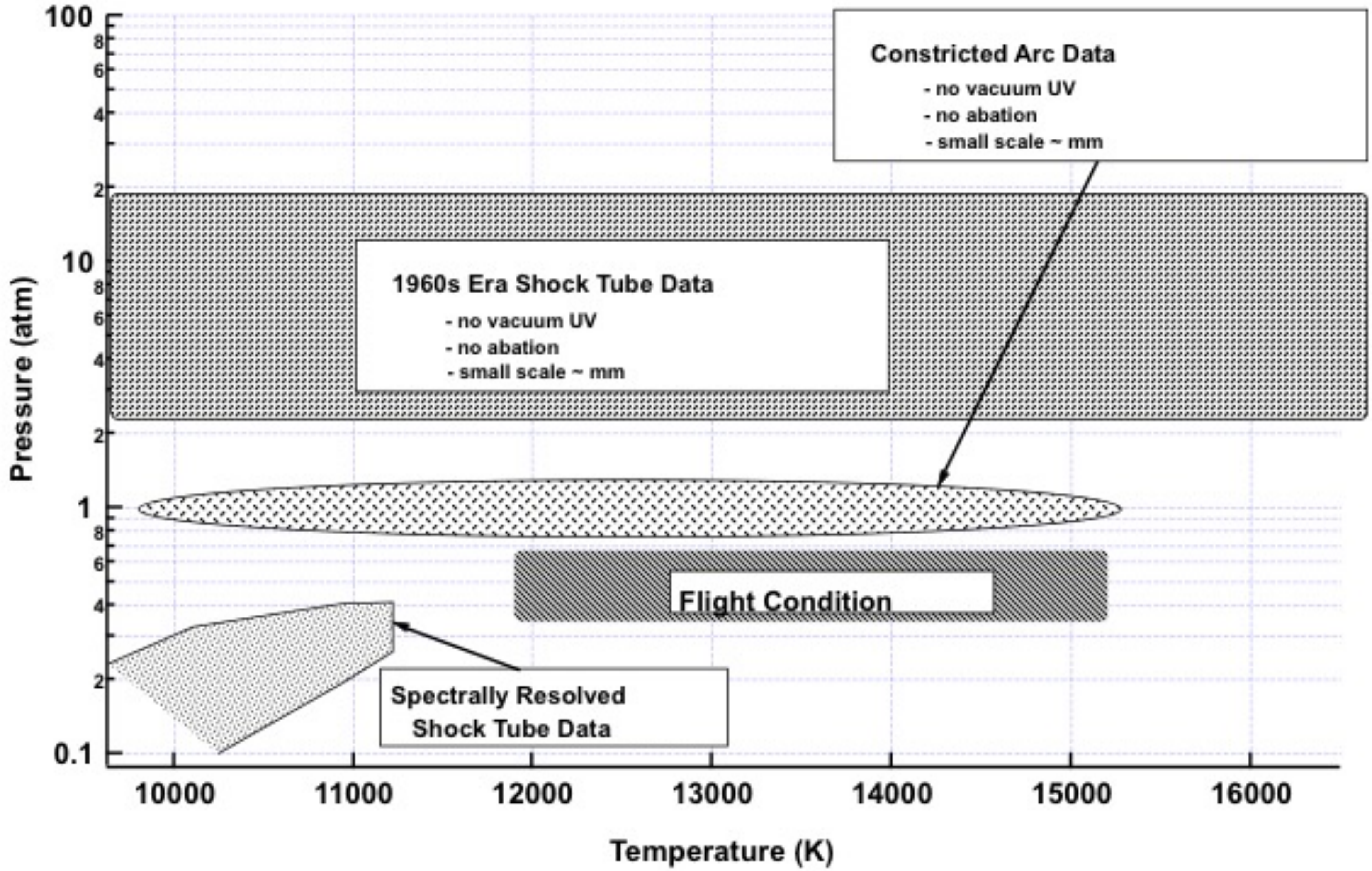
Lots of interesting and exciting opportunities for research…

National Aeronautics and
Space Administration

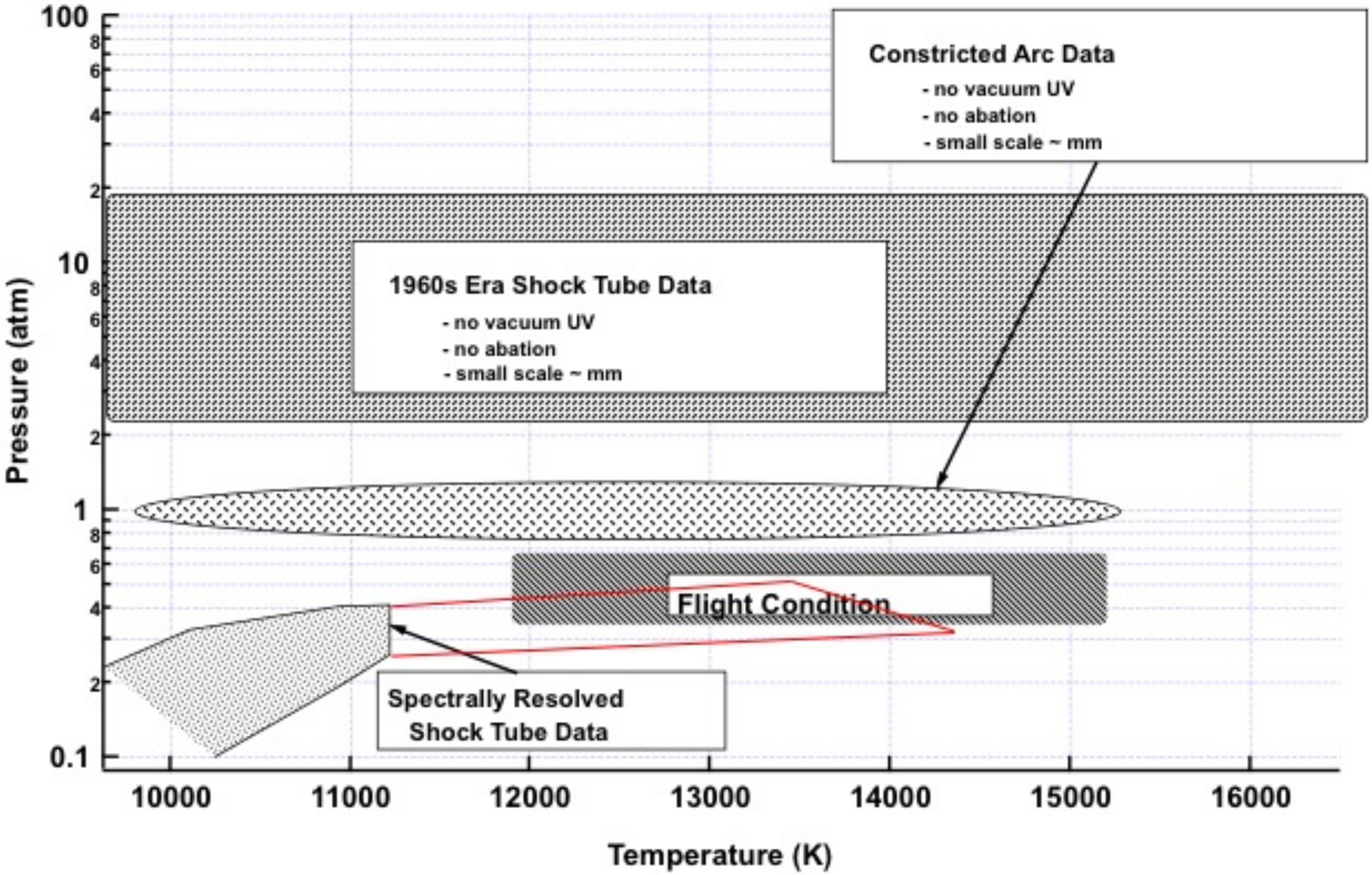
Ames Research Center
Entry Systems and Technology Division


High Speed Earth Return
October 20, 2017
University of Kentucky

High Speed Earth Entry Data



High Speed Earth Entry Data



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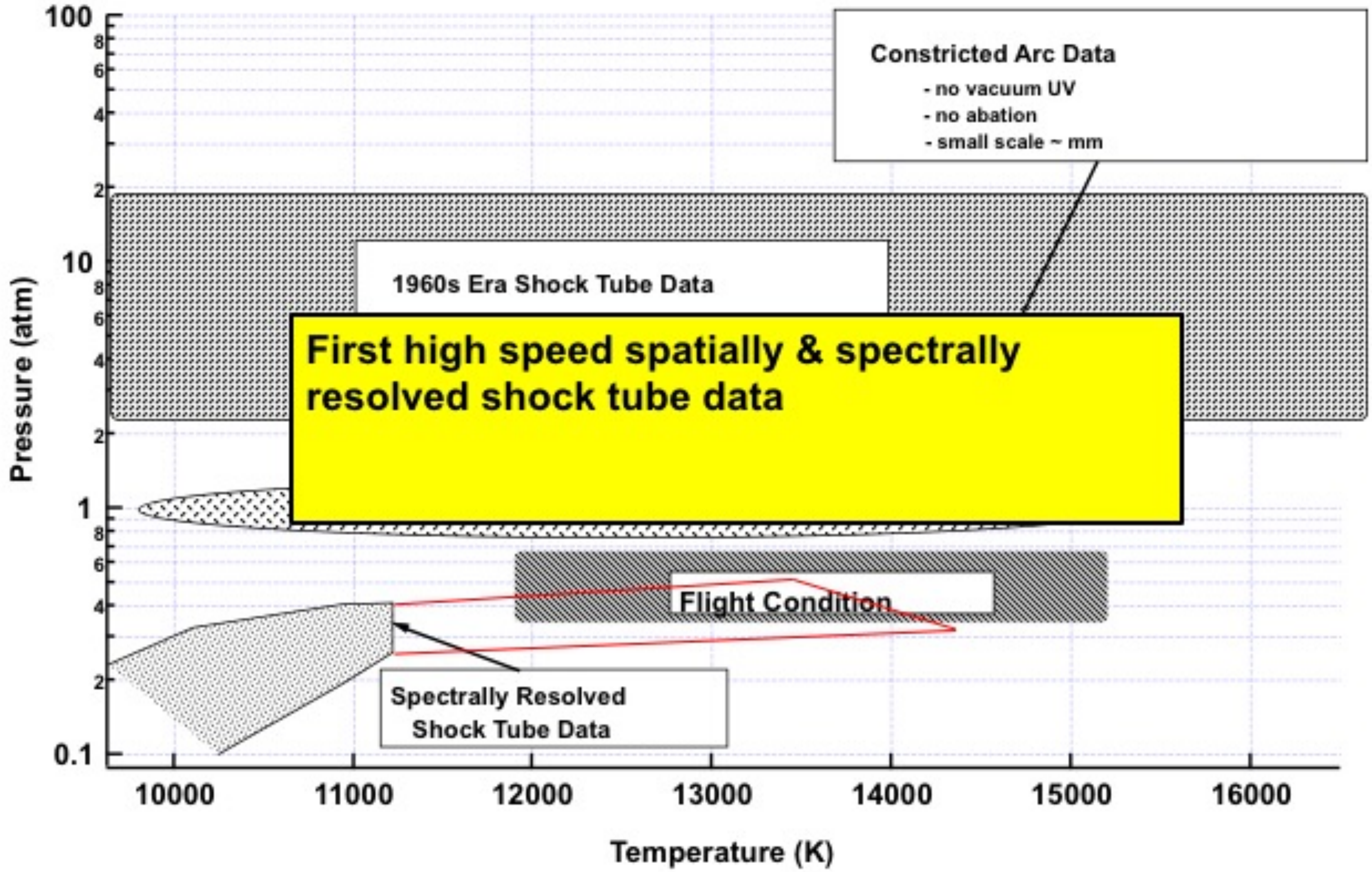

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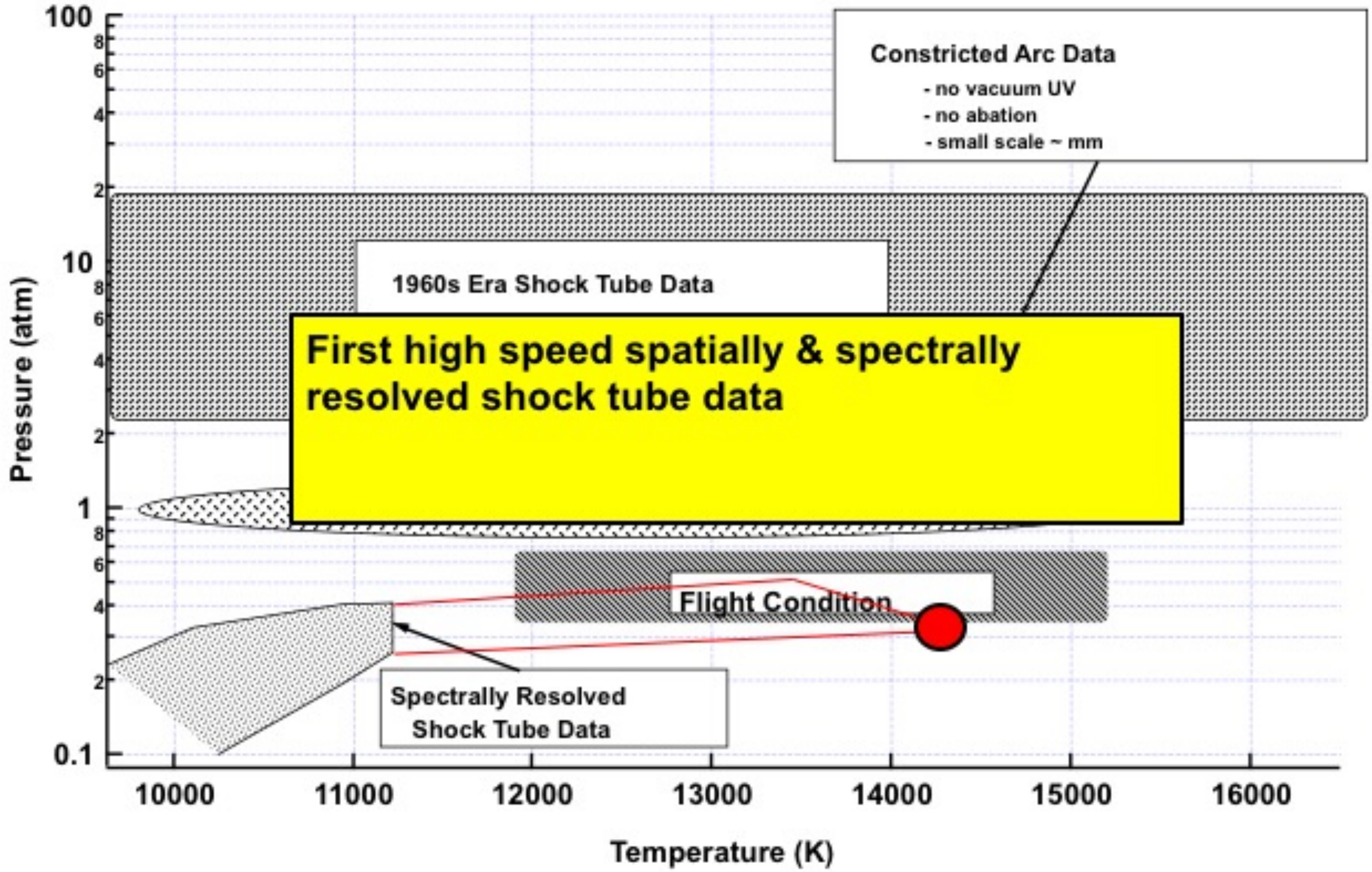
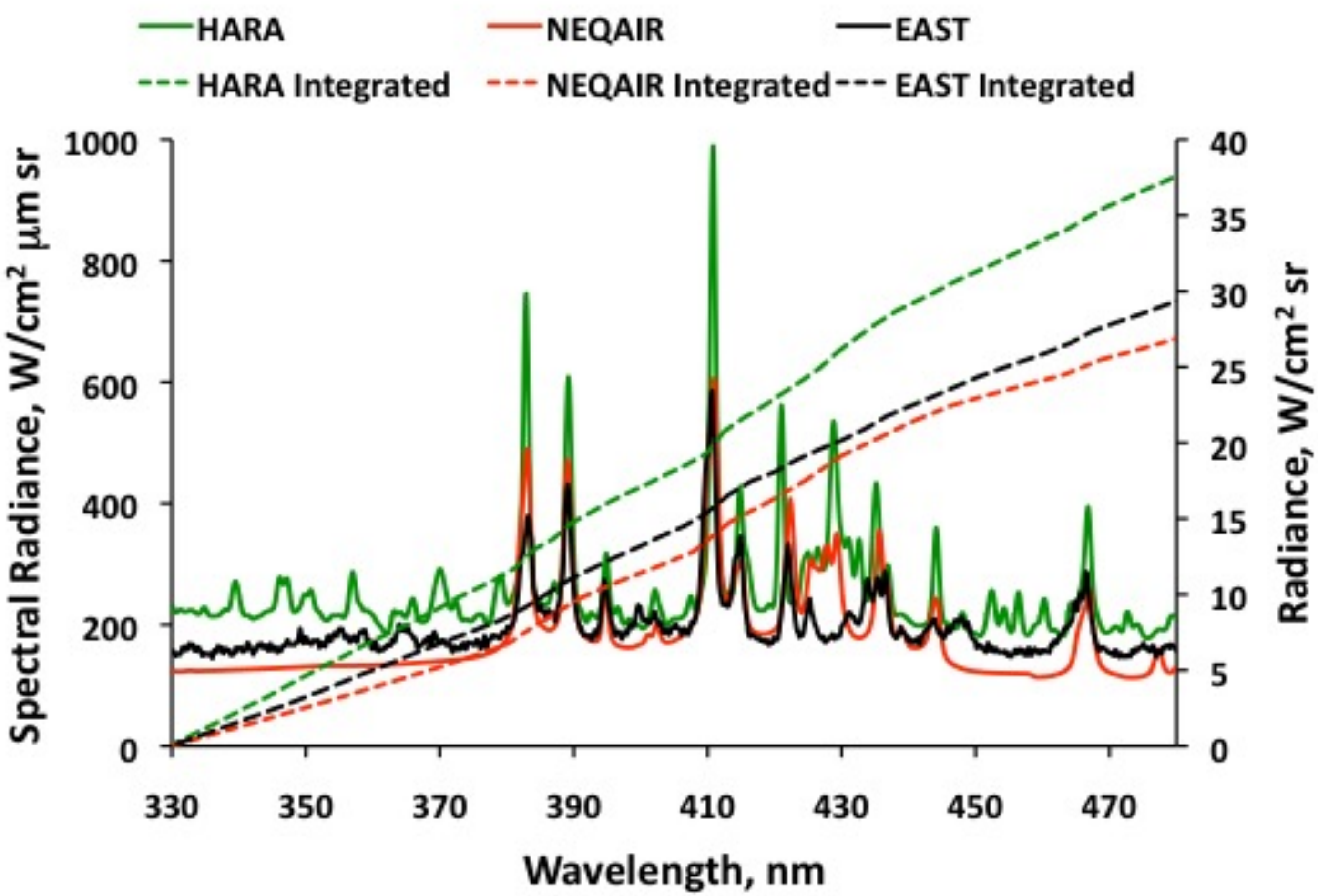


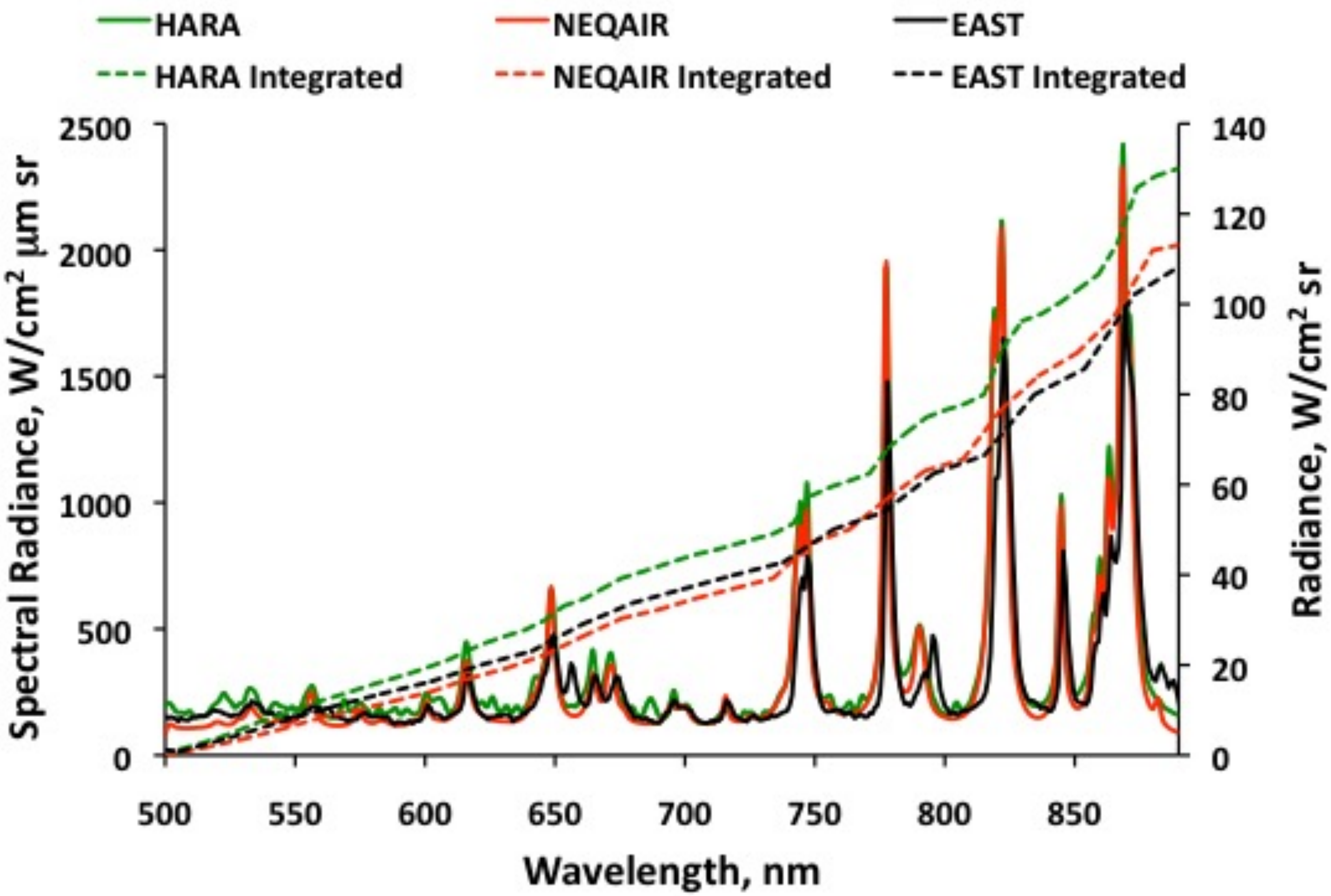
Spectral Comparison 15.5 km/s: UV/Vis

Good agreement for both codes in UV/Vis within 30%



Spectral Comparison 15.5 km/s: Vis/NIR

Excellent agreement for both codes in Vis/NIR within 20%



Improving Our Understanding to Explore the Gas Giants