Measurement and Prediction of Radiative Non-equilibrium for Air Shocks Between 7-9 km/s

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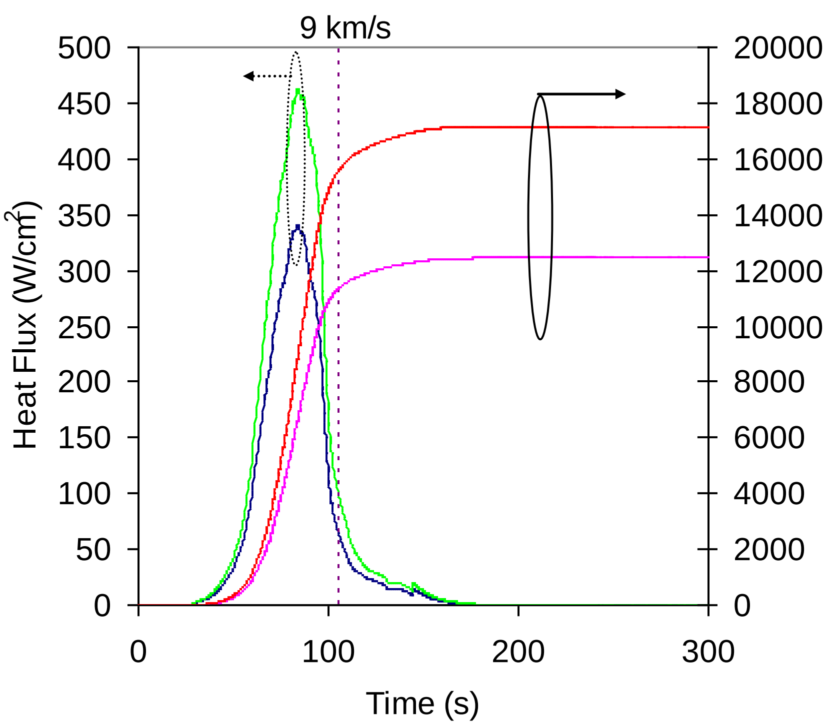
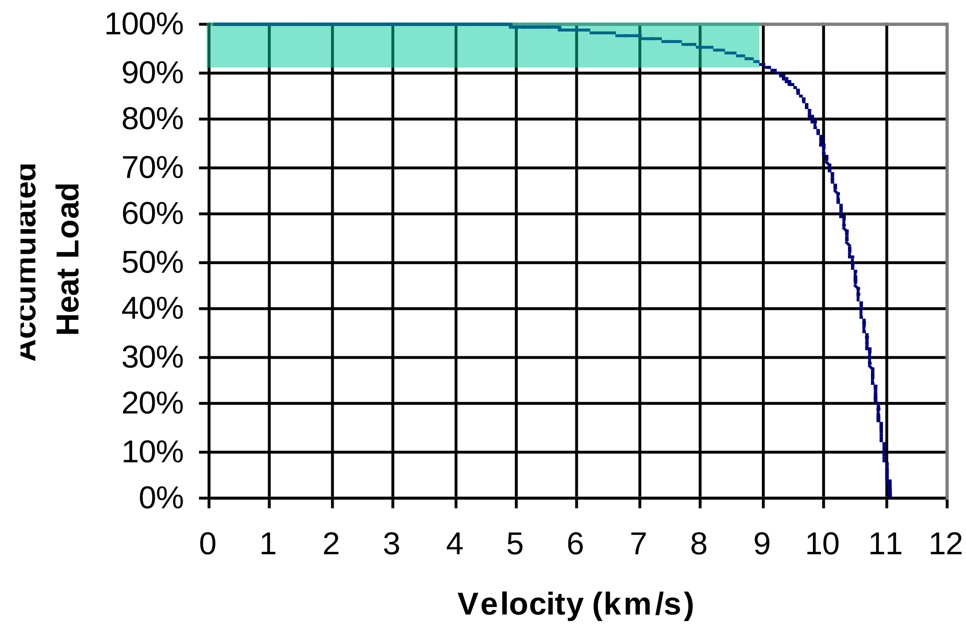
Outline

- **Motivation**
- **Experimental Approach**
- **Sample Data**
  - **Comparison of Data across two shock tubes at 0.14 Torr**
  - **Full data Set on data.nasa.gov**
- **Model Adjustments**
  - **Nitric Oxide (NO) Radiation**
  - **Revisions for Atomics, N2, N2+ - in paper**
- **Comparison of Predictions to Data**
  - **0.01 Torr and 0.70 Torr**
  - **0.05, 0.14 and 0.3 Torr in paper**
- **Conclusions**
- **Outlook**

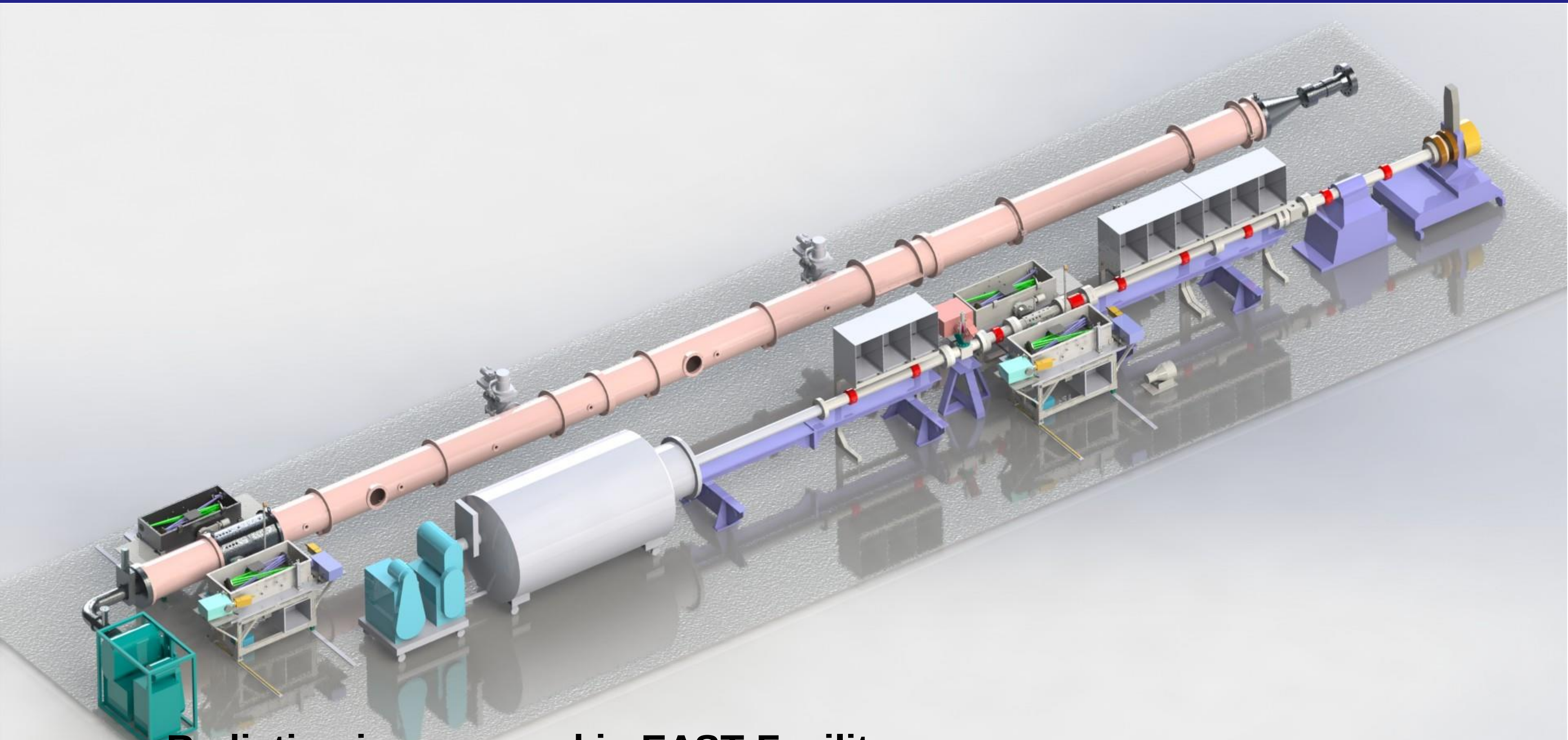
Motivation





- **About 8% of Lunar Return radiative heating occurs below 9 km/s**
  - **Based on current models**
- **Return from lower altitude (e.g. EFT1) is entirely in this speed regime**
- **Radiation phenomena not well validated in this speed regime**

Approach



- **Radiation is measured in EAST Facility**
  - **24" Diameter tubes for low (<0.1 Torr) pressure**
  - **4" Diameter tube for higher (>0.1 Torr) pressure**
- **Measurement by between 2-4 spectrometers covering 190-1450 nm**

Conditions Measured

- **51 shots between 7-9 km/s**
  - **33 (27 good) on the 24" Tube (0.01, 0.05, 0.14 Torr)**
    - **15 from 190-500 nm**
    - **12 from 500-1450 nm**
  - **18 (17 good) on the 4" Tube (0.14, 0.30, 0.50, 0.70 Torr)**
    - **All from 190-1450 nm**
- **Subset of 10 tests selected for further analysis (1 per pressure/wavelength/tube diameter combination):**

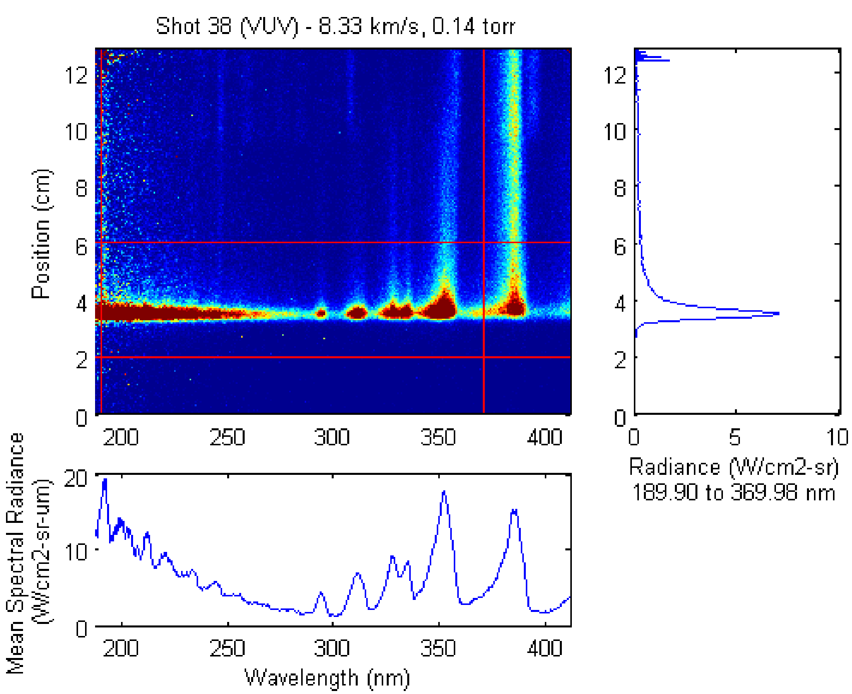
Shot No	Velocity (km/s)	Pressure (torr)	Range (nm)	Tube Diameter (cm)
15	8.18	0.01	190-500	60.33
32	8.57	0.01	500-1450	60.33
8	8.62	0.05	190-500	60.33
24	8.87	0.05	500-1450	60.33
20	8.29	0.14	190-500	60.33
22	8.36	0.14	500-1450	60.33
38	8.33	0.14	190-1450	10.16
42	8.09	0.3	190-1450	10.16
46	7.71	0.5	190-1450	10.16
50	7.34	0.7	190-1450	10.16

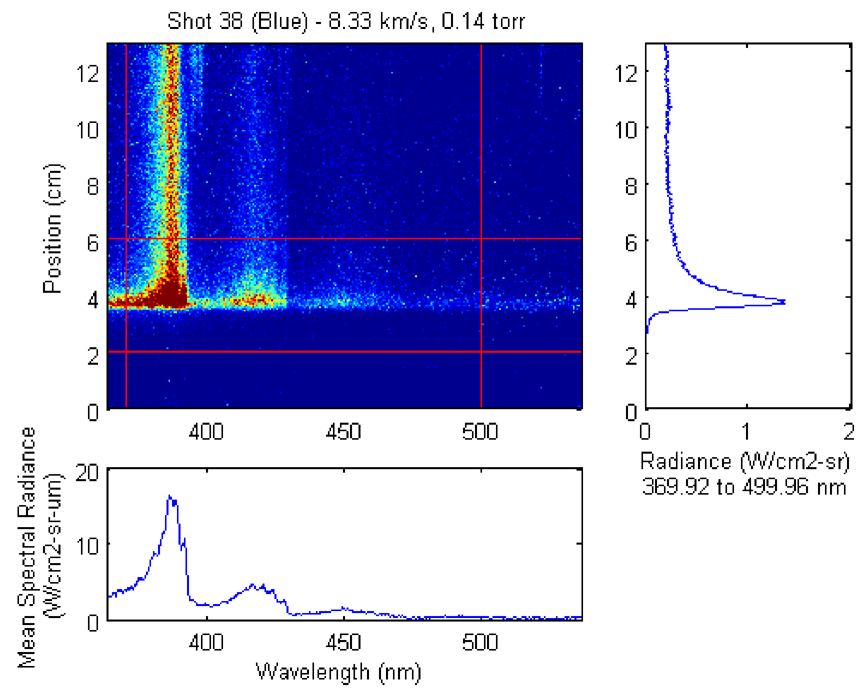
Model Tests

Paper

Consistency Check

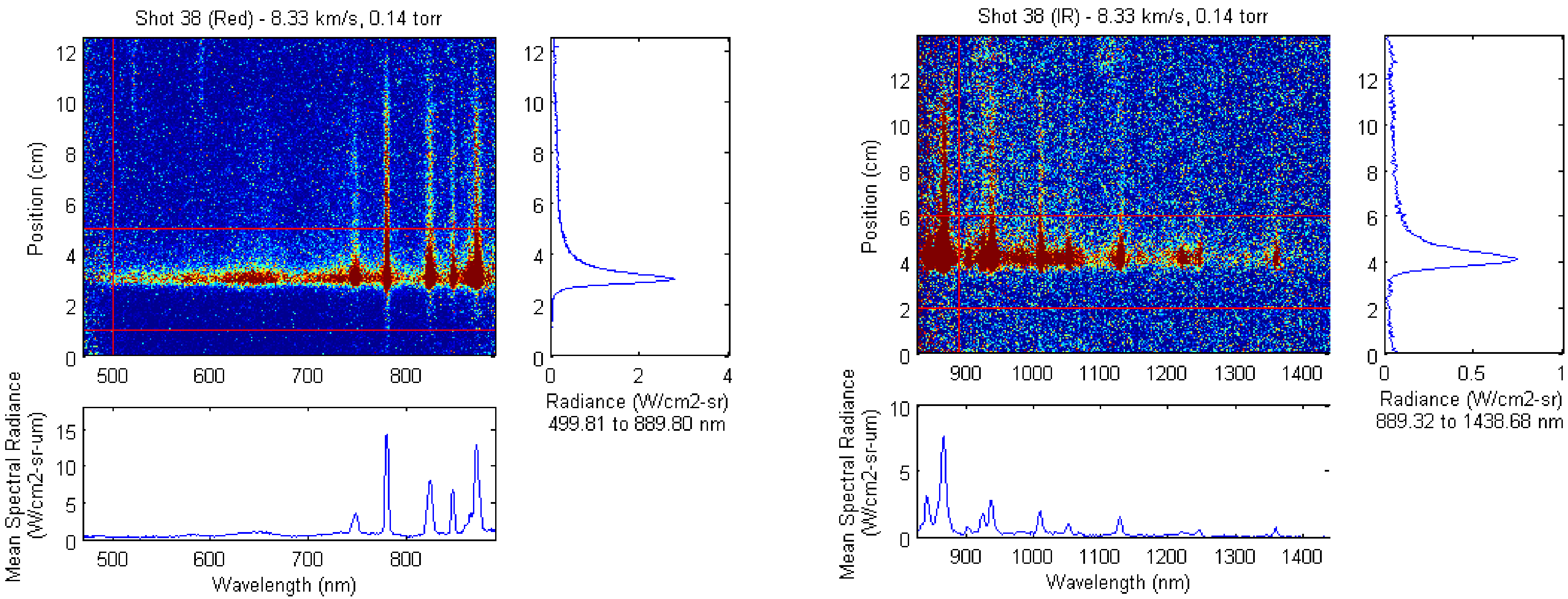
Sample Data (190-500 nm)





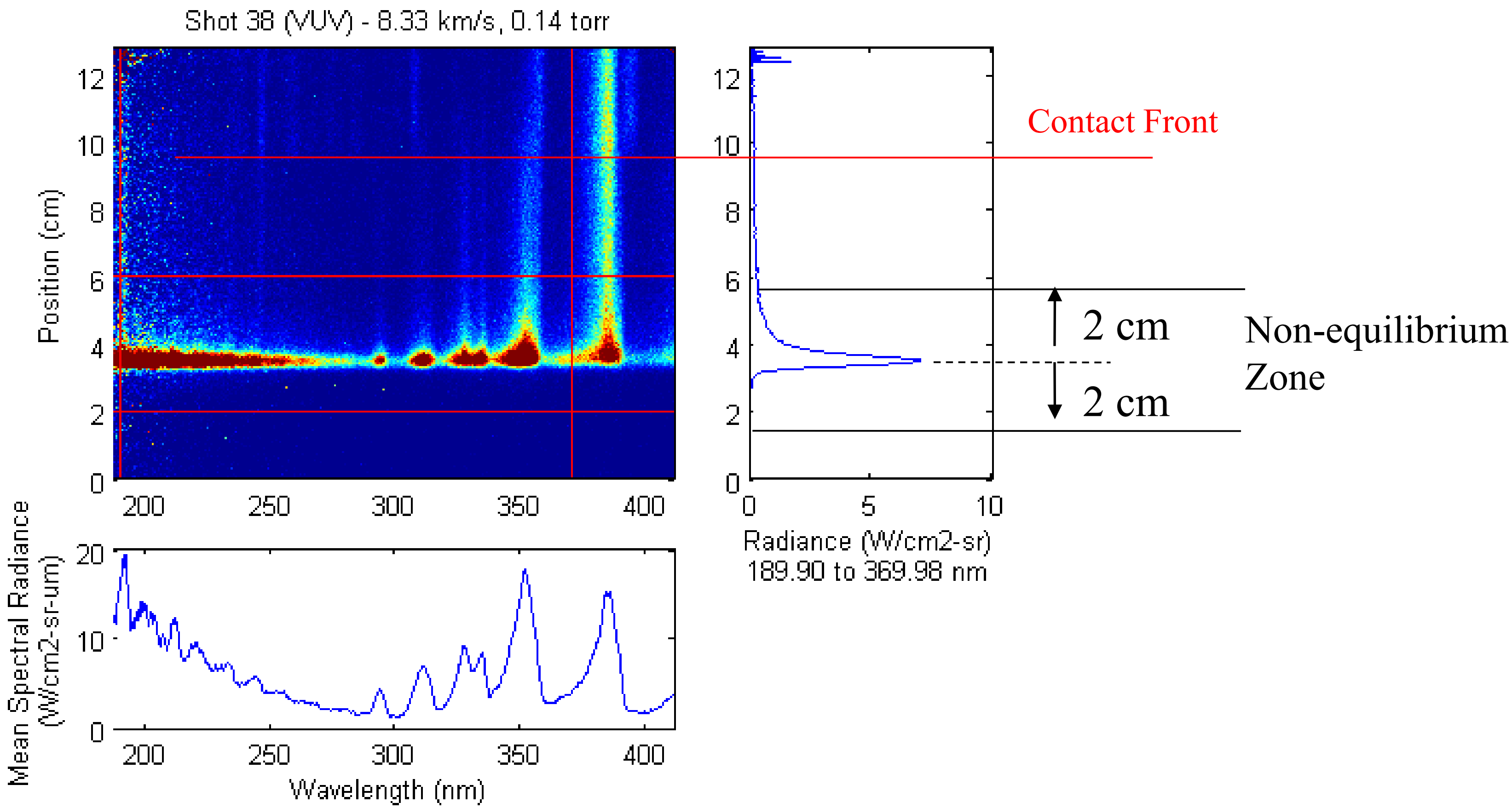
- **Spectra are resolved in wavelength and position behind shock**

Sample Data (500-1450 nm)



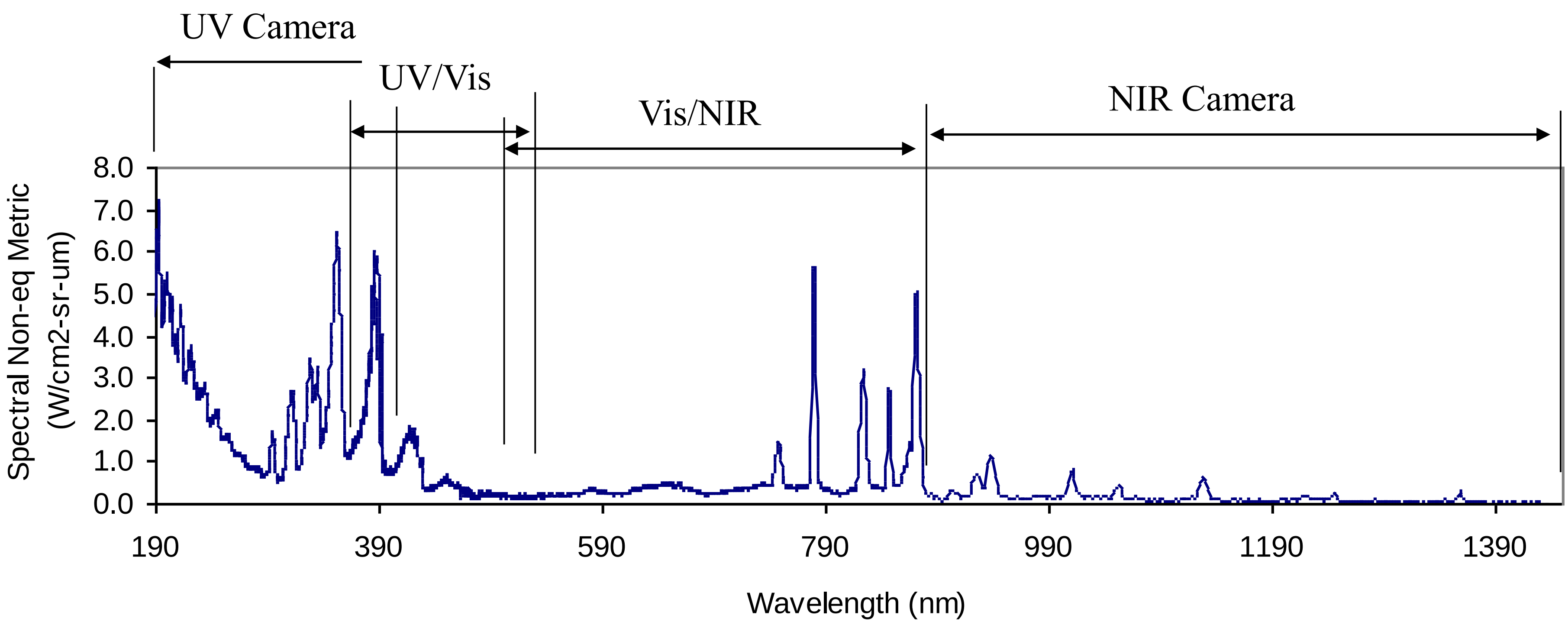
- **Spectra are resolved in wavelength and position behind shock**

Non-equilibrium Analysis



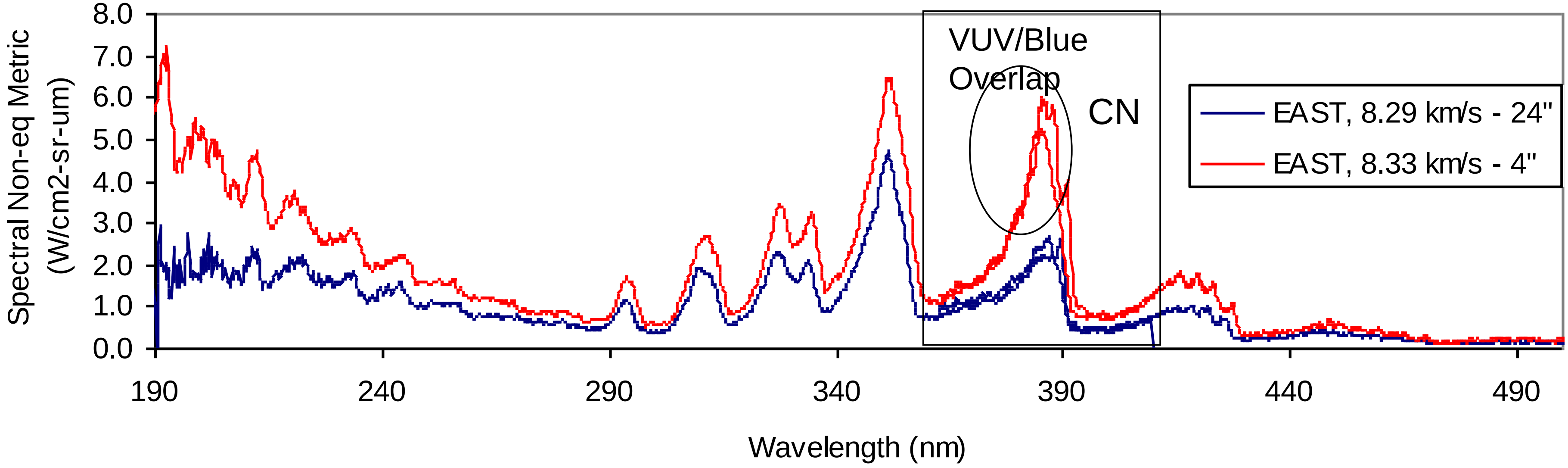
- (somewhat) arbitrarily assign ±2 cm of peak as "non-equilibrium zone"
- Integral of this, divided by tube diameter, is the "non-equilibrium metric"
- Presented as function of wavelength : "spectral non-equilibrium metric"

Spectral Non-equilibrium Metric



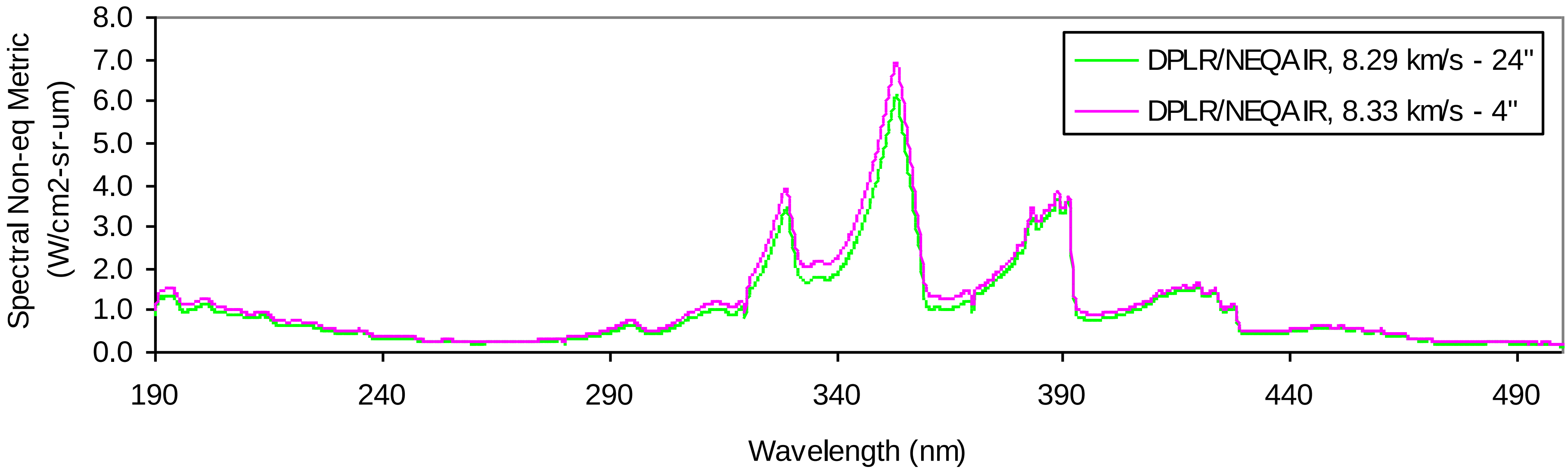
- **Non-equilibrium metric composite from 4 different spectrometers**
- **Spectral Non-equilibrium Metric has units of radiance**
  - **It is equal to the radiance accumulated through the non-equilibrium zone if the non-equilibrium region is optically thin**

0.14 Torr Tube-Tube Comparison (190-500 nm)



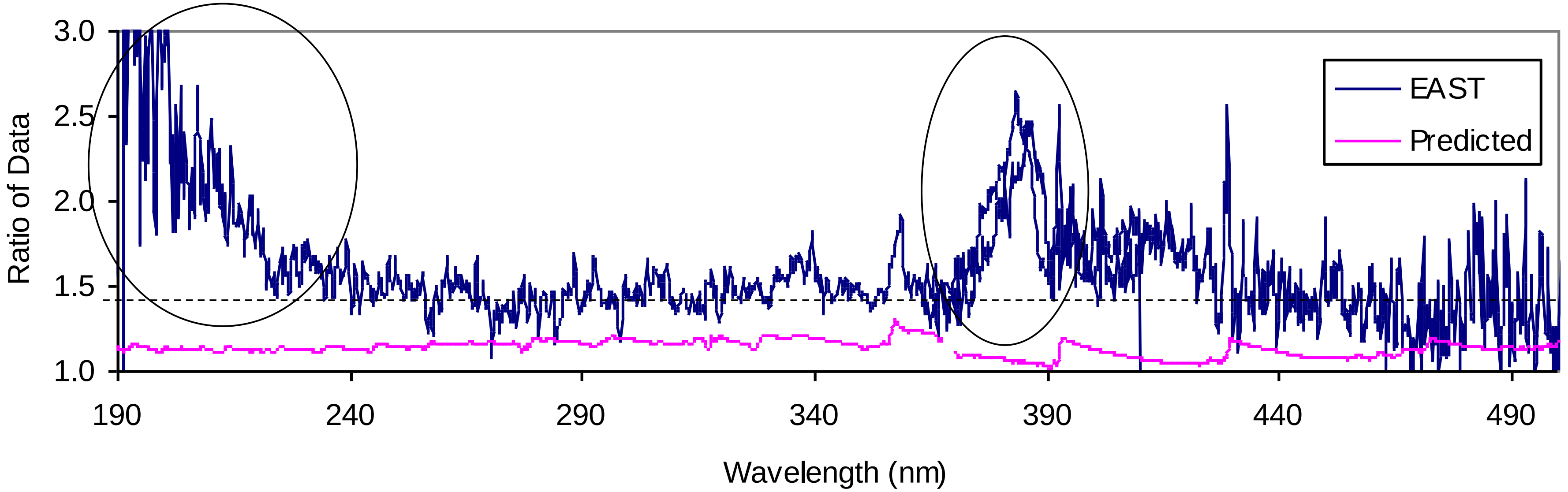
- **Spectral metric is larger in 4” tube than 24” tube**
- **Overlap region of spectrometer is consistent**
- **CN Contamination in 4” Tube**
- **Velocities differ, optical thickness may differ**
  - **Check predictions**

DPLR/NEQAIR Comparison (190-500 nm)



- **Some increase in radiation predicted at 8.33 km/s**
- **Increase is sensitive to rate model**
- **Prediction does not match data**

Tube Disagreement (190-500 nm)



- **Median disagreement : 46% (cf. 16% predicted)**
  - **Not clear how much of remaining 30% is due to errors in prediction or experiment**
- **Divergence at low wavelength**
  - **24" Tube calibration suspect based on S/N**
- **CN contamination radiance**

0.14 Torr Tube-Tube Comparison (500-890 nm)

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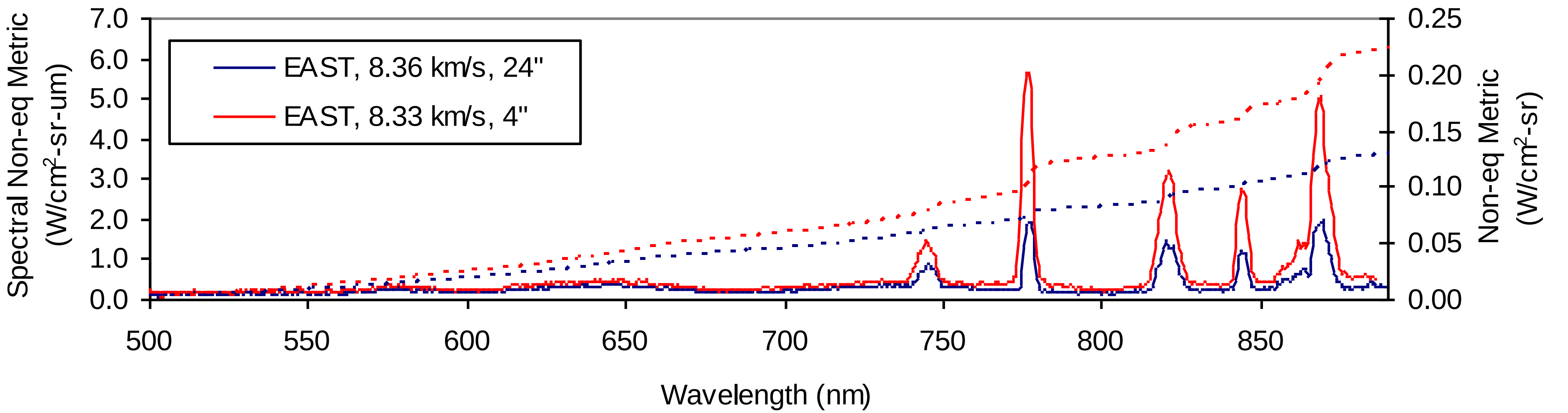
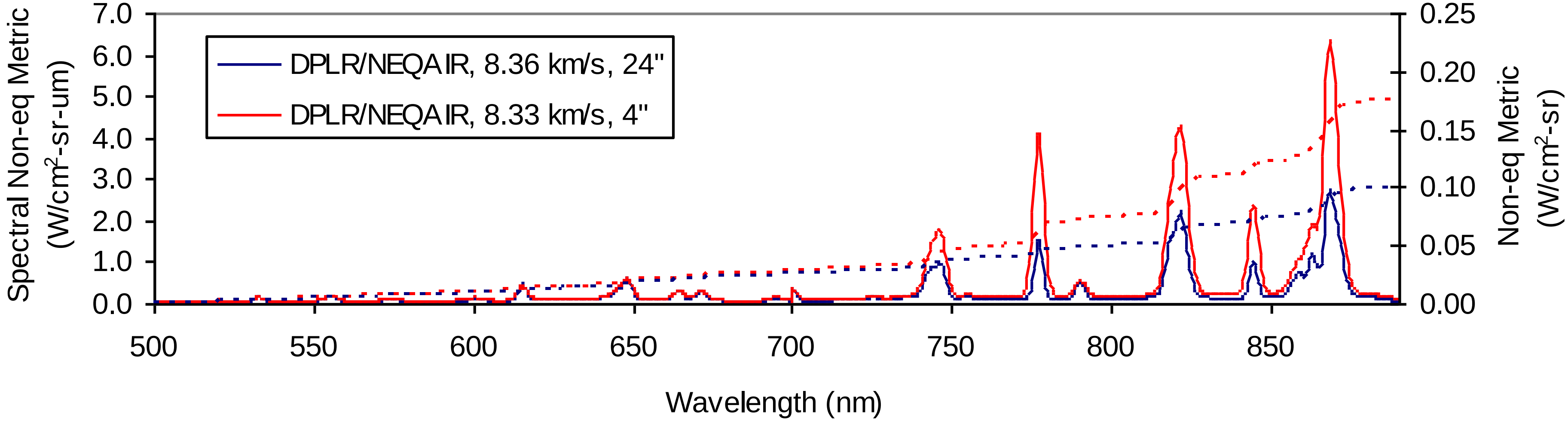


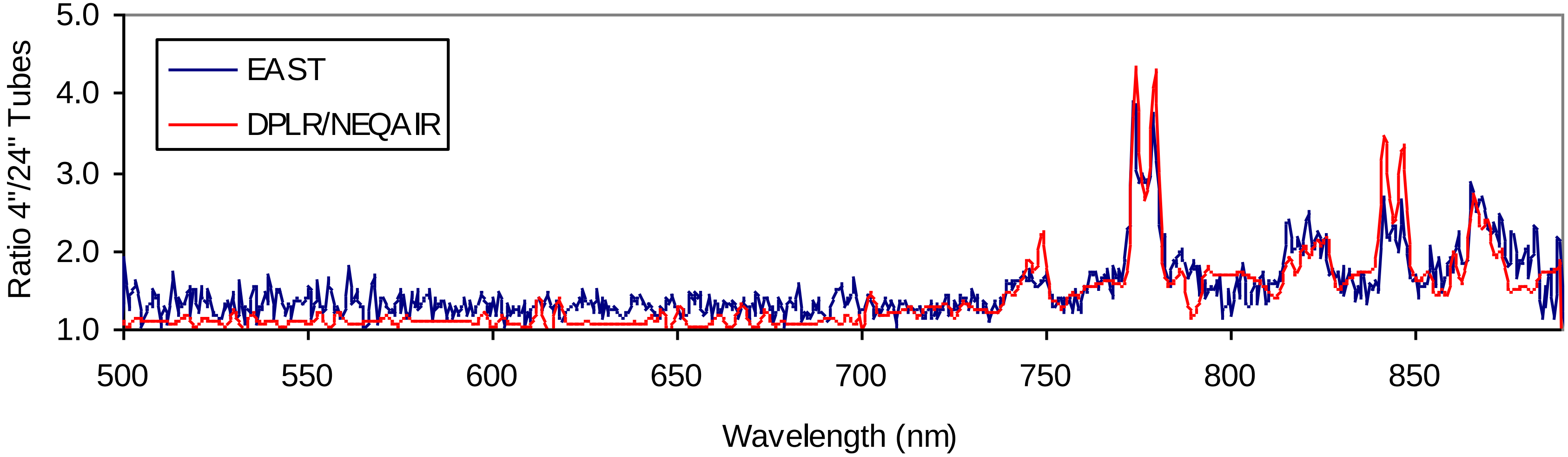
- **Molecular emission (500-700 nm)**
  - **4" Tube 30% larger than 24" Tube**
- **Atomic radiation signifcantly higher in 4" Tube**
  - **Lines may be optically thick**

Predicted Non-equilibrium metric



- **DPLR/NEQAIR prediction shows larger metric in 4" Tube**
  - **Indicates atomic lines are optically thick**
- **Molecular radiation not predicted by NEQAIR**

Ratio of Tube measurements (500-890 nm)



- **Ratio observed in EAST matches predicted ratio for atoms**

Predictive Modeling

- **DPLR/NEQAIR are used to produce 1D (stag. line) profiles for comparison to shock tube data**
- **Three “heritage” modeling options discussed**
  - **Park90 with Te=Tt (DPLR Default)**
  - **Park93 with Te=Tv**
  - **Johnston14 with Te=Tv (LAURA default)**
- **Revisions to Model will be discussed**
  - **Use data to guide reasonable modeling assumptions**
  - **Use third party measurements of input parameters**
  - **Do not “tune to fit”**
  - **Maintains some level of independence between model and data set**

Spectral Non-equilibrium Metric

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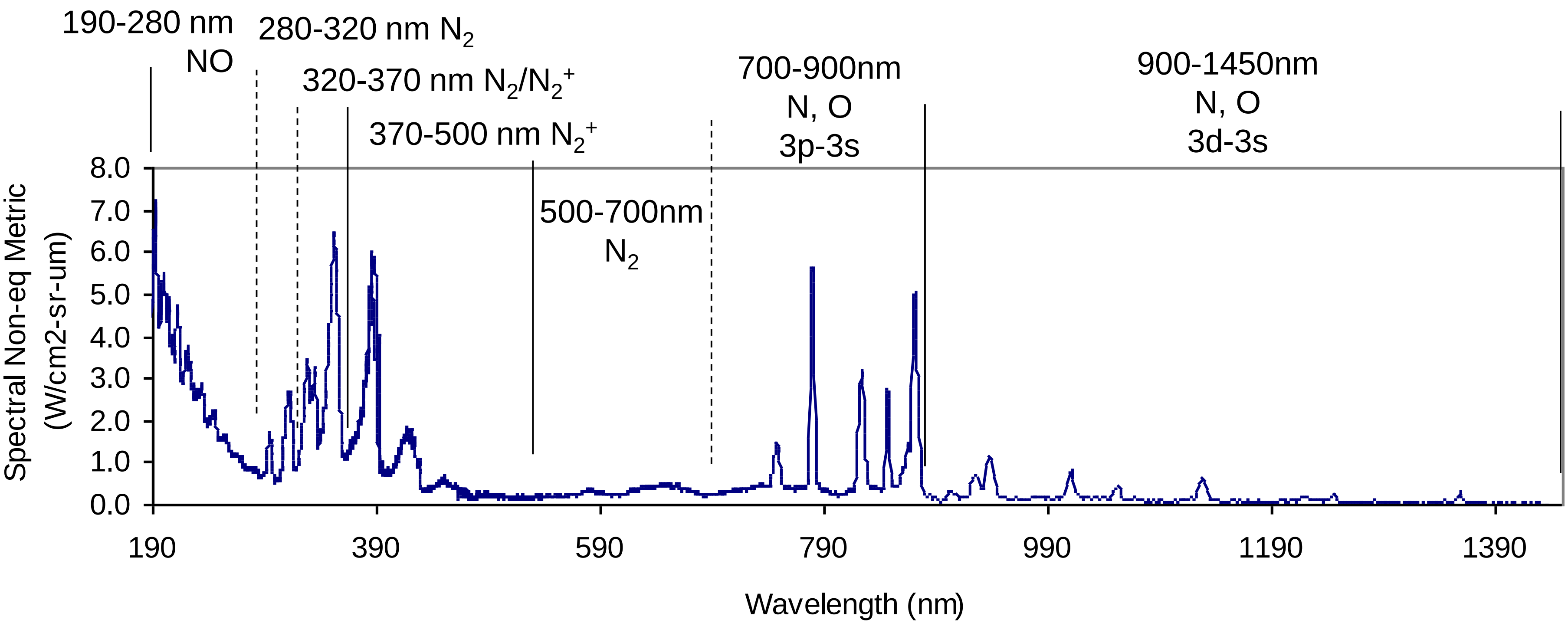

- **Analysis will be divided by spectral features for discussion**

NO Radiance

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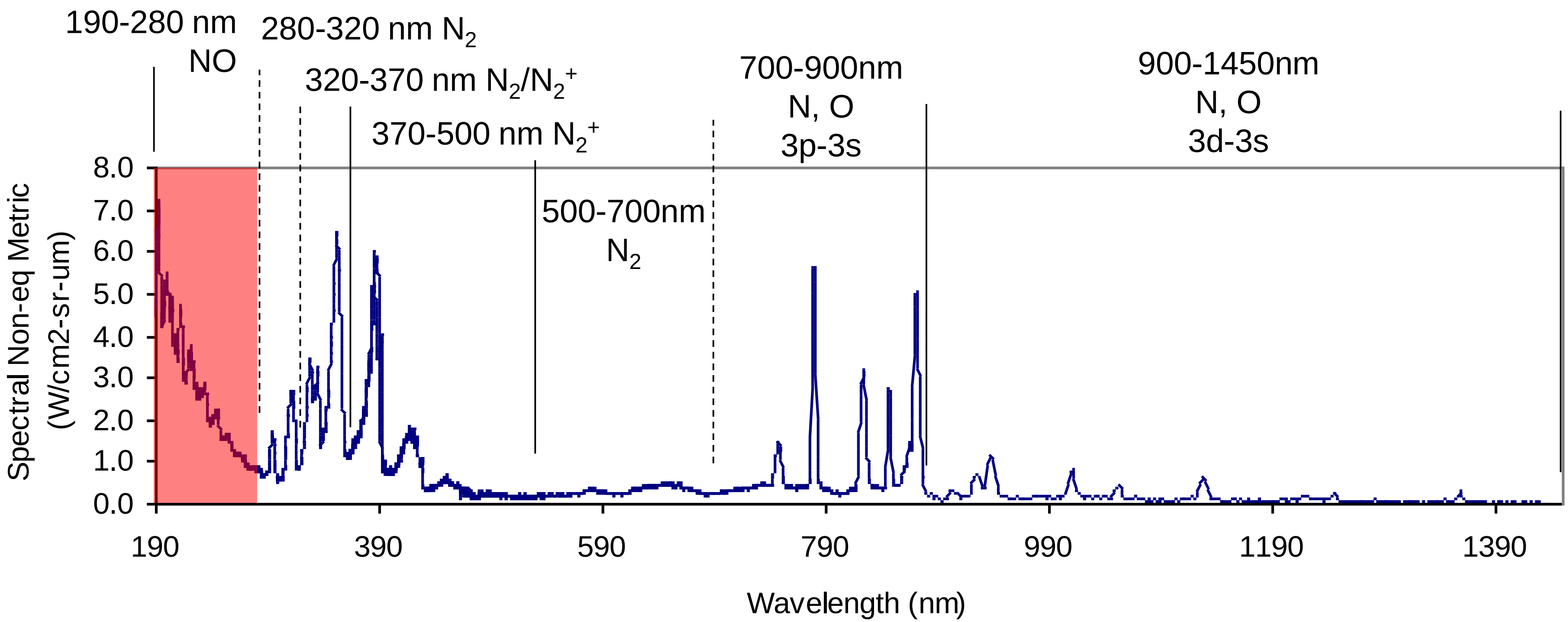
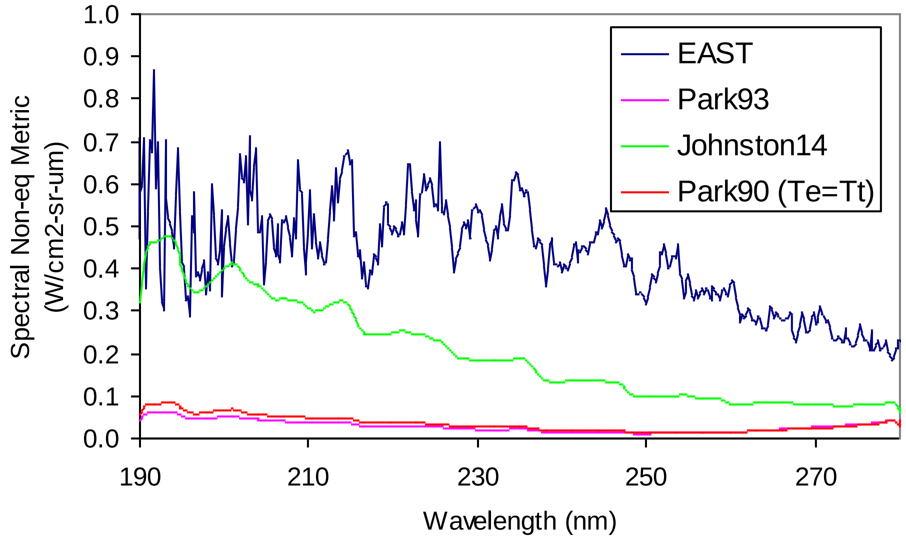


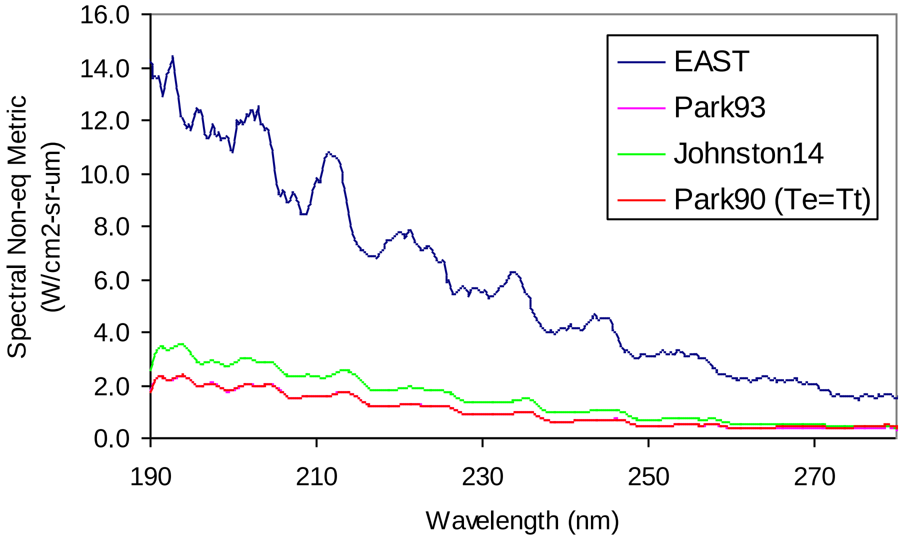
- **NO Radiance from (primarily) γ, ε bands**
  - **Originate from $A^2\Sigma$ and $D^2\Sigma$ states**
- **Also δ band ($C^2\Pi$)**

NO Comparison to Heritage

8.18 km/s, 0.01 Torr



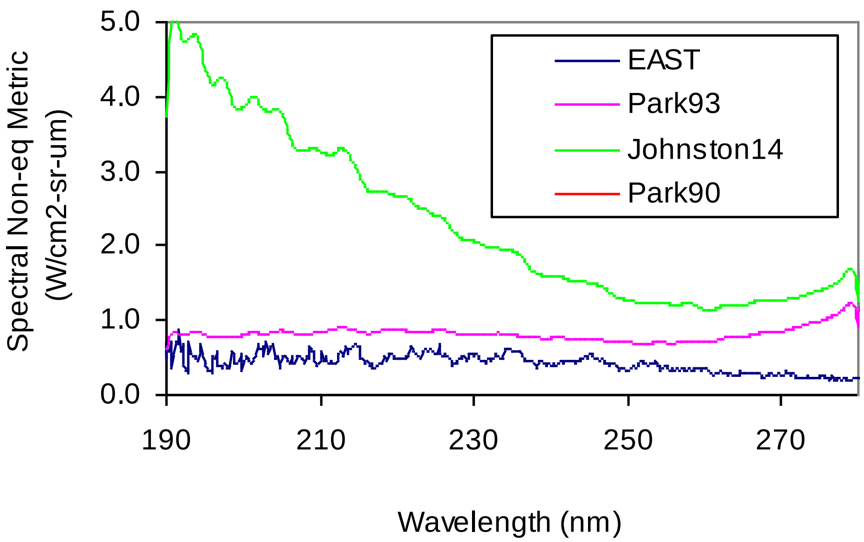
7.34 km/s, 0.70 Torr



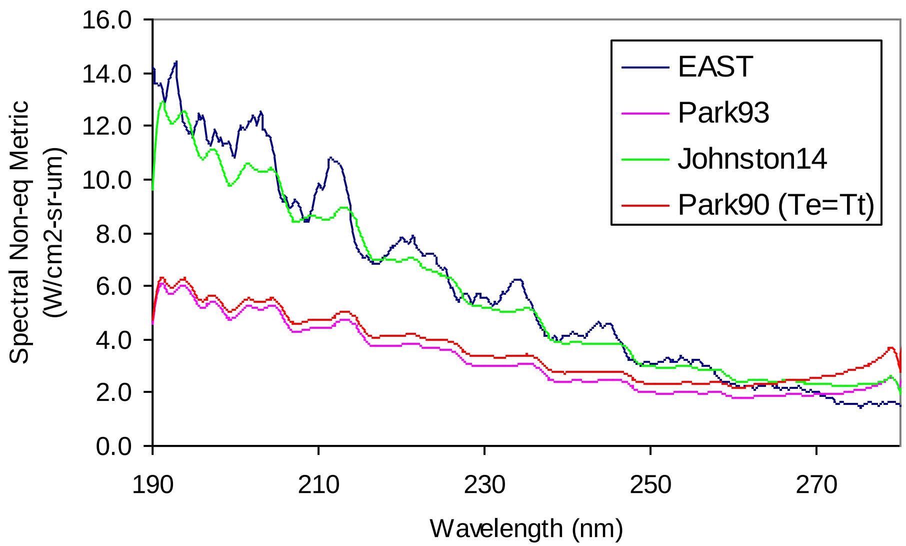
- **Underpredicted at all conditions, by all models**

NO Boltzmann

8.18 km/s, 0.01 Torr



7.34 km/s, 0.70 Torr



- **Boltzmann Radiance is typically an upper bound for non-equilibrium radiation (in compression)**
- **Park models cannot match Boltzmann radiance at 0.7 Torr**
  - **Must check reaction rates**
- **Boltzmann radiation too high at 0.01 Torr**
  - **Non-Boltzmann model needs examination**

NO Reaction Kinetics

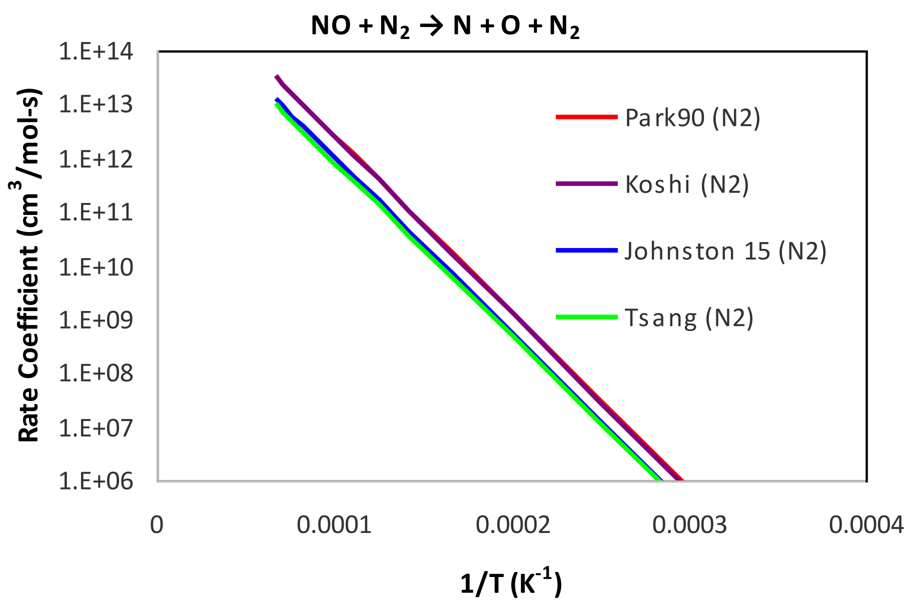
- **NO Formation is driven by so-called Zel'dovich exchange Reactions:**

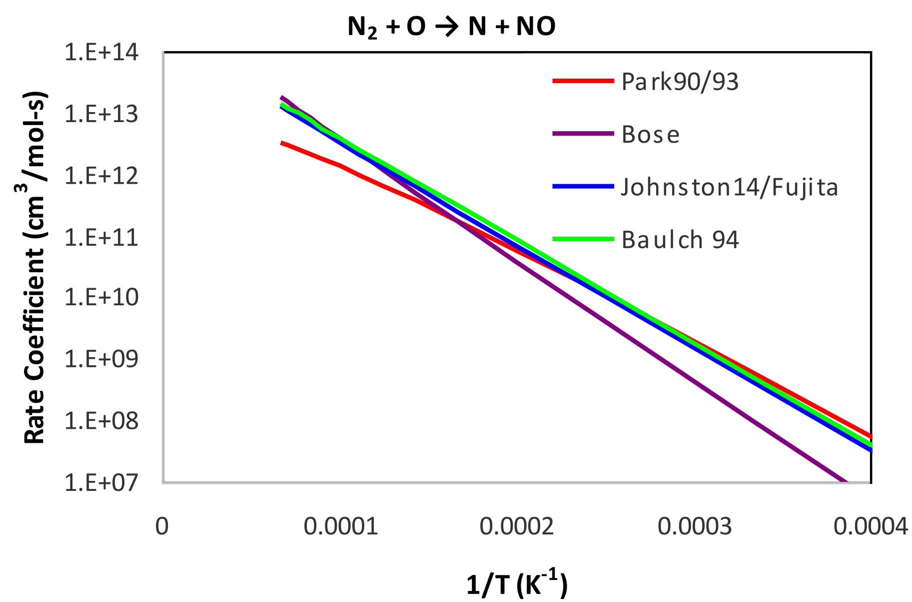
$$N_2 + O \leftrightarrow NO + N$$

$$O_2 + N \leftrightarrow NO + O$$

- **NO Destruction depends on direct dissociation:**

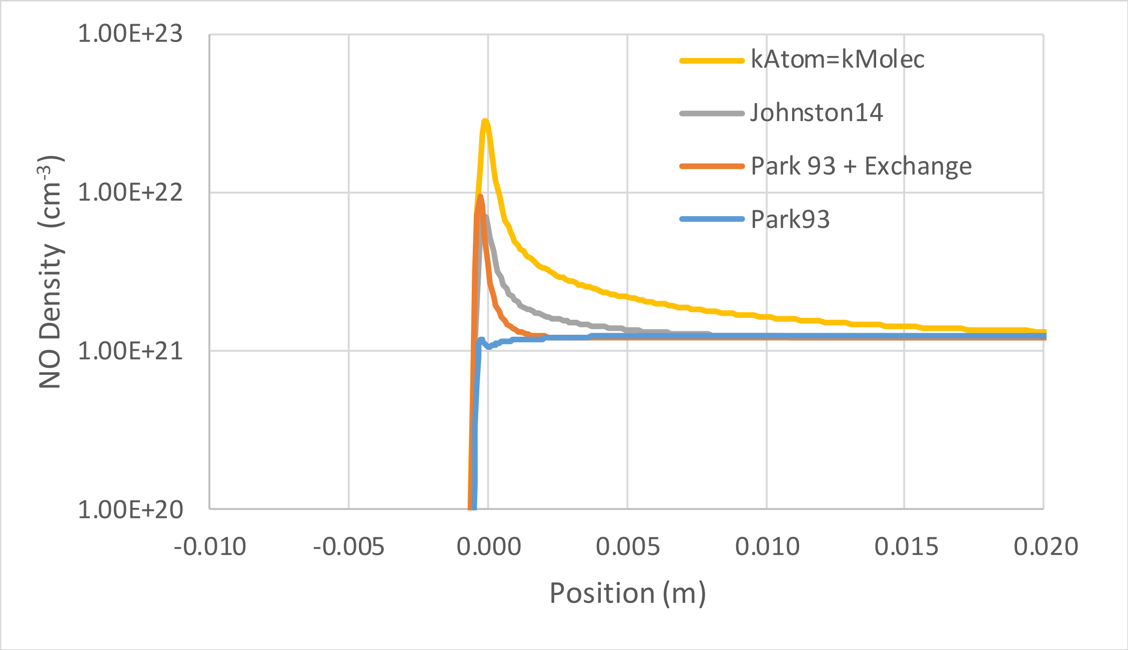
$$NO + M \leftrightarrow N + O + M$$





We opt to carry rates from combustion literature (Tsang/Baulch)

Impact on NO concentration (0.7 Torr)



- **Updating Exchange Reactions increases peak NO density**
- **Reducing dissociation rate reduces decay**
- **Changing the ratio of dissociation by atoms vs. molecules further increases NO density**
  - **Johnston follows Park : ratio is 22**
  - **Figure shows ratio of 1.0**
  - **Tsang recommended ratio of <1**

NO Non-Boltzmann modeling

- For these conditions, NO non-Boltzmann is dominated by heavy particle processes
- Internal excitation:

  NO(X) + M ↔ NO(A,C,D) + M
- Heavy particle impact Dissociation:

  NO(A,C,D) + M ↔ N + O + M

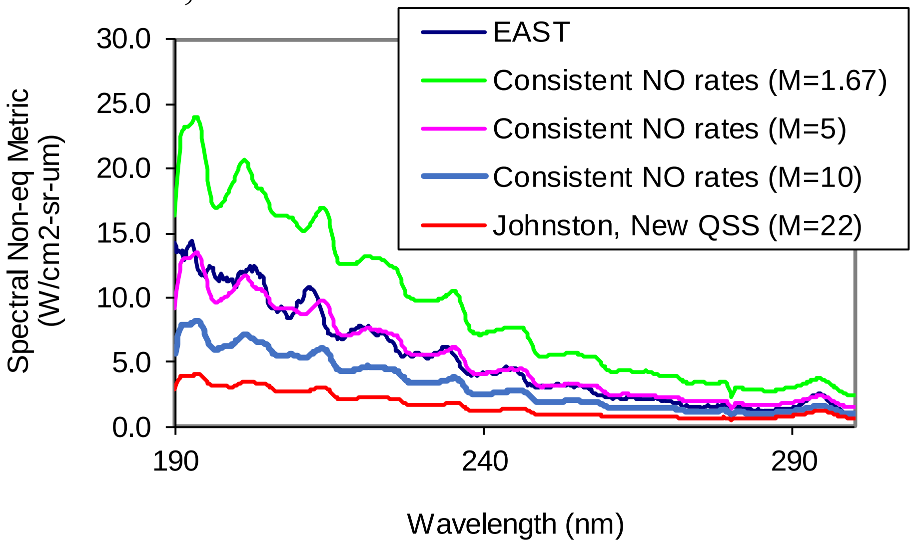
- Internal excitation rates in NEQAIR are only approximate, fundamental data is not available
- The reverse of internal excitation is quenching : rates are available at 300K. Assume:

$$k_q = k_{q,0}\sqrt{\frac{T_t(K)}{300}}$$

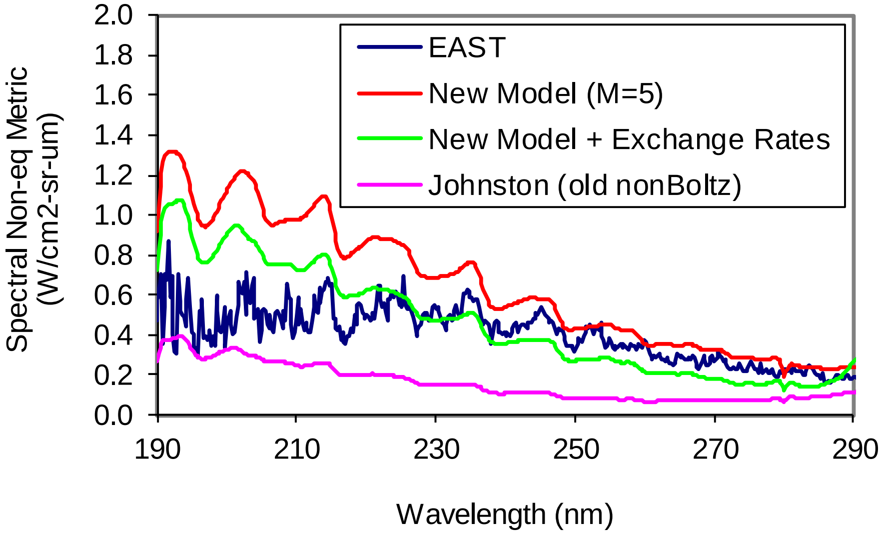
- Heavy particle impact dissociation is updated to be consistent with rate chemistry
- Ratio of atomic to molecular driven dissociation is still undetermined

Adjust Atom/Molecule Rates

7.34 km/s, 0.70 Torr



8.18 km/s, 0.01 Torr



- **Rates adjusted consistently in DPLR and NEQAIR**
- **Ratio of 5 matches 0.7 Torr data**
- **Also matches NO γ at 0.01 Torr**
- **NO δ is overpredicted at 0.01 Torr**
  - **Possibly experimental error due to lower sensitivity in this region**

Summary of Model Revisions

- **Flowfield model**
  - Update NO dissociation and exchange rates to be consistent with combustion literature
  - Alter ratio of NO dissociation by atoms vs. molecules to 5
  - Electron impact dissociation rate from radiation model used for flowfield
  - Associative Ionization controlled by T_e
  - Update selected charge exchange rates
- **Non-Boltzmann Radiation Model - Molecules**
  - Heavy particle dissociation rate consistent with flowfield dissociation rate
  - Use quenching rates from literature to calculate heavy particle excitation rates for molecules
  - Electron impact dissociation calculation corrected
    - Estimate and include contributions from excited states
- **Non-Boltzmann Radiation Model – Atoms**
  - Excitation rates updated to hybrid of Huo (dipole allowed) and Park (unallowed)
  - Include Associative Ionization process

Results – 0.7 Torr, 7.34 km/s (190-500 nm)

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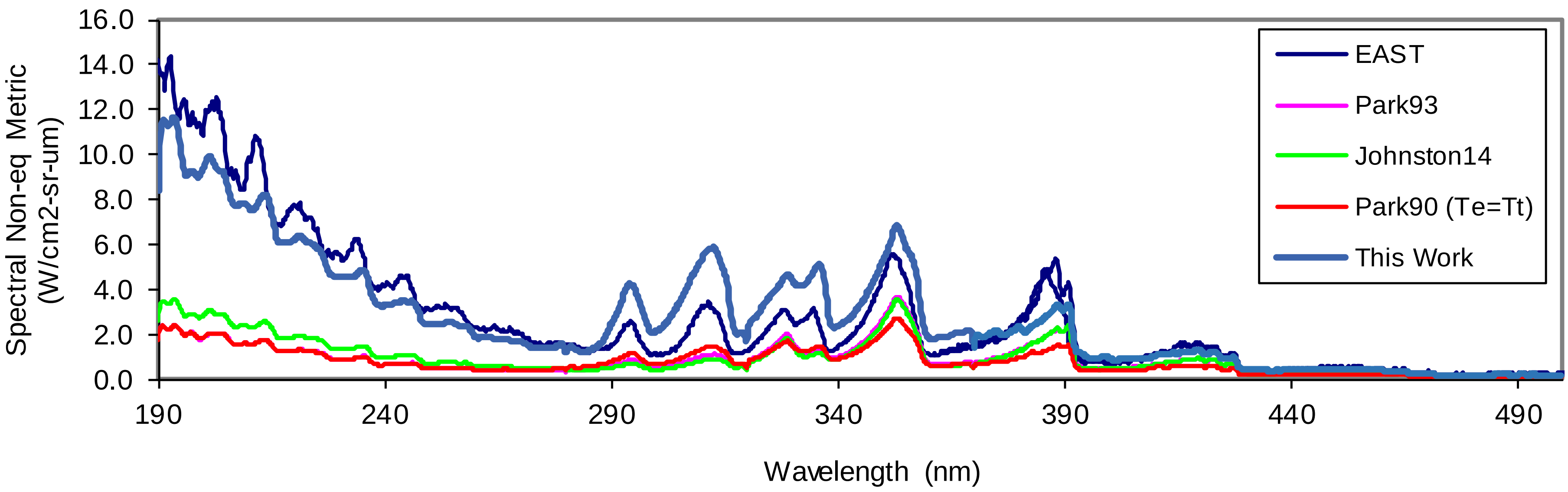
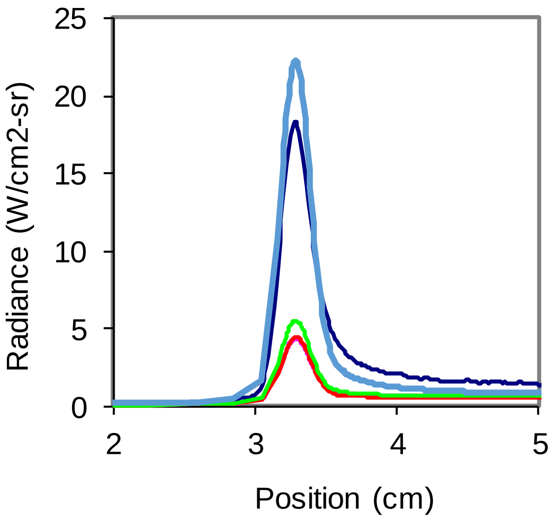
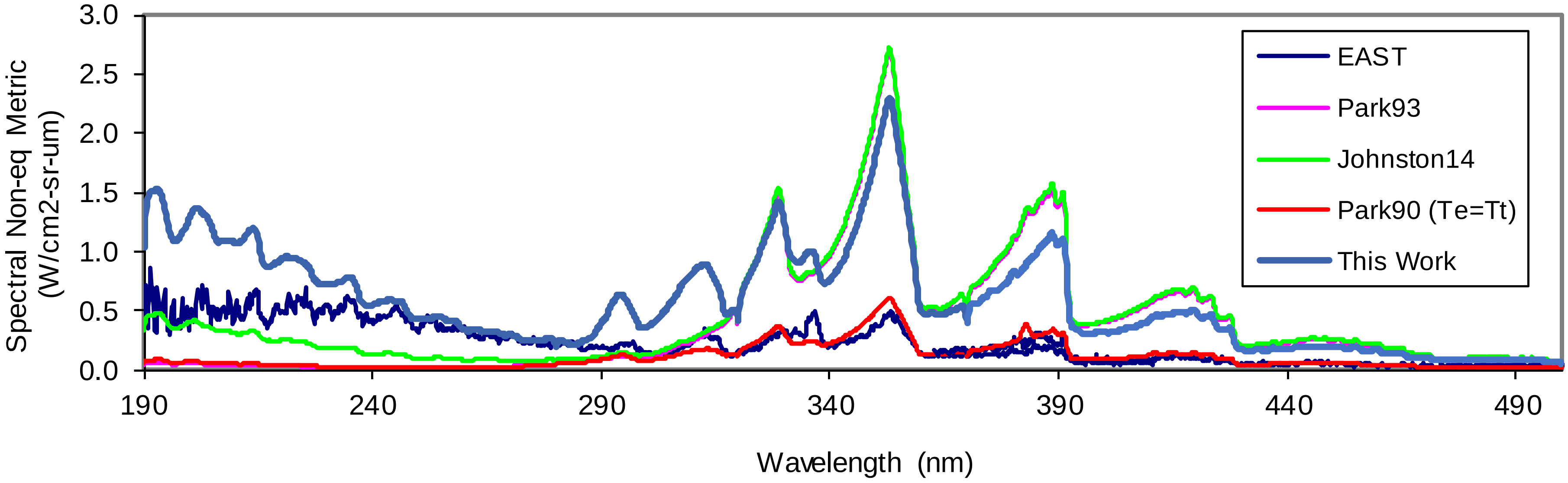


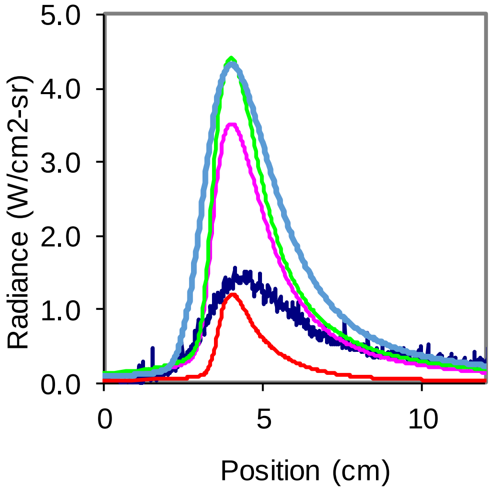
- NO and N_2^+ underpredictions rectified (mostly)
- N_2 2nd Positive Somewhat Overpredicted
- Reasonable match to temporal trend



Results – 0.01 Torr, 8.18 km/s (190-500 nm)



- N_2^+ still overpredicted
- N2 2nd Positive overpredicted
- NO matched 240-290nm (Gamma bands)
- NO overpredicted < 240 nm (Epsilon bands)



Results – 0.7 Torr, 7.34 km/s (500-890 nm)

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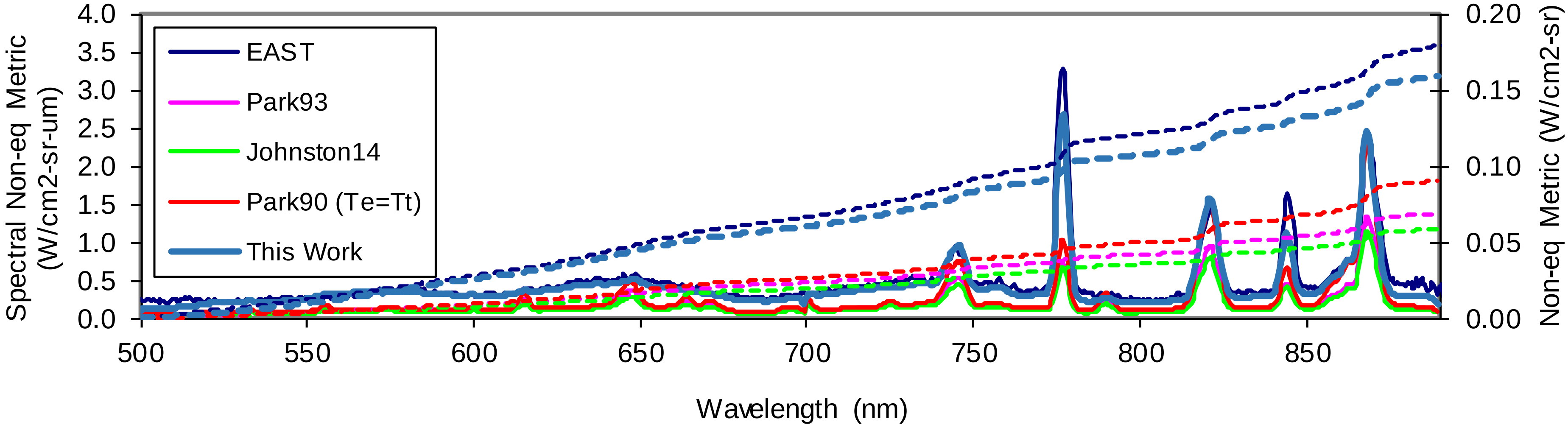
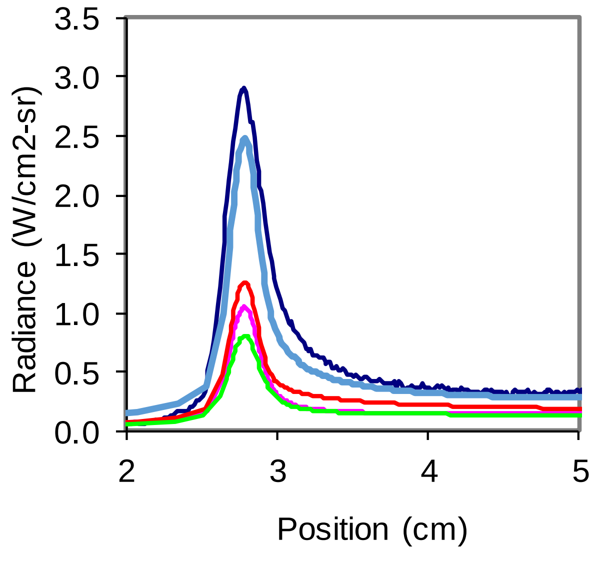


- **N_2 1st Positive Matched**
- **Atomic lines nearly matched**
- **Reasonable match to temporal trend**



Results – 0.01 Torr, 8.58 km/s (500-890 nm)

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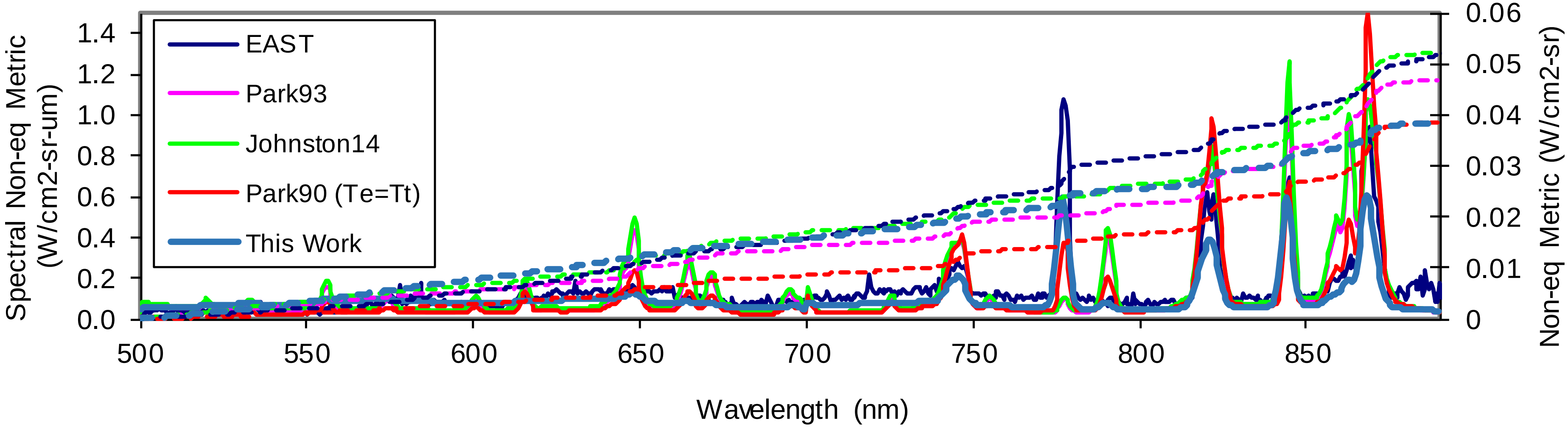
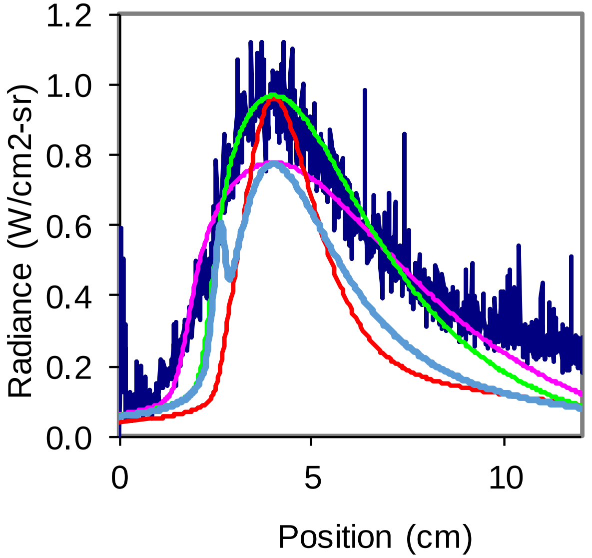
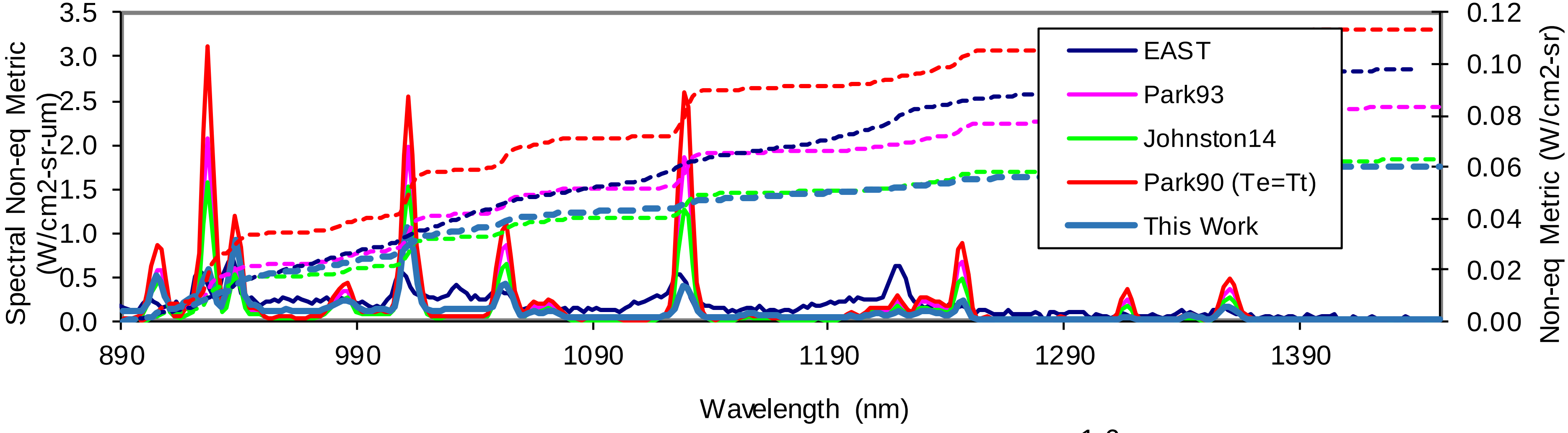


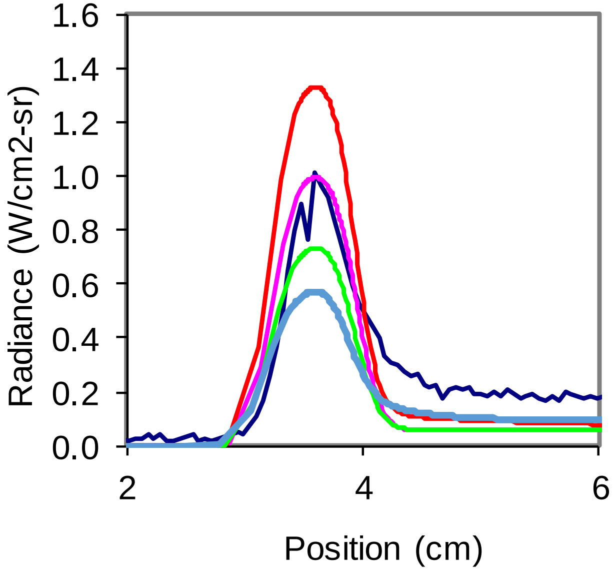
- **Underprediction N_2 1st Positive Matched**
- **Extra atomic lines eliminated**
- **Other atomic lines underpredicted**
- **Temporal trend shows spike at shock front**



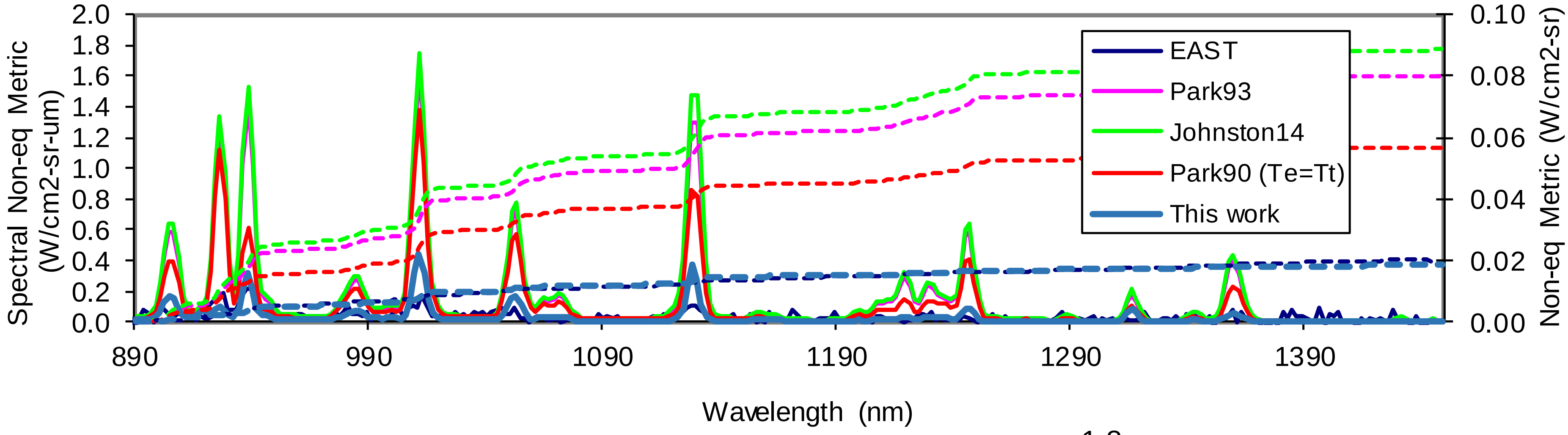
Results – 0.7 Torr, 7.34 km/s (890-1450 nm)



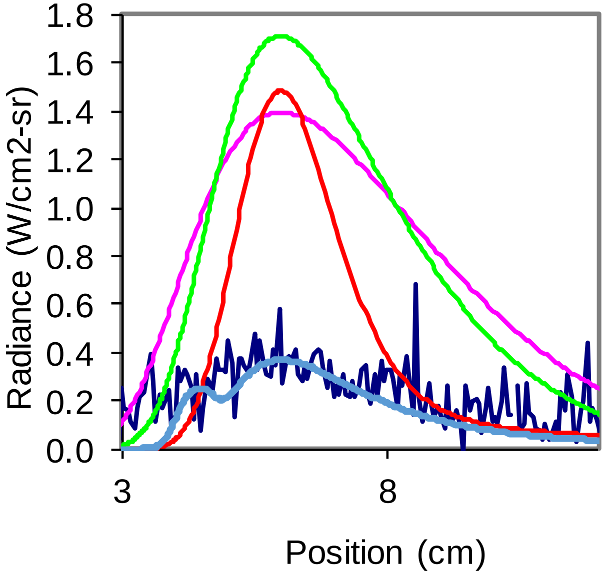
- **Atomic overprediction eliminated, lines that are present are reasonably close**
- **Missing molecular radiation source (TBD)**
- **Temporal trend looks ok**



Results – 0.01 Torr, 8.58 km/s (890-1450 nm)



- **Atomic overprediction eliminated**
- **Integral matches data**
- **Spike observed at shock front, trend otherwise ok**



Summary

- **Non-equilibrium Radiation Data Measured from 7-9 km/s at 6 freestream pressures from 0.01-0.70 Torr**
  - **Comparison across two tubes with different diameter, calibration source indicate confidence in data of ~30% (in UV) or better (Vis/NIR)**
  - **Presentation focuses on highest and lowest pressure ranges**
- **Agreement to Predictive (DPLR/NEQAIR) Model has been improved**
  - **Underprediction of N_2/NO resolved by changes to rate chemistry, heavy particle excitation rates**
  - **N_2^+ overpredicted at low pressure, revised rate/excitation model fixes underprediction at high pressure**
  - **Predctiion of atomic radiation improved by**
    - **Changing excitation model (high energy states)**
    - **Including associative ionization in non-Boltzmann model (3p states)**
- **How does your model do?**

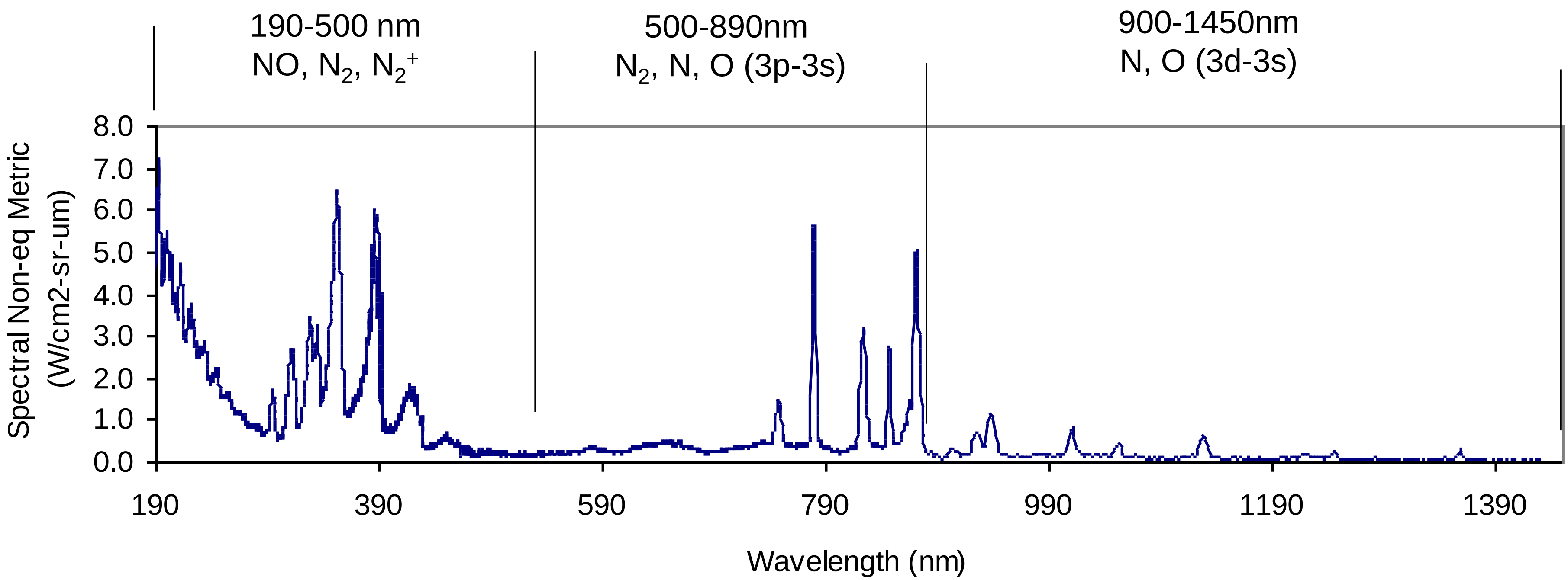
https://data.nasa.gov/docs/datasets/aerothermodynamics/EAST/index.html

Work to go

- **Low pressure overpredictions of**
  - **N_2^+ : State specific associative ionization?**
  - **NO, N_2 : Pre-dissociation rates?**
- **Missing molecular features in infrared (high pressure)**
- **Spike in shock front at low pressure**
- **Underpredicted atomic lines at low pressure**
- **non-Boltzmann associative ionization model : needs realistic statewise rates**

Backup

Spectral Non-equilibrium Metric



- **Identification of features suggests regions for further analysis**

Reaction Rates

- **There are between up to 23 reactions rates across the 3 models, 11 of which have some differences:**

These rates not important

$NO + M \leftrightarrow N + O + M$	increased by Johnston
$N_2 + O \leftrightarrow NO + N$	Johnston used rate from Fujita, 2006
$NO + O \leftrightarrow O_2 + N$	Johnston uses rate from Bose, 1997
$N + O \leftrightarrow NO^+ + e^-$	Updated Park93, Johnston/Park90 same
$N + N \leftrightarrow N_2^+ + e$	Updated Park93, Johnston/Park93 same
~~$O + O \leftrightarrow O_2^+ + e$~~	~~Updated Park93, Johnston/Park93 same~~
~~$O^+ + NO \leftrightarrow N^+ + O_2$~~	~~Activation energies differ~~
$N^+ + N_2 \leftrightarrow N_2^+ + N$	Missing from Park90, Johnston/Park93 same
$O_2^+ + O \leftrightarrow O^+ + O_2$	Missing from Park90*, Johnston/Park93 same
$N_2 + e \leftrightarrow N + N + e$	Differs across all three chemistries
$O_2 + e \leftrightarrow O_2^+ + e$	Missing from Park90/Park93

* As implemented in DPLR

Revised Kinetic Model

Reaction	M	A (cm^3/mol·s)	n	E_a (K)	Controlling Temperature	Ref
$N_2 + M \rightarrow 2N + M$	Molecule	7.0×10^{21}	-1.6	113,200	$\sqrt{TT_{ev}}$	[5]
	Atom	3.0×10^{22}				
	e^-	1.2×10^{7}	2.69		T_e	This work
$O_2 + M \rightarrow 2O + M$	Molecule	2.0×10^{21}	-1.5	59,500	$\sqrt{TT_{ev}}$	[5]
	Atom	1.0×10^{22}				
$NO + M \rightarrow N + O + M$	Molecule	1.5×10^{15}			$\sqrt{TT_{ev}}$	[21]
	Atom	7.3×10^{15}	0	74,570		This work
	e^-	5.7×10^{18}			T_e	This work
$N + e^- \rightarrow N^+ + 2e^-$		2.5×10^{34}	-3.82	168,600	T_e	[6]
$O + e^- \rightarrow O^+ + 2e^-$		3.9×10^{33}	-3.78	158,500	T_e	[5]
$N_2 + O \rightarrow NO + N$		1.8×10^{14}	0	38,249	T_t	[24]
$O_2 + N \rightarrow NO + O$		9.0×10^{9}	1.0	3,270	T_t	[24]
$N + O \rightarrow NO^+ + e^-$		8.8×10^{8}	1.0	31,900	T_e	[6]
$N + N \rightarrow N_2^+ + e$		4.4×10^{7}	1.5	67,500	T_e	[6]
$O + O \rightarrow O_2^+ + e$		7.1×10^{2}	2.7	80,600	T_e	[6]
$N^+ + N_2 \rightarrow N_2^+ + N$		7.0×10^{6}	1.47	13,130	T_t	This work
$O^+ + N_2 \rightarrow N_2^+ + O$		9.1×10^{11}	0.36	22,800	T_t	[5]
$O_2^+ + O \rightarrow O^+ + O_2$		4.0×10^{12}	-0.09	18,000	T_t	[6]
$O^+ + NO \rightarrow N^+ + O_2$		1.4×10^{5}	1.9	26,600	T_t	[6]
$NO^+ + O_2 \rightarrow O_2^+ + NO$		2.4×10^{13}	0.41	32,600	T_t	[5]
$NO^+ + N \rightarrow N_2^+ + O$		7.2×10^{13}	0	35,500	T_t	[5]
$NO^+ + O \rightarrow N^+ + O_2$		1.0×10^{12}	0.5	77,200	T_t	[5]
$O_2^+ + N \rightarrow N^+ + O_2$		8.7×10^{13}	0.14	28,600	T_t	[5]
$O_2^+ + N_2 \rightarrow N_2^+ + O_2$		9.9×10^{12}	0	40,700	T_t	[5]
$NO^+ + N \rightarrow O^+ + N_2$		3.4×10^{13}	-1.08	12,800	T_t	[5]
$NO^+ + O \rightarrow O_2^+ + N$		7.2×10^{12}	0.29	48,600	T_t	[5]
$NO + N^+ \rightarrow NO^+ + N$		1.8×10^{12}	0.57	0	T_t	This work

Park 90

Park 93

Combustion Literature

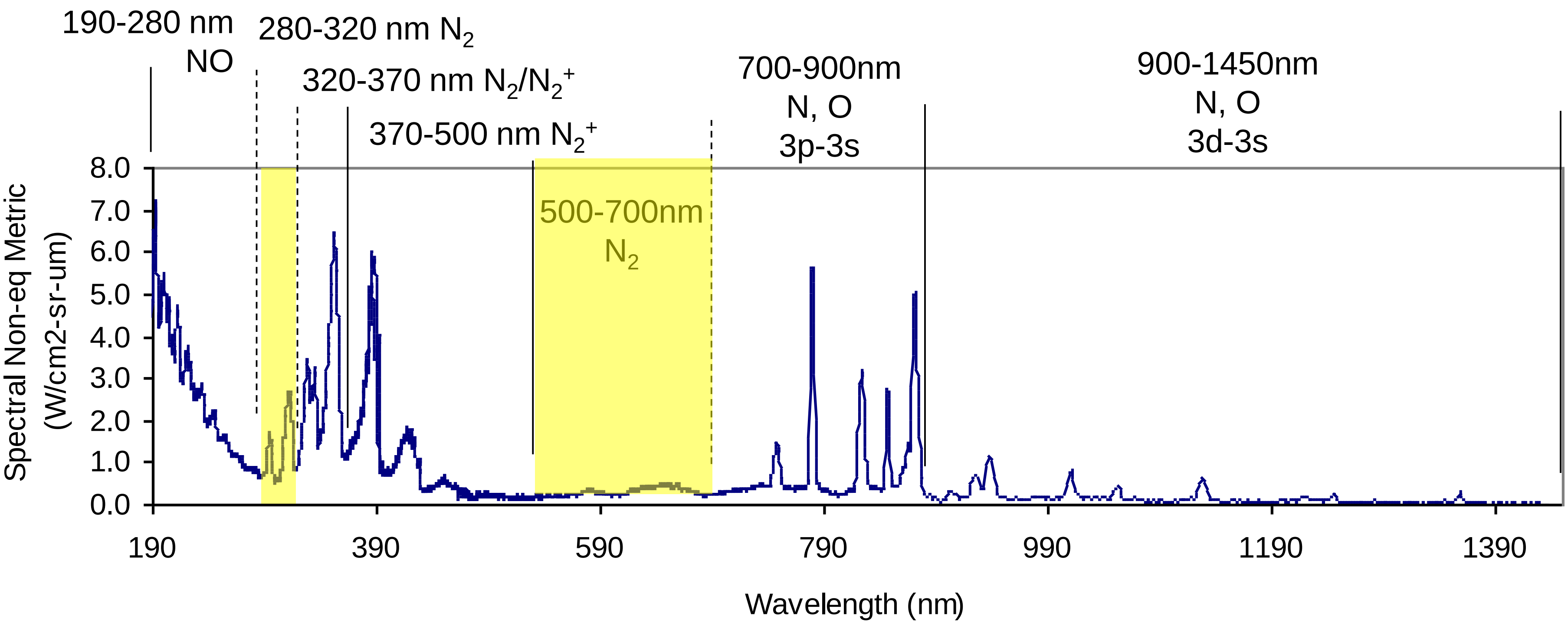
Evaluated from ion collision cross-section data

From electron-impact cross-sections

Adjusted to match data

N_2 Model

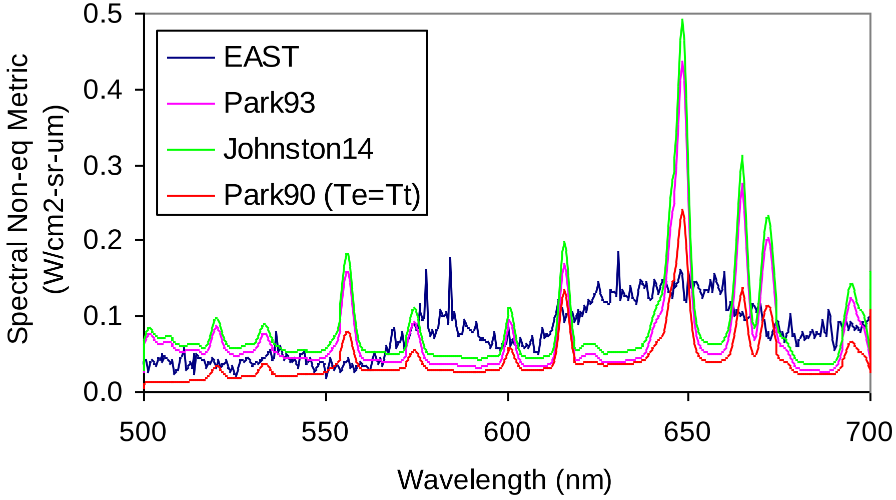
N_2 Radiance



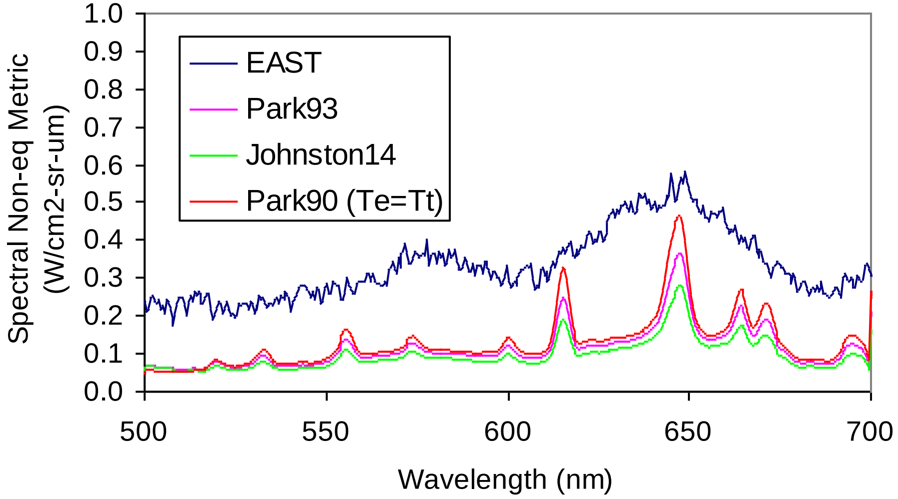
- **N_2 Features from**
  - **1st Positive System ($B^3\Pi \rightarrow A^3\Pi$) 500-750 nm**
  - **2nd Positive System ($C^3\Pi \rightarrow B^3\Pi$) 280-390 nm**

N_2 1st Positive

8.18 km/s, 0.01 Torr



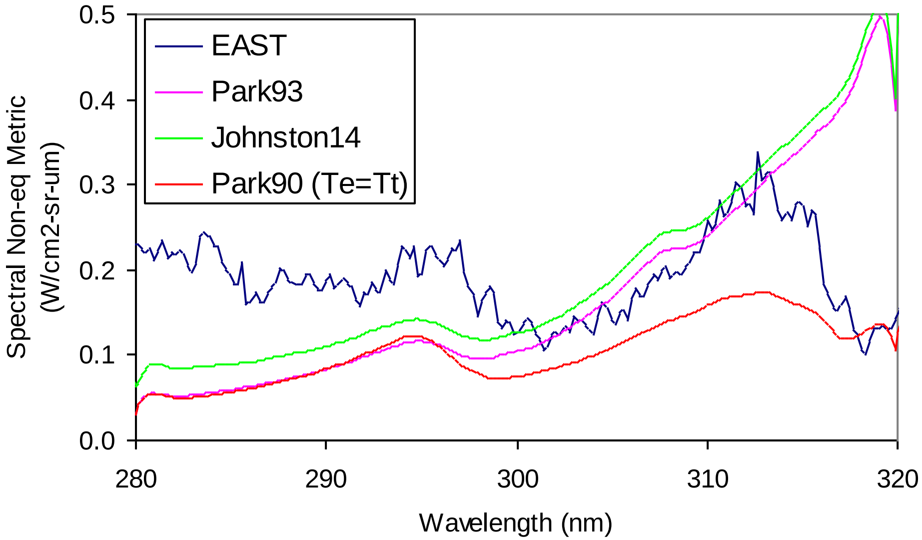
7.34 km/s, 0.70 Torr



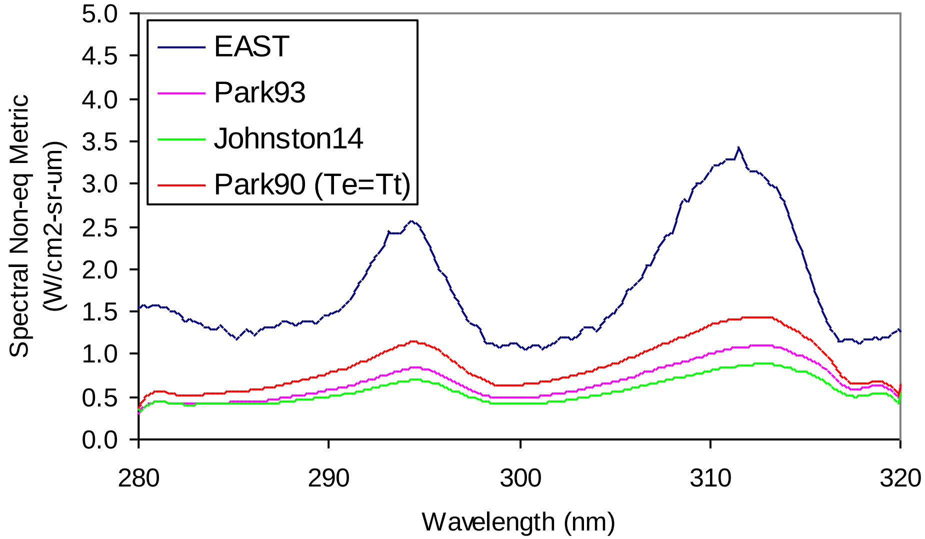
- **Underpredicted at all conditions**
- **Bonus Atomic Lines!**

N_2 2nd Positive

8.18 km/s, 0.01 Torr



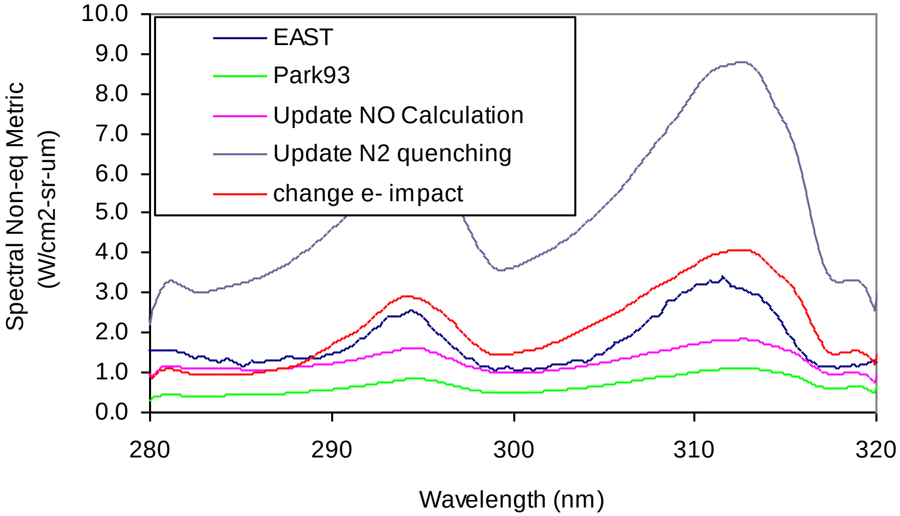
7.34 km/s, 0.70 Torr

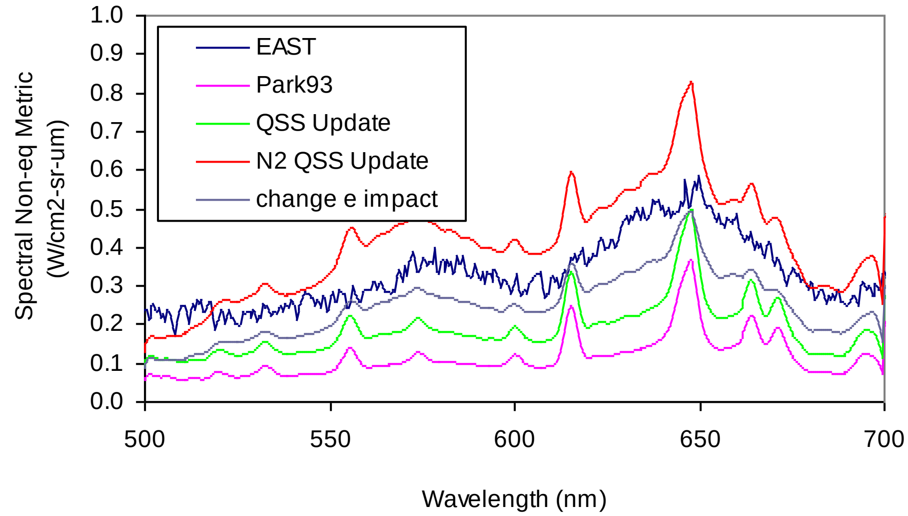


- **Underpredicted at all conditions**
- **Partly obscured by N_2^+ radiation at 0.01 Torr**

Update to N_2 QSS

7.34 km/s, 0.70 Torr



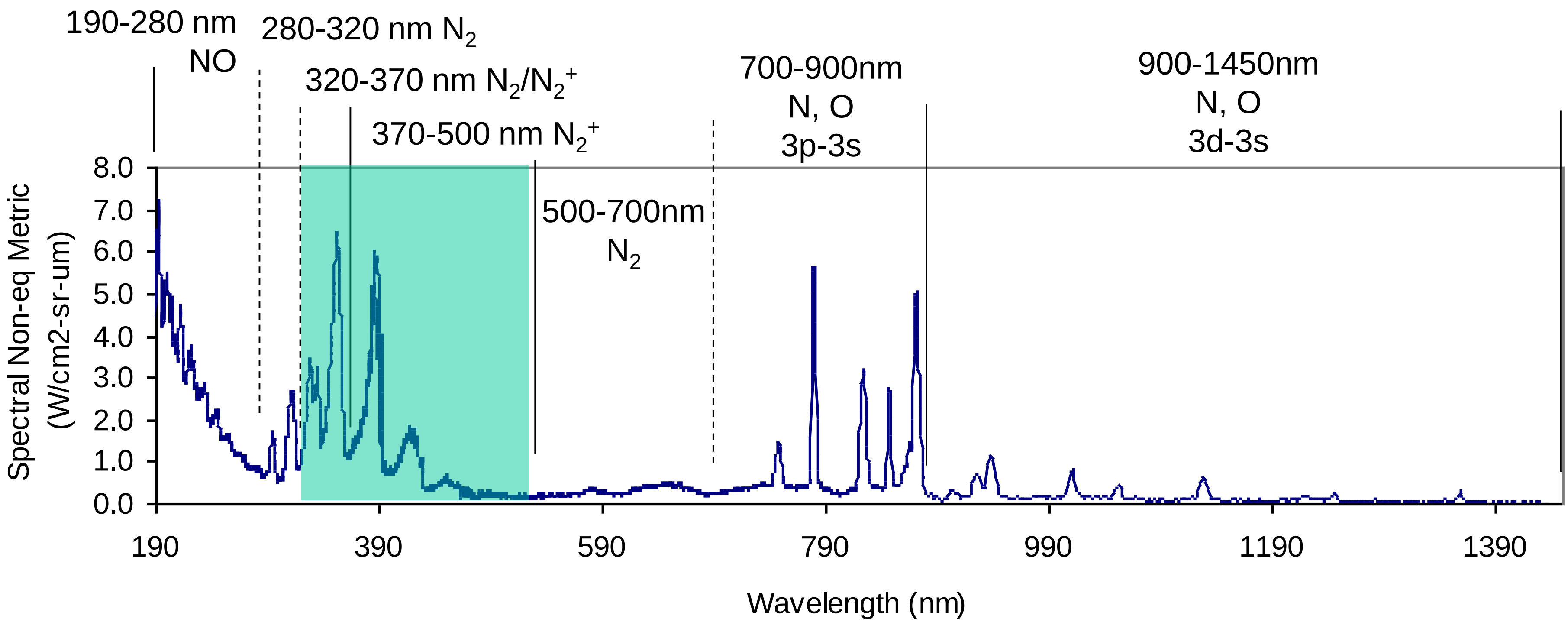


- **Changing NO rates reduced underprediction @ 0.7 Torr**
- **Introducing N_2 Quenching rates brought data into overprediction**
- **Updating electron impact processes obtains near-agreement**
  - **Slight underprediction of N_2 1st Positive, overprediction of 2nd Positive**

- **0.01 Torr data (not shown) now overpredicted in UV, matched in Visible**

N_2^+ Model

N_2^+ Radiance

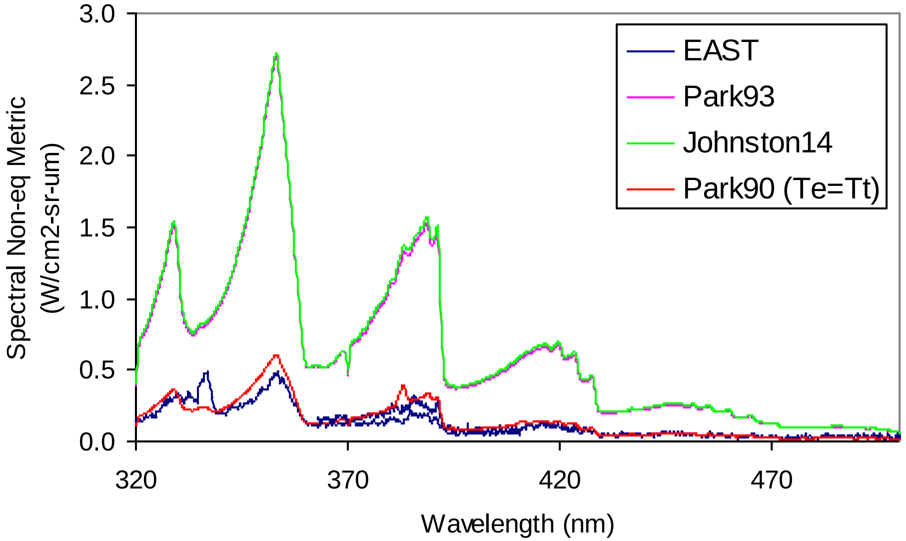


- **N_2^+ Radiation from**
  - **1st Negative System ($B^2\Sigma \rightarrow X^2\Sigma$) 320-500 nm**

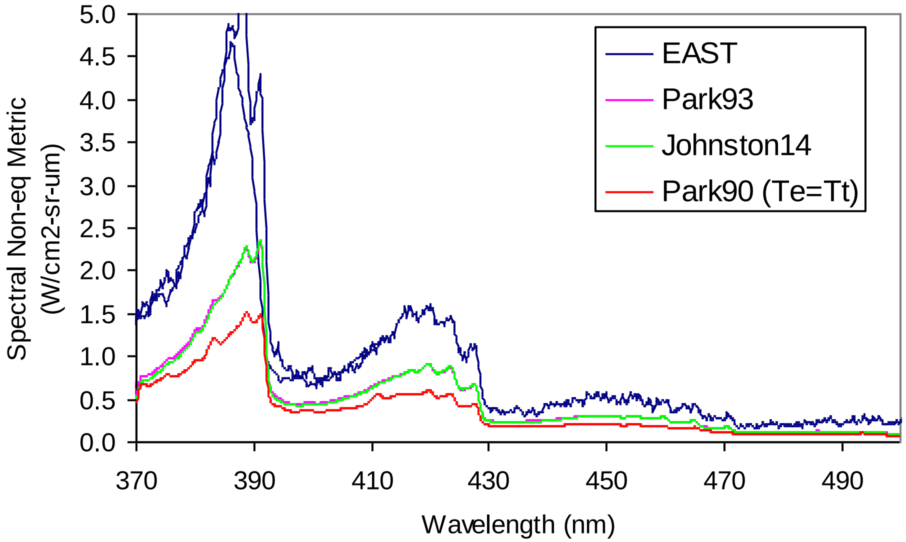
N_2^+ Comparison to Heritage

Entry Systems and Technology Division

8.18 km/s, 0.01 Torr



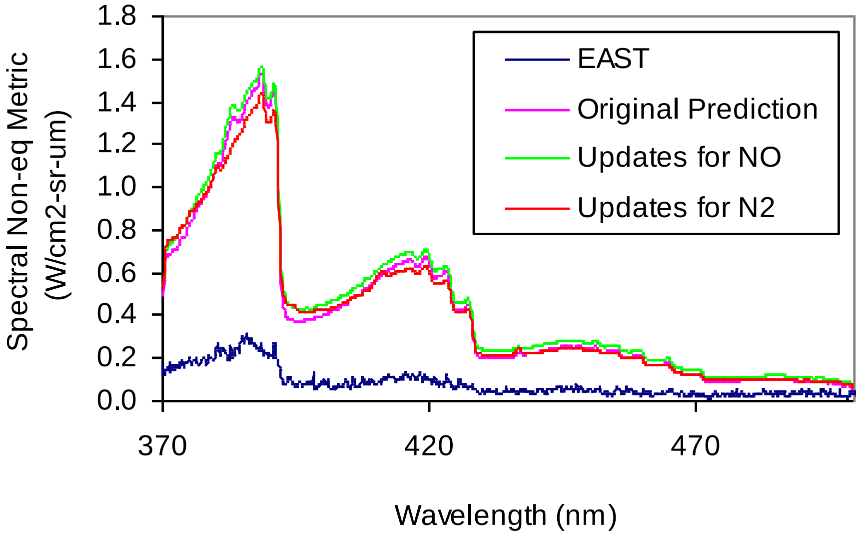
7.34 km/s, 0.70 Torr



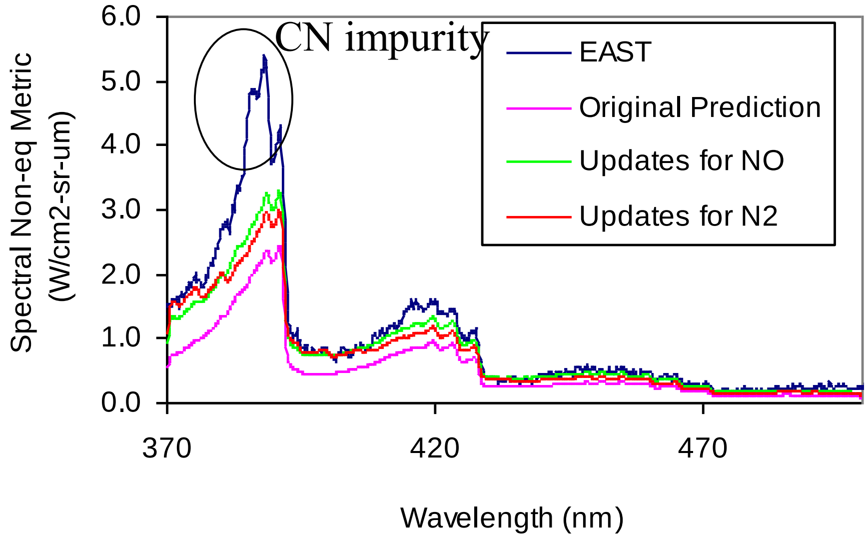
- **Underpredicted at high pressure**
- **Overpredicted at low pressure**
  - **Park90 gets right magnitude, but transient (not shown) is incorrect**

N_2^+ after updates

8.18 km/s, 0.01 Torr



7.34 km/s, 0.70 Torr



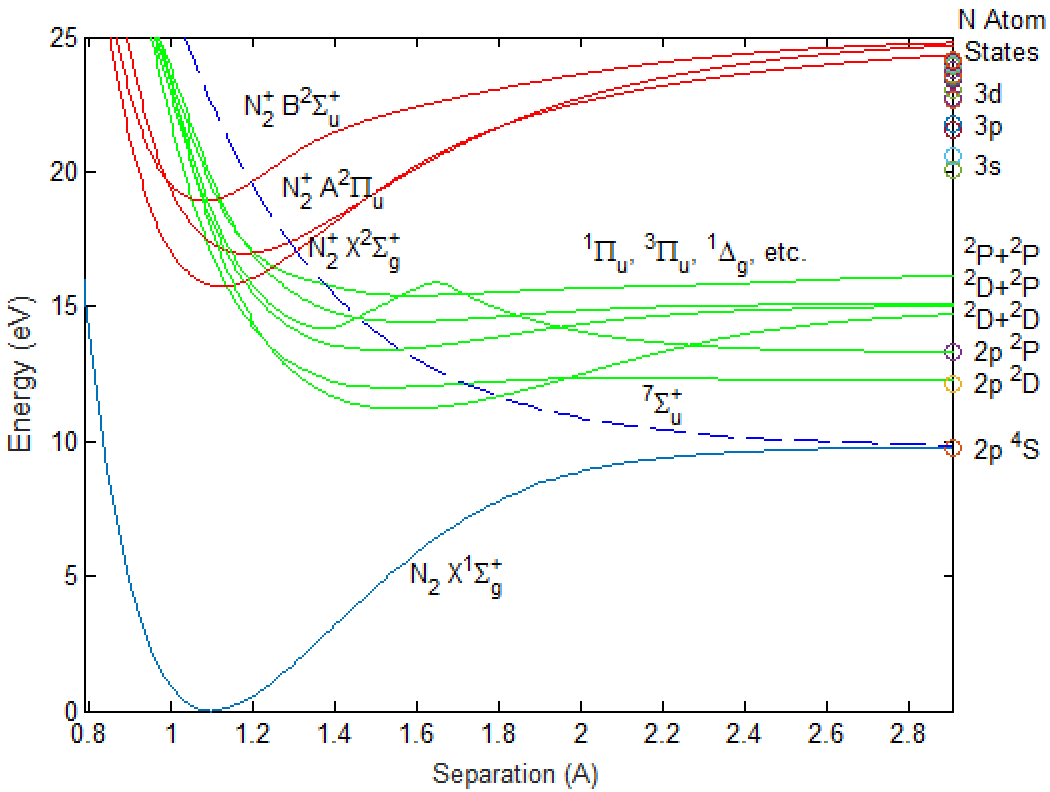
- **Discrepancy at higher pressure mostly solved by revisions to rate model**
- **Low pressure discrepancy remains**

Low Pressure N_2^+ : Controlling Reaction

- **N_2^+ primarily formed by associative ionization:**

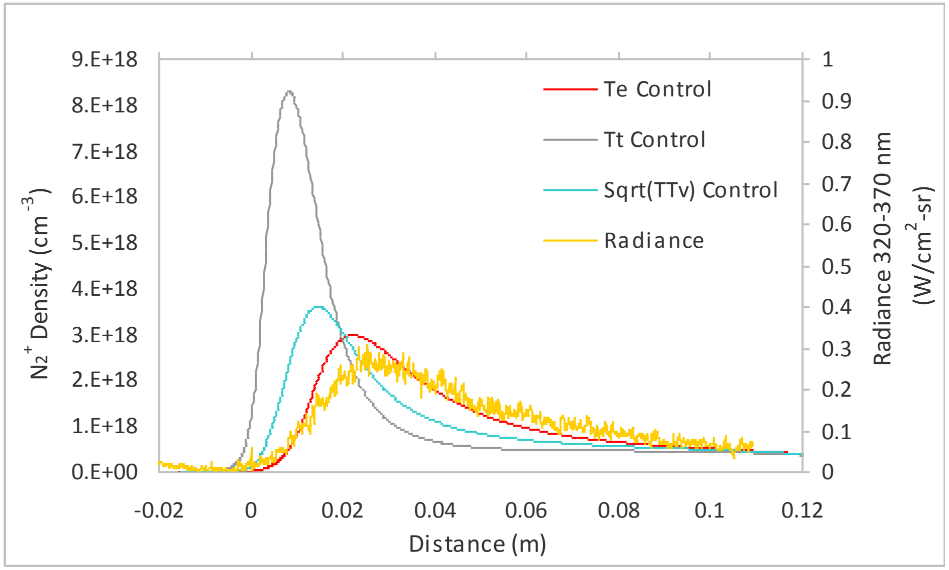
$$N + N \longleftrightarrow N_2^+ + e^-$$

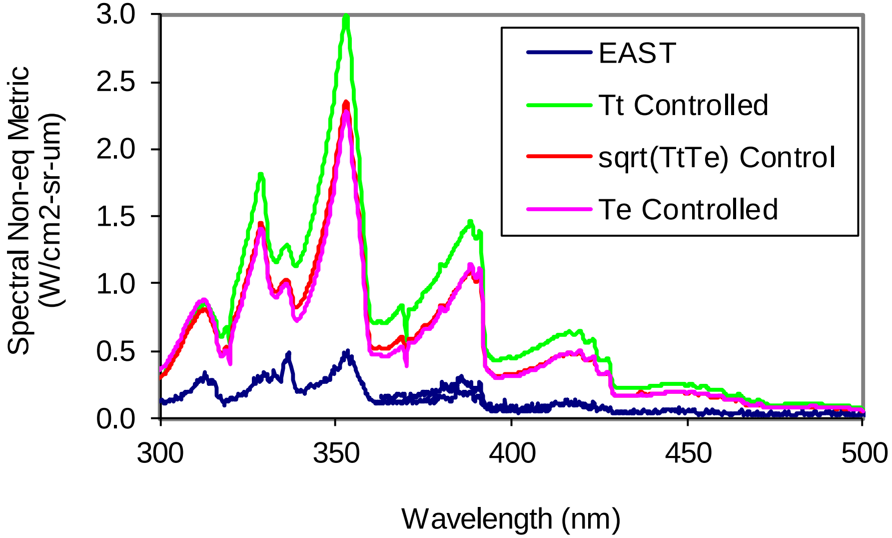
- **This rate typically controlled by T_t : becomes rapid when thermal non-equilibrium is significant**



- **However, ground state N does not cross N_2^+ states**
- **Reactions proceed through metastable (and possibly excited) N atoms**
- **This creates dependence on T_e**

Change Controlling Temperature

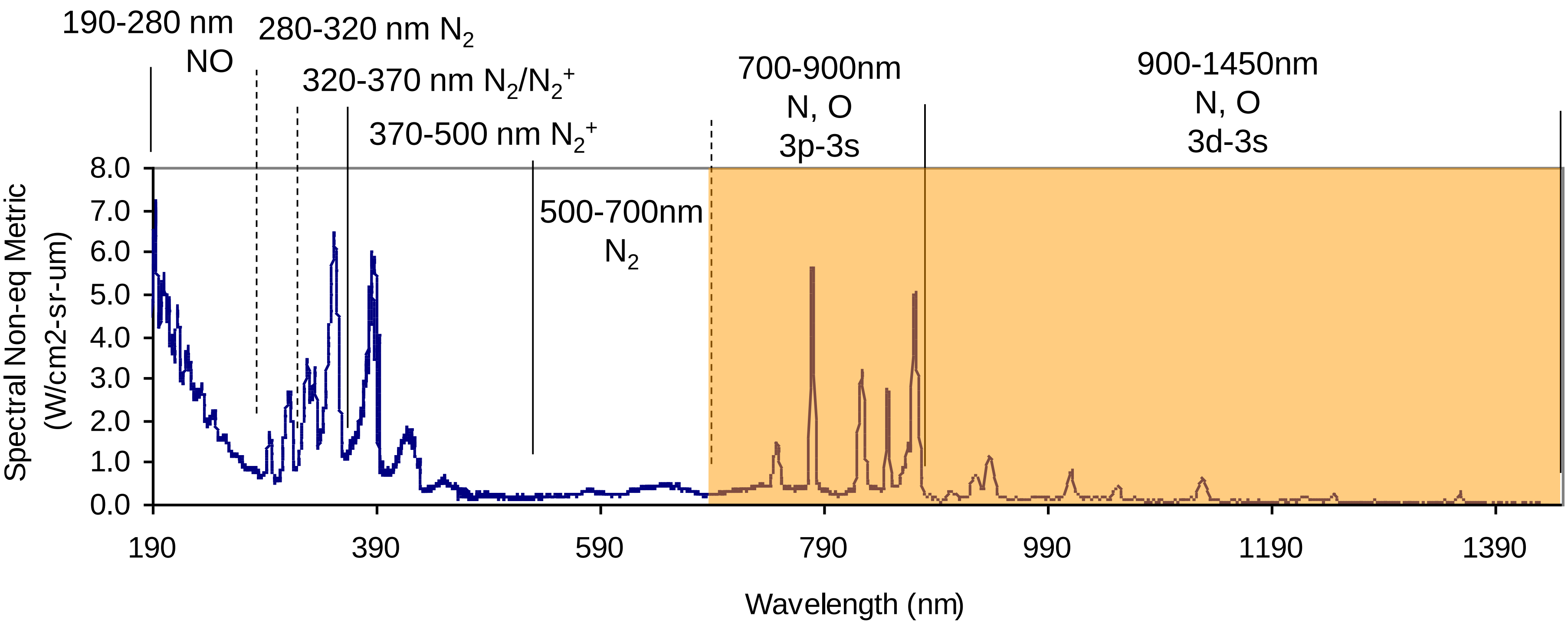




- **Experimental Radiation profile matches N_2^+ density when T_e controlling**

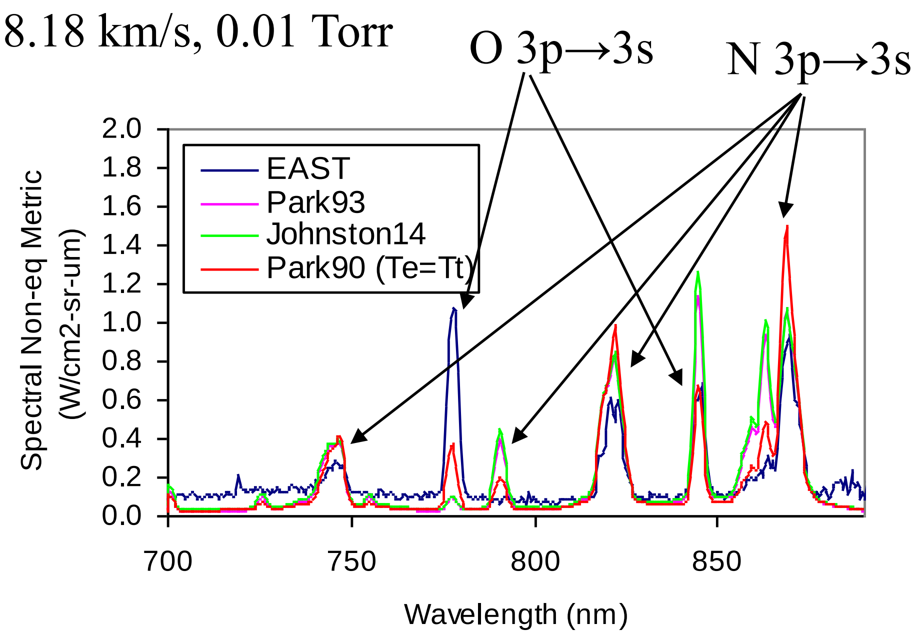
- **The predicted radiance (and profile) does not match, however**

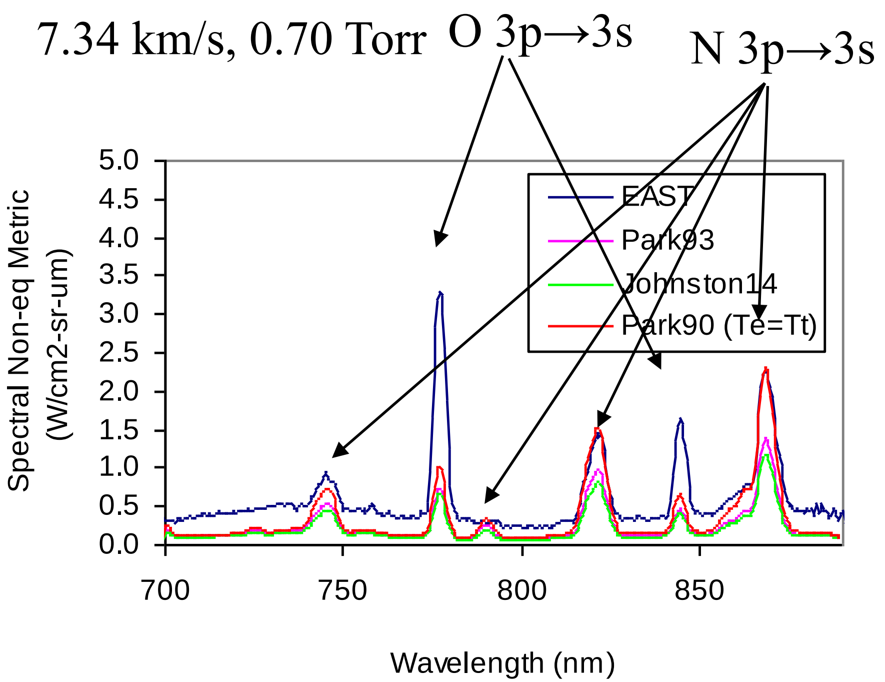
Atomic Radiance



- **Atomic Radiation**
  - **3p states** **700-900 nm**
  - **3d states** **900-1450 nm**

N, O 3p Comparison to Heritage





- **O atom:**
  - **777 nm underpredicted at all cases**
  - **845 nm underpedicted high pressure, matched low pressure**
- **N atom:**
  - **Low pressure : Fair agreement**
  - **High pressure : adjusting for baseline, matched by Park93/Johnston, overpredicted by Park90**

N, O 3d Comparison to Heritage

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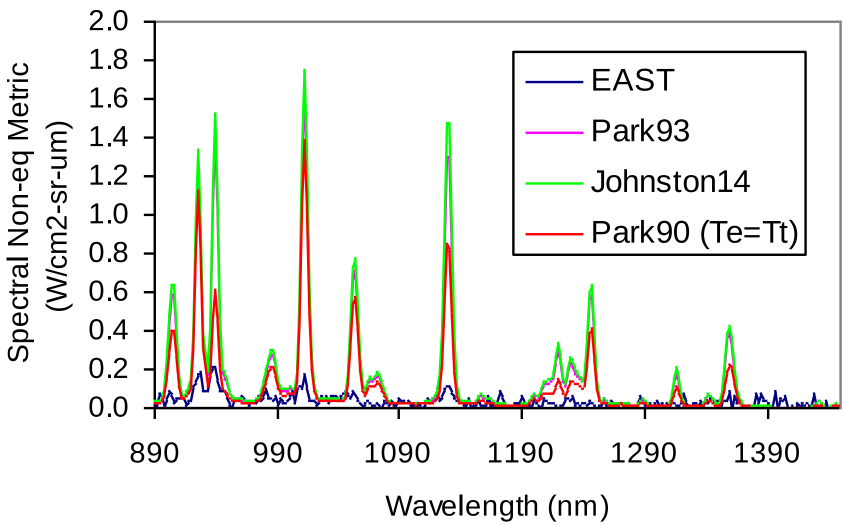
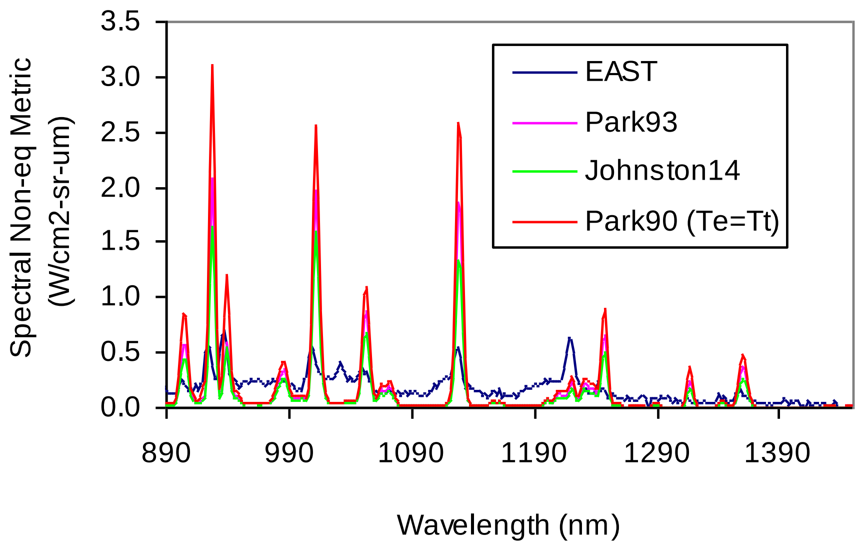
8.18 km/s, 0.01 Torr

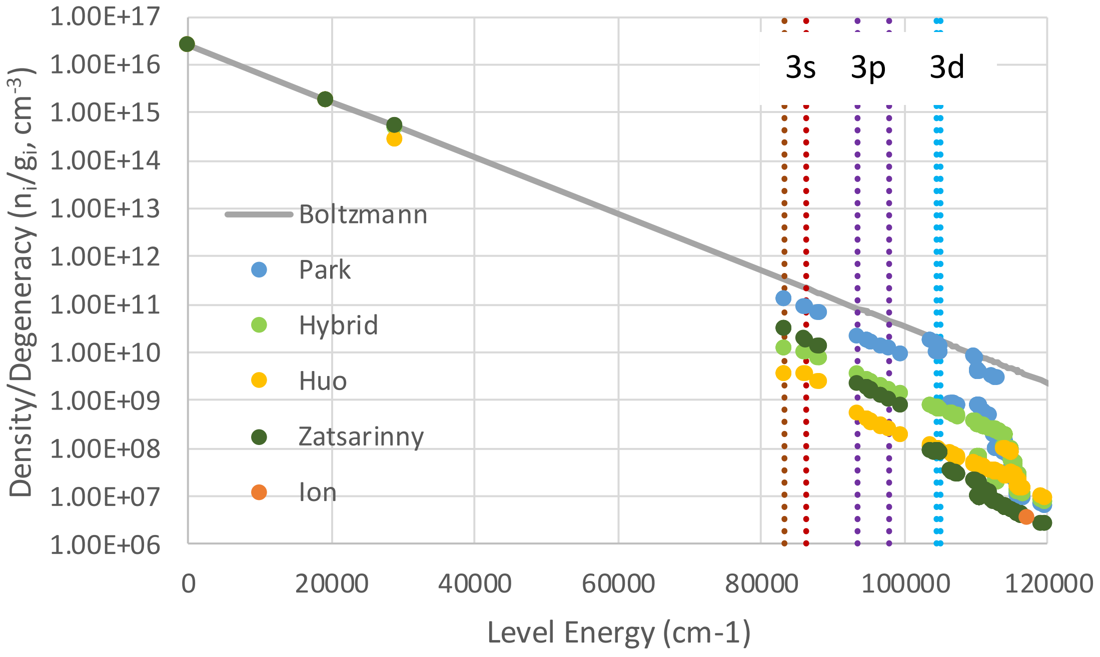


7.34 km/s, 0.70 Torr



- **Significant overprediction, all lines/pressures**

Internal Excitation Rates



Peak Radiance

7.34 km/s, 0.7 Torr

$T_t = 10{,}598K$

$T_e = 10{,}645K$

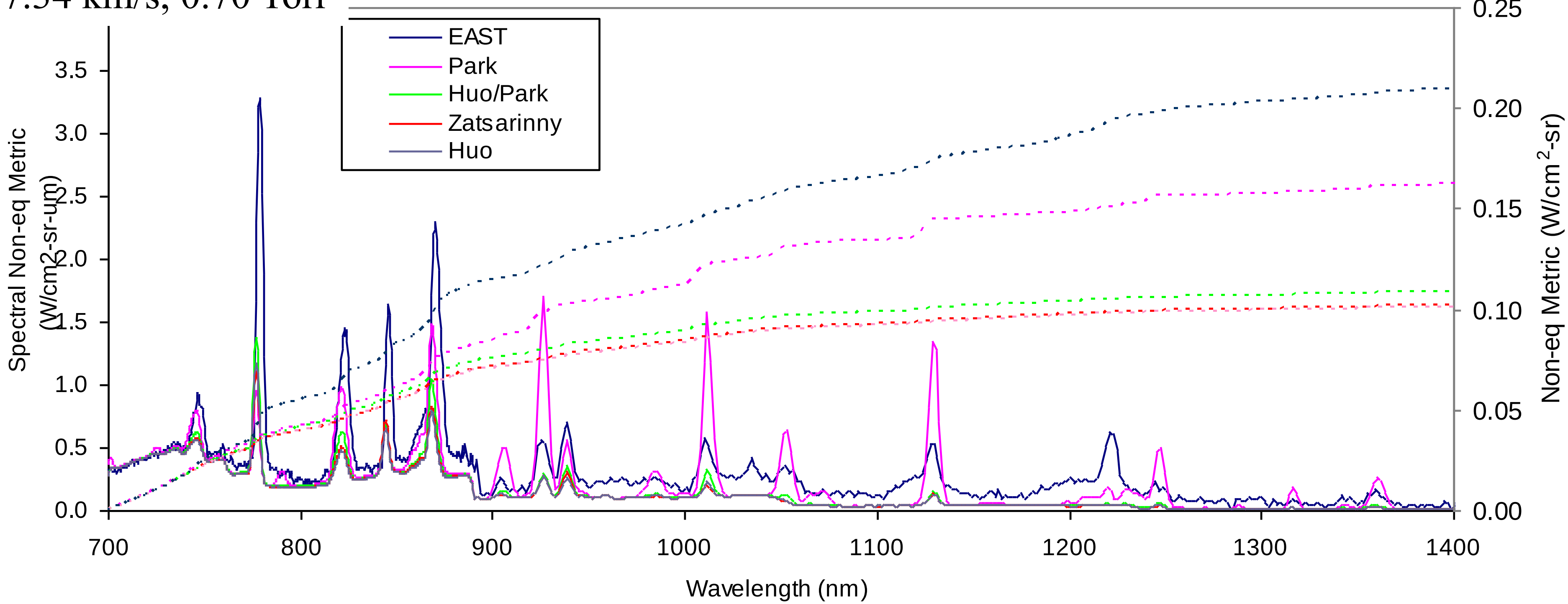
$N = 1.27 \times 10^{17}\ cm^{-3}$

$N^{+} = 2.42 \times 10^{14}\ cm^{-3}$

- **Park rates place 3d states at Boltzmann level (overpredicted)**
- **Huo rates equilibrate all states closer to ionization level**
- **Zatsarinny rates place highest states near ionization limit, lower states progress toward Boltzmann**
- **Hybrid Huo/Park equilibrates between Boltzman/Saha**

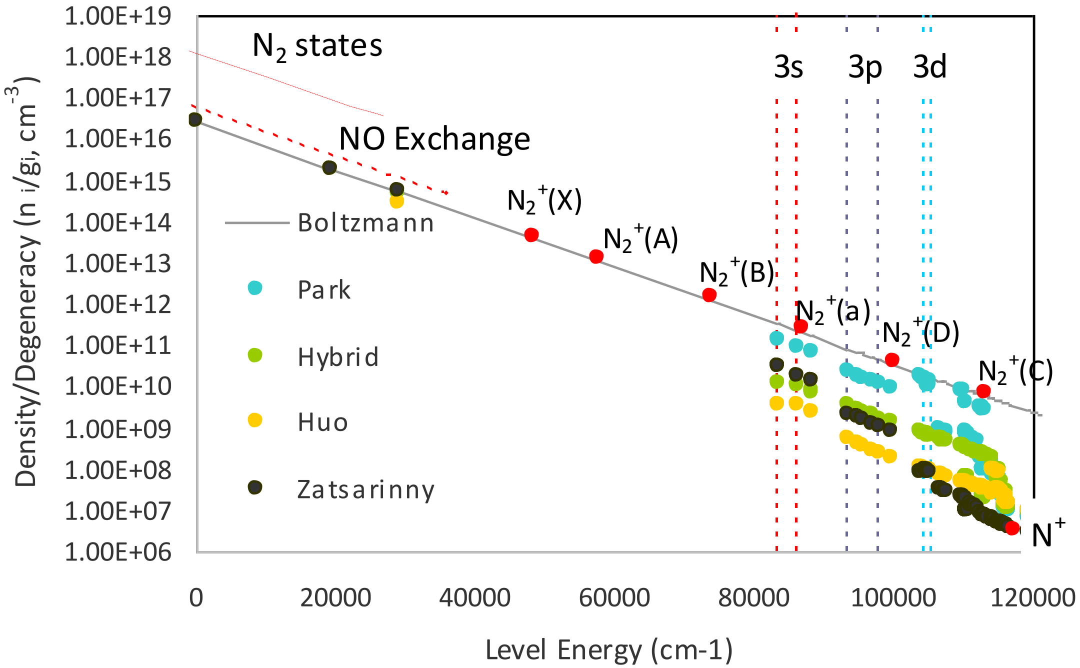
Impact of Excitation Rate on Radiance

7.34 km/s, 0.70 Torr



- **Revised rates underpredict 3p atomic lines**
- **Three alternatives eliminate 3d overprediction**
- **Huo/Park slightly higher than Huo or Zatsarinny**

Additional Processes



Peak Radiance

7.34 km/s, 0.7 Torr

T_t = 10,598K

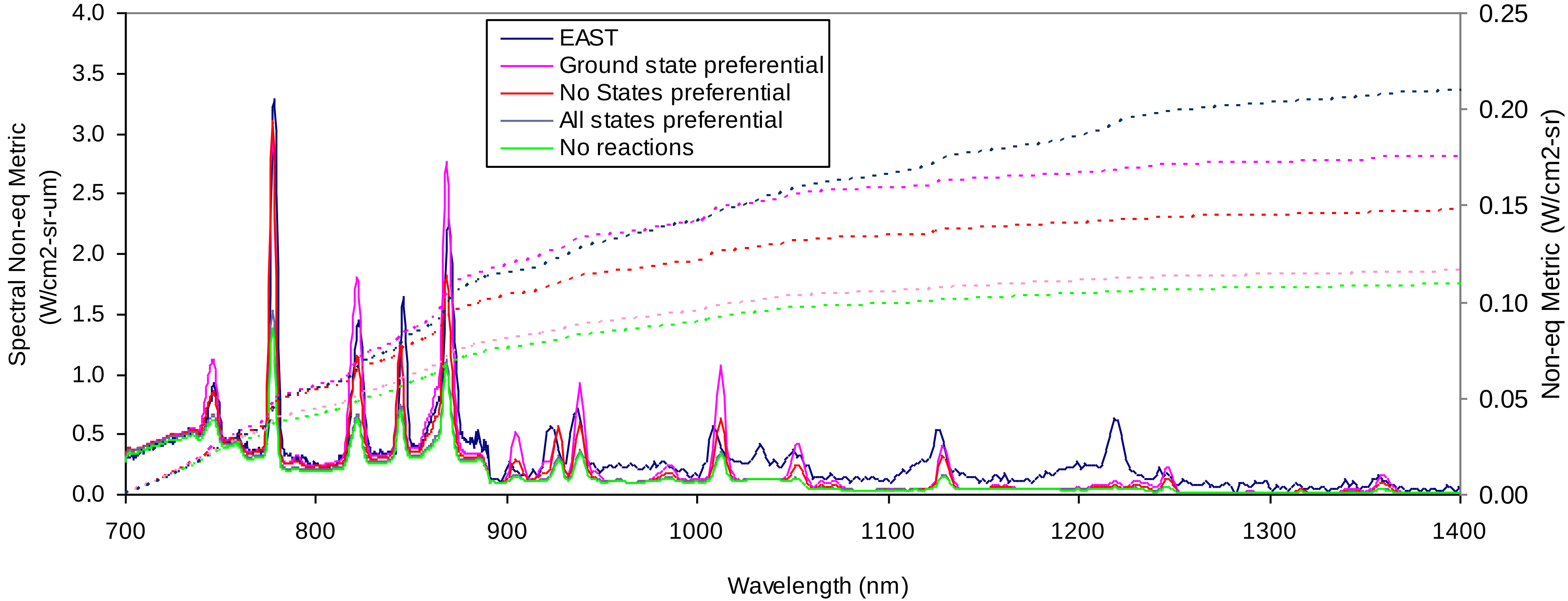
T_e = 10,645K

N = 1.27×10^{17} cm^{-3}

N^+ = 2.42×10^{14} cm^{-3}

- **Traditionally, QSS balances internal excitation with ionization**
- **But, Ionization accounts for 0.15% of N atom chemistry**
- **N atom mass derivative is:**
  - **81% exchange reactions**
  - **10% molecular dissociation**
  - **9% associative ionization**

Including Dissociative Recombination in QSS

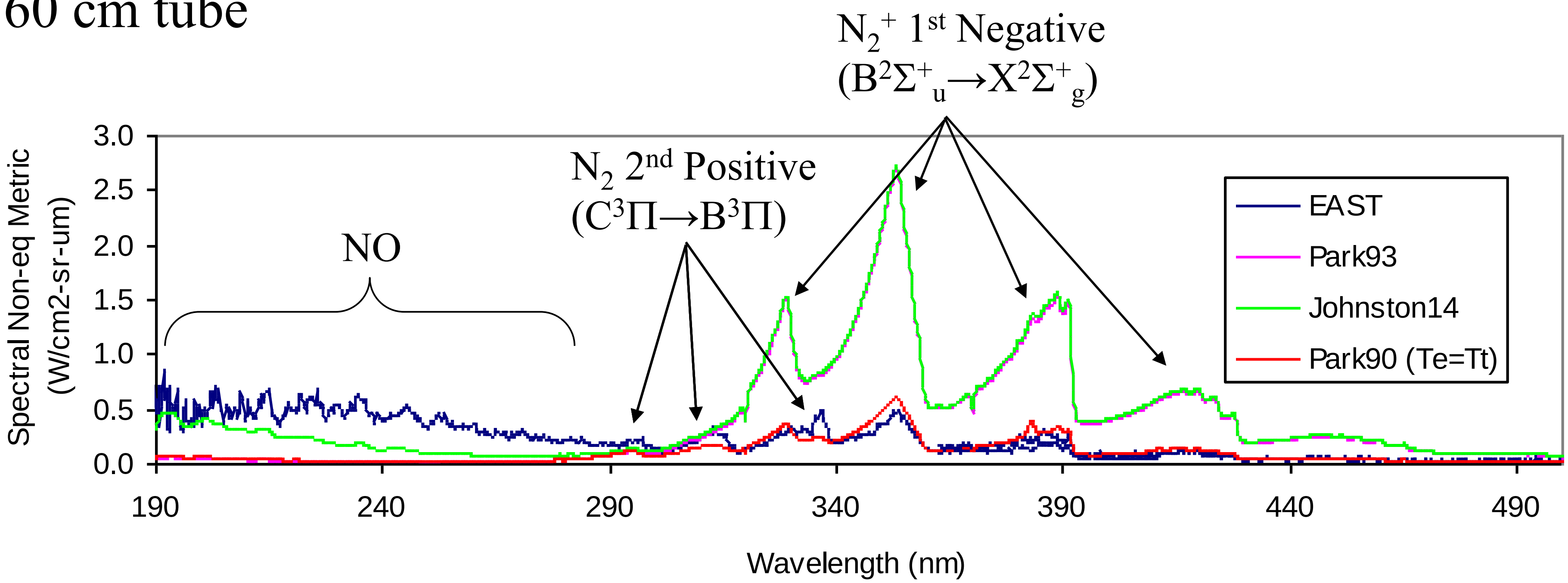


- **State-wise associative ionization rates assumed proportional to overall associative ionization rates**
- **Preference factors dictate which atomic states are formed from a given ion state**
- **Best agreement uses literature data for ground state preference, no preference for other states of N_2^+**

Flip-through of Non-equilibrium Metric Comparisons

Non-equilibrium – 190-500 nm (0.01 Torr, 8.2 km/s)

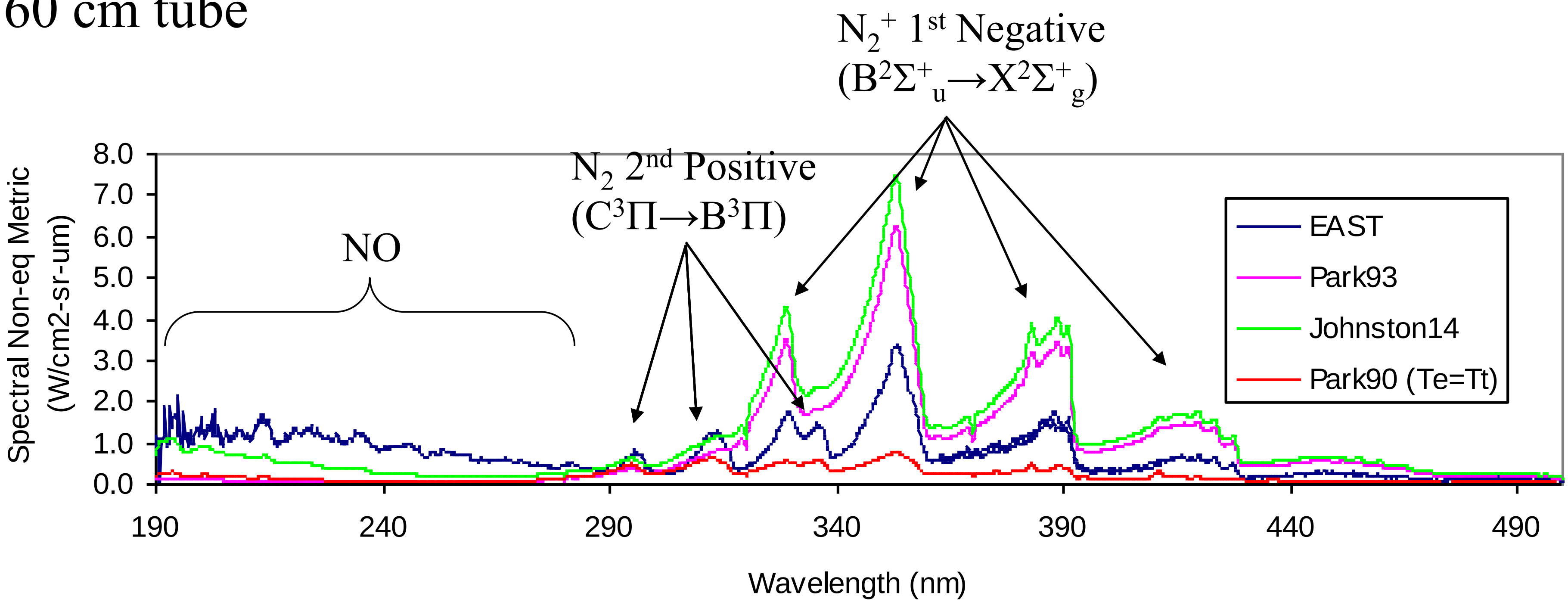
60 cm tube



- **All models underpredict NO**
- **N_2^+ overpredicted by T_e=T_v options, Heritage does ok**
- **N_2 2nd Positive underpredicted**

Non-equilibrium – 190-500 nm (0.05 Torr, 8.6 km/s)

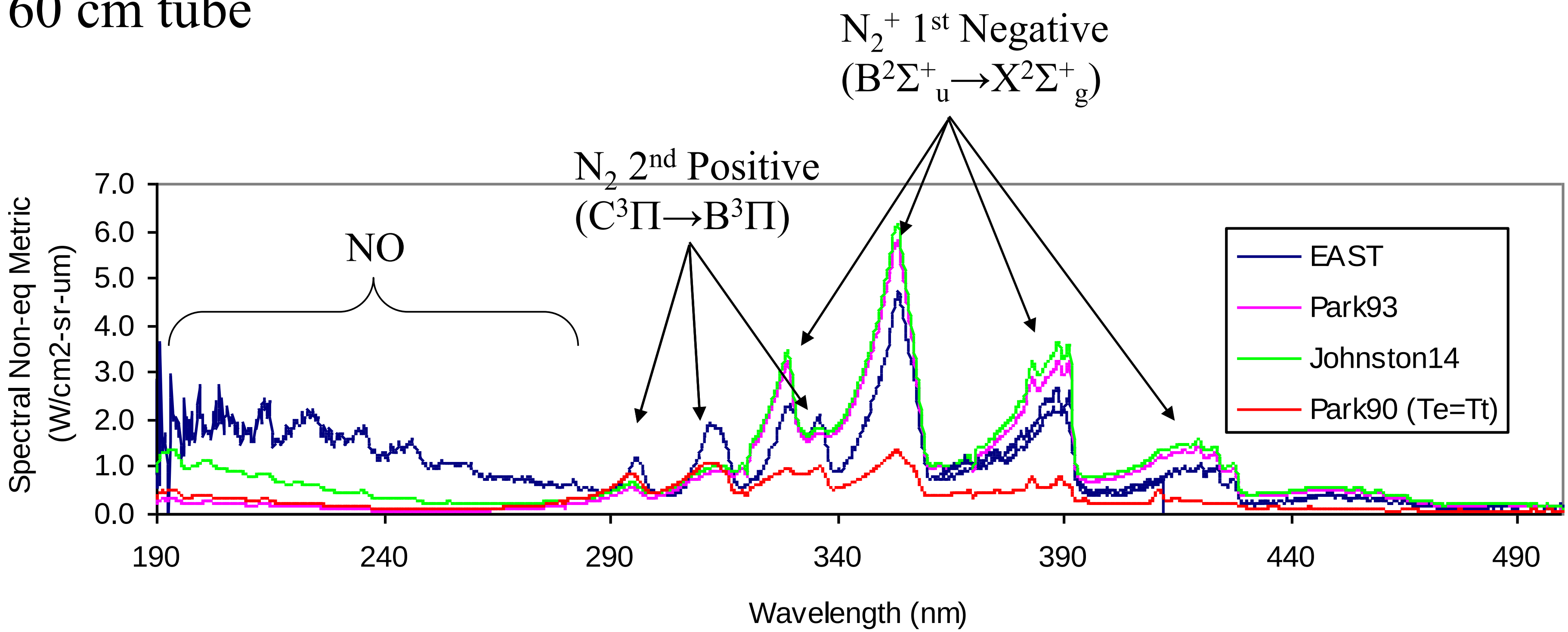
60 cm tube



- **NO still underpredicted**
- **N_2^+ improving for T_e=T_v options, Heritage now too low**
- **N_2 2nd Positive still underpredicted**

Non-equilibrium – 190-500 nm (0.14 Torr, 8.3 km/s)

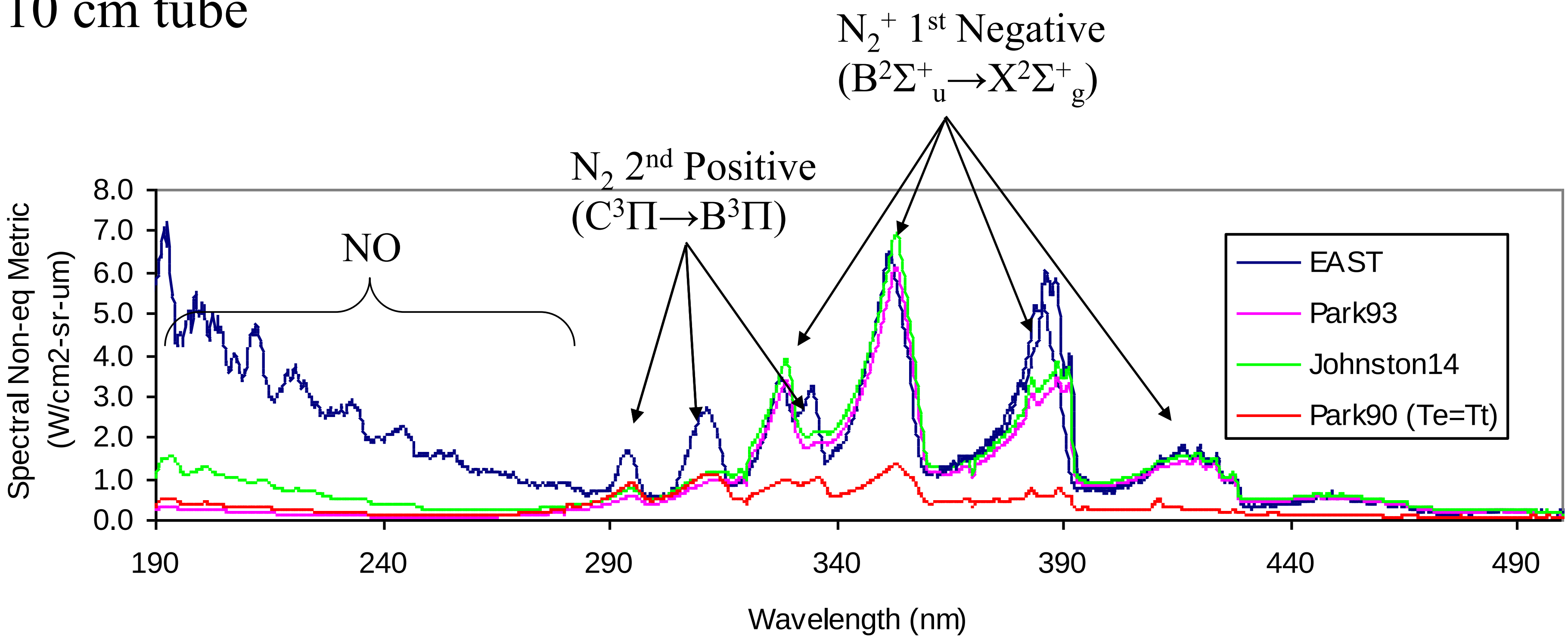
60 cm tube



- **NO still underpredicted**
- **N_2^+ slightly over for T_e=T_v options, Heritage underpredicts**
- **N_2 2nd Positive underpredicted**

Non-equilibrium – 190-500 nm (0.14 Torr, 8.3 km/s)

10 cm tube



- **NO underpredicted**
- **N_2^+ matched for T_e=T_v options, Heritage underpredicts**
  - **CN contamination accounts for disagreement at 388 nm**
- **N_2 2[nd] Positive underpredicted**

Non-equilibrium – 190-500 nm (0.30 Torr, 8.1 km/s)

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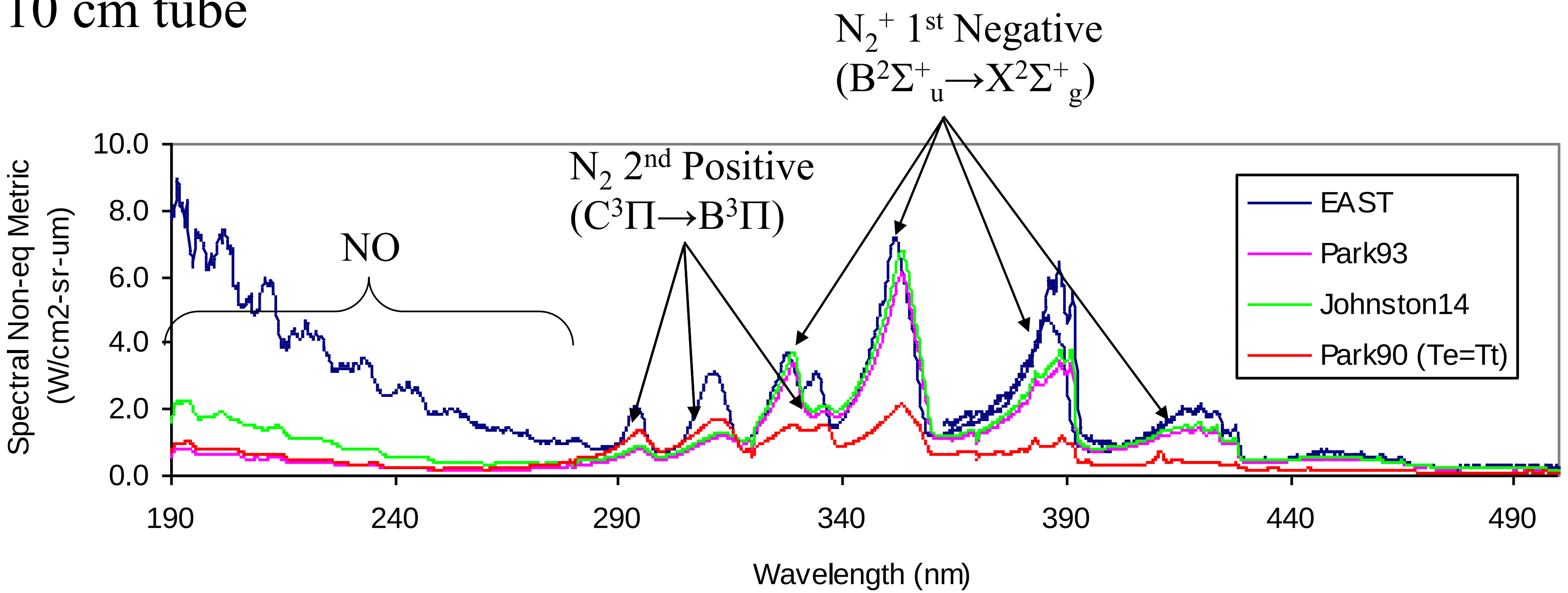
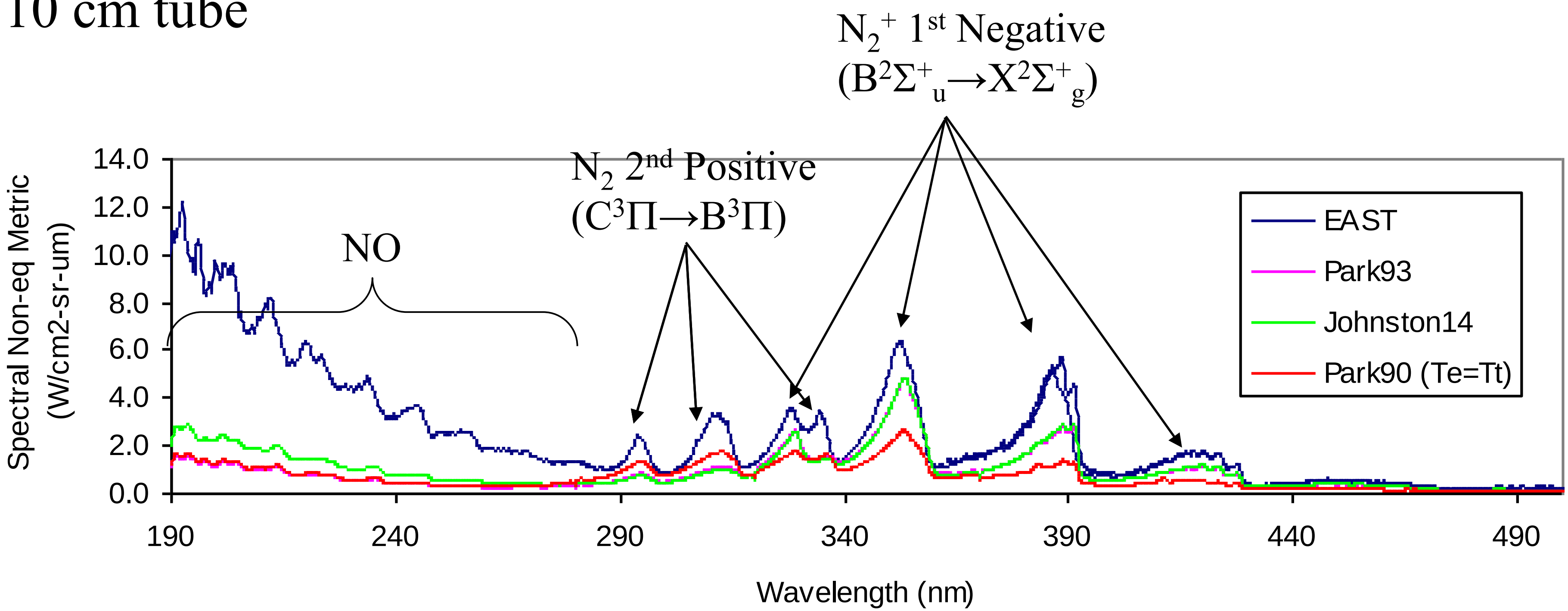
10 cm tube



- **NO underpredicted**
- **N_2^+ matched for T_e=T_v options, Heritage underpredicts**
  - **CN contamination accounts for disagreement at 388 nm**
- **N_2 2nd Positive underpredicted**

Non-equilibrium – 190-500 nm (0.50 Torr, 7.7 km/s)

10 cm tube



- **NO still underpredicted**
- **N_2^+ being underpredicted**
  - **Worse for Heritage**
- **N_2 2nd Positive underpredicted**

Non-equilibrium – 190-500 nm (0.70 Torr, 7.3 km/s)

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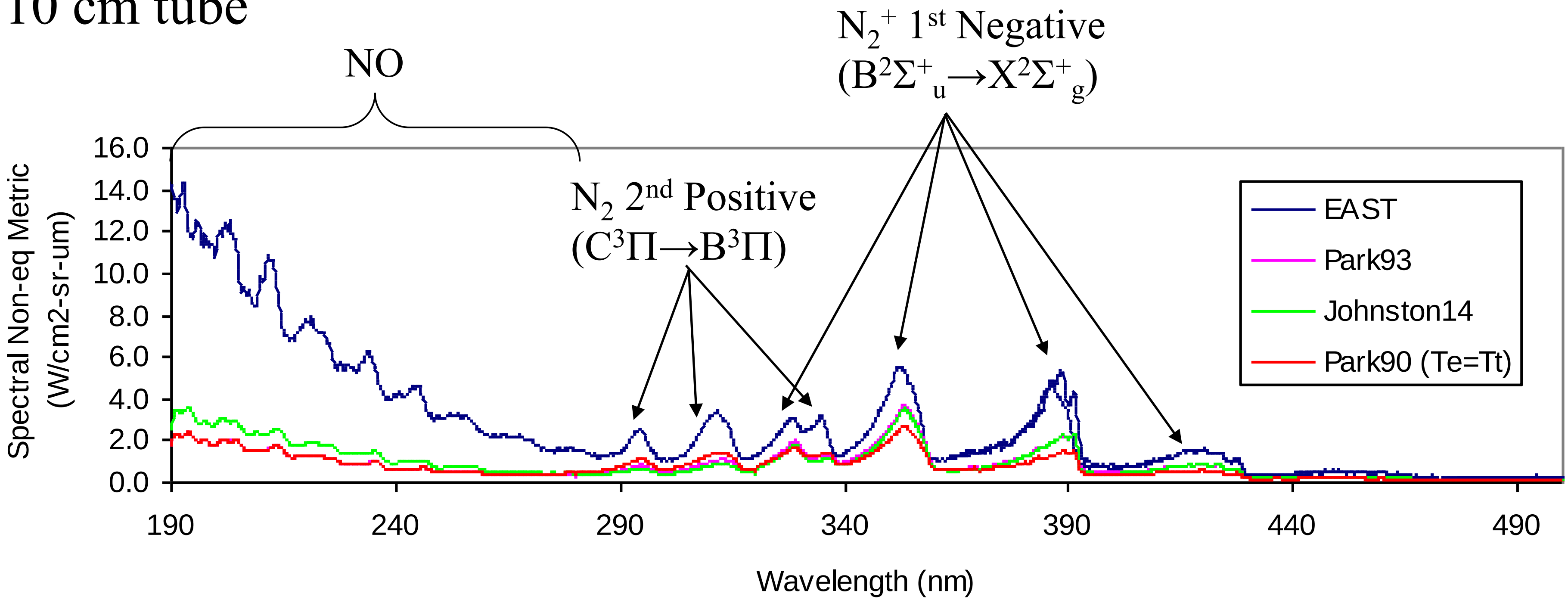
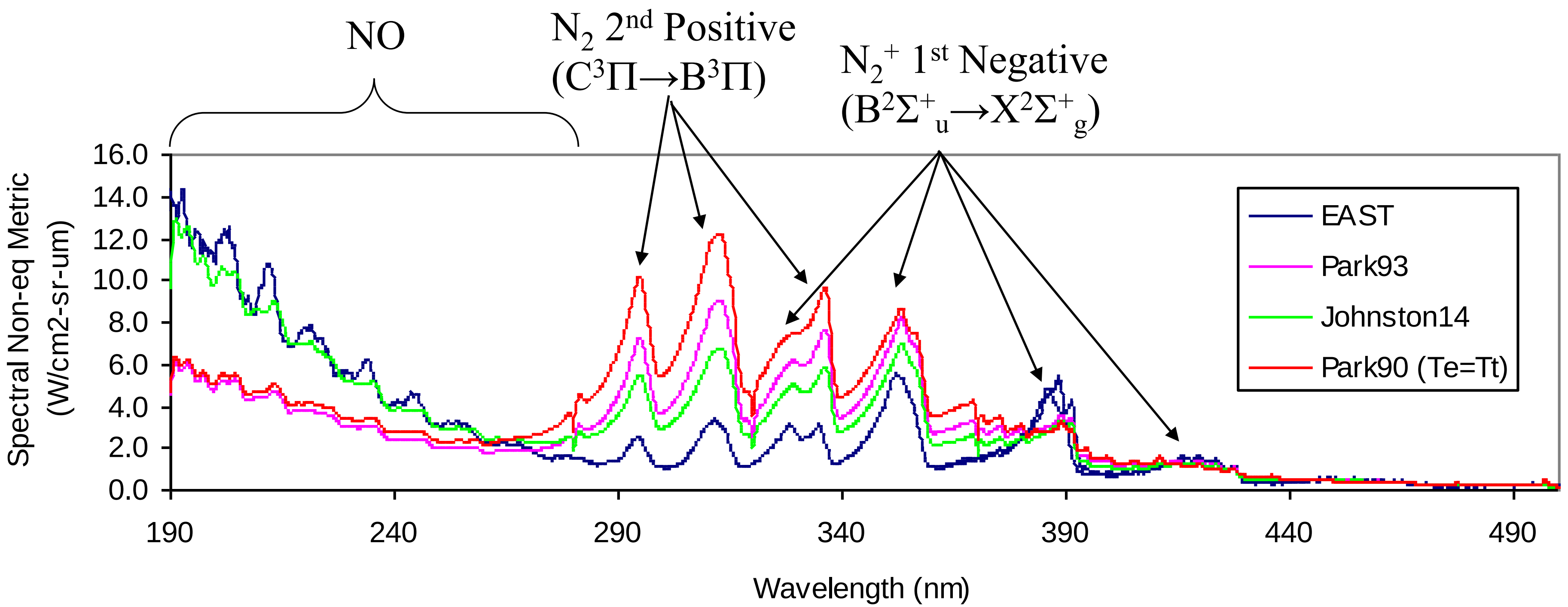
10 cm tube



- **NO still underpredicted**
- **N_2^+ more underpredicted**
  - **Heritage and newer models becoming more similar**
- **N_2 2nd Positive underpredicted**

Non-equilibrium – 190-500 nm (0.70 Torr, 7.3 km/s)

10 cm tube – with Boltzmann state populations



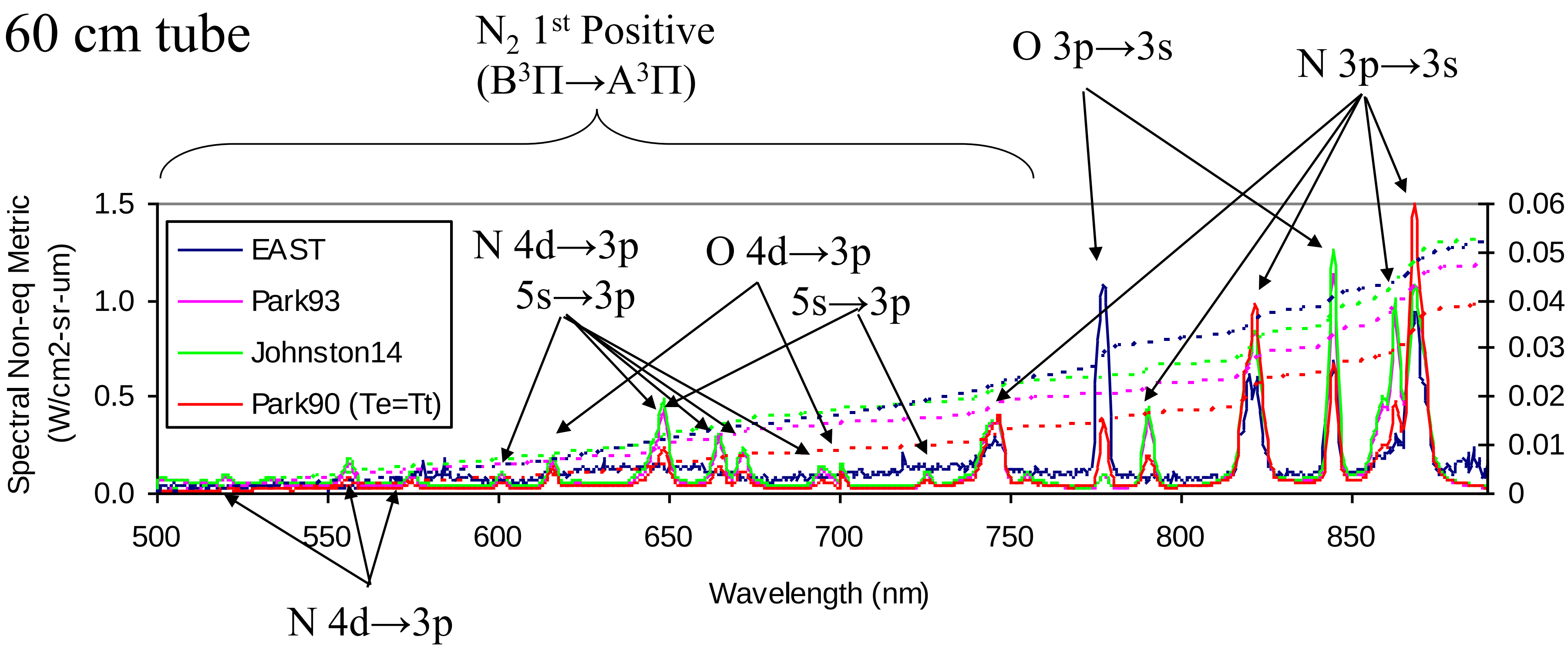
- **NO matched with Boltzmann distribution for Johnston rates**
- **N_2^+ and N_2 are overpredicted by Boltzmann model**

Summary 190-500 nm

- **NO is always underpredicted**
- **N_2 2nd Positive always underpredicted**
- **N_2^+ 1st Negative underpredicted at high pressure, overpredicted at low pressure**

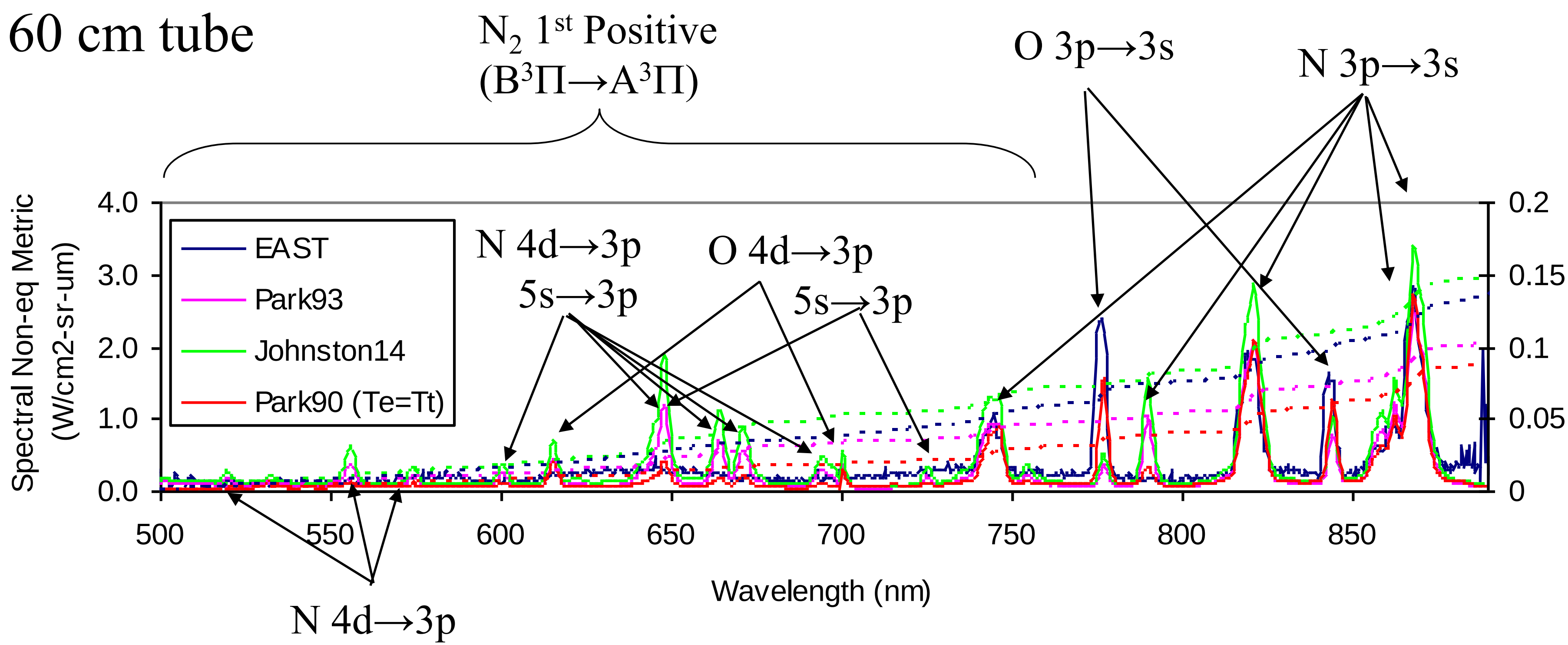
Non-equilibrium – 500-890 nm (0.01 Torr, 8.6 km/s)

60 cm tube



- Broad features due to N_2 1st Positive absent from prediction
- High level (4d,5s) N and O lines absent from data
- O 3p : 777 underpredicted, 845 underpredicted
- N 3p : overpredicted
- Errors cancel out when integrated – radiance appears well matched

Non-equilibrium – 500-890 nm (0.05 Torr, 8.9 km/s)



- **Broad features due to N_2 1st Positive still absent**
- **High level (4d,5s) N and O lines still overpredicted**
- **O 3p : underpredicted, but closer than before**
- **N 3p : matched by Park90/Park93, overpredicted Johnston**
- **Errors cancel out when integrated – Johnston appears to matched**

Non-equilibrium – 500-890 nm (0.14 Torr, 8.4 km/s)

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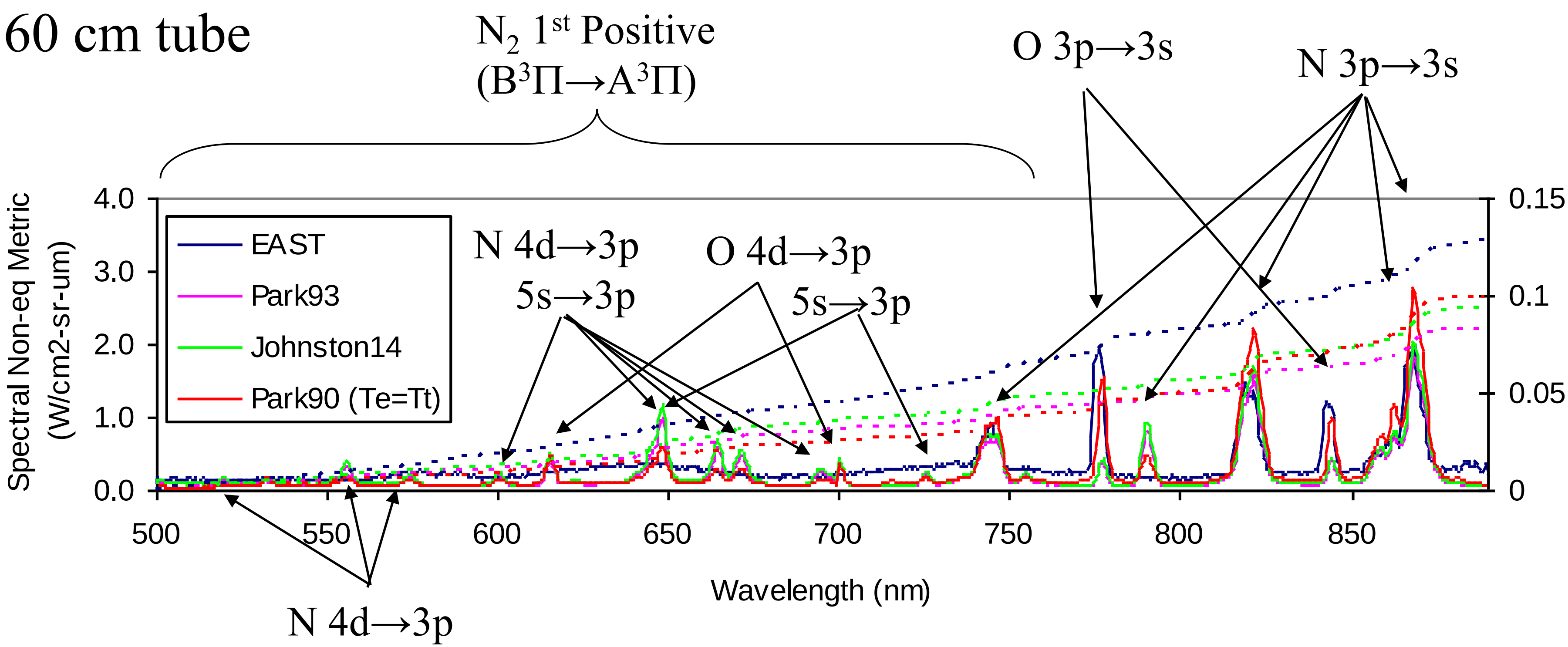

- **Broad features due to N_2 1st Positive still absent**
- **High level (4d,5s) N and O lines still overpredicted**
- **O 3p : matched by heritage model, underpredicted other models**
- **N 3p : overpredicted by heritage, matched other models**

Non-equilibrium – 500-890 nm (0.14 Torr, 8.3 km/s)

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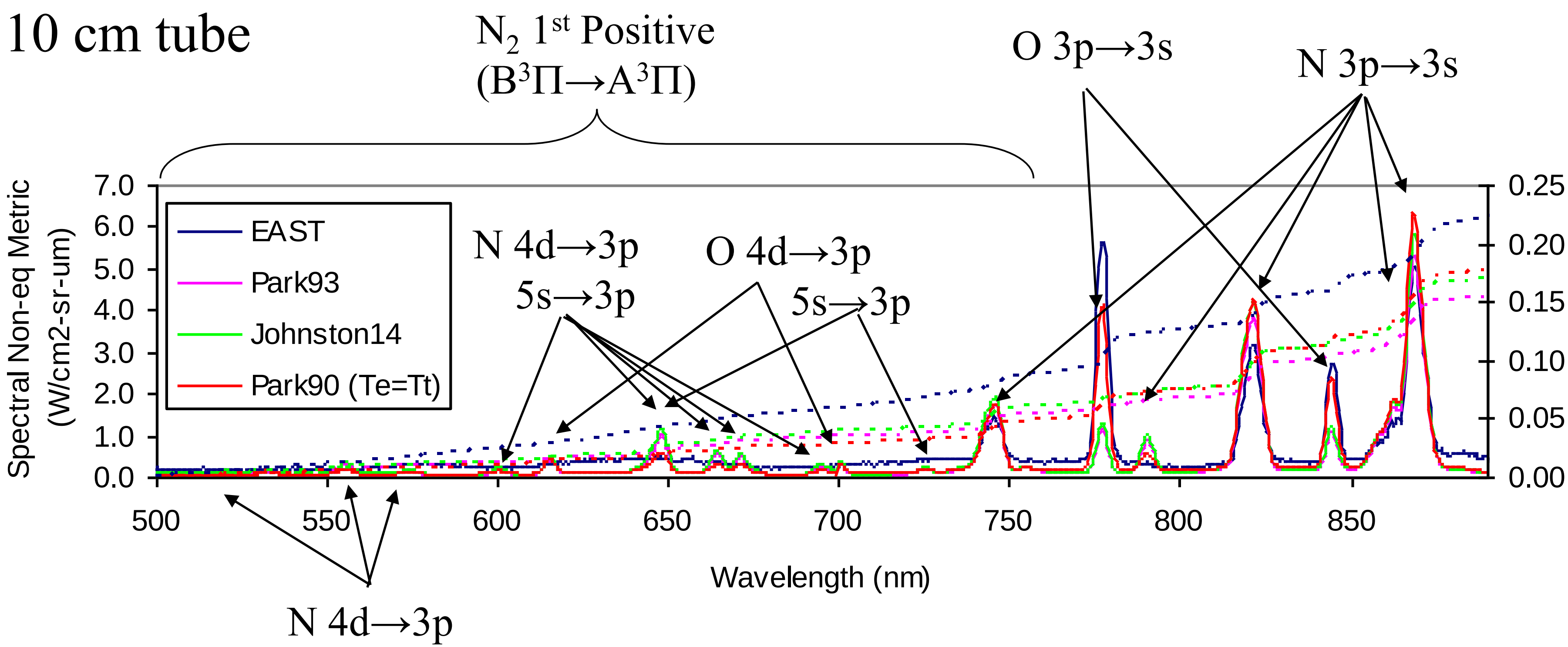
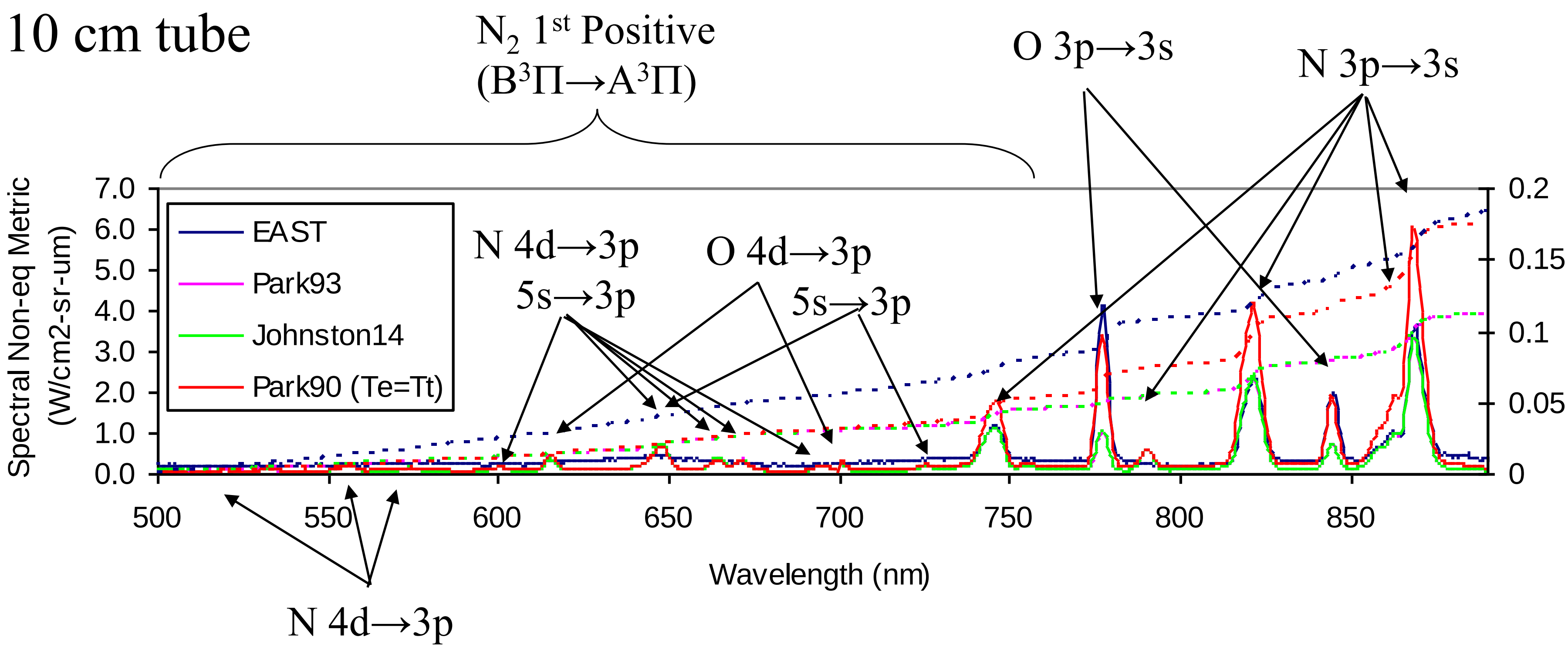


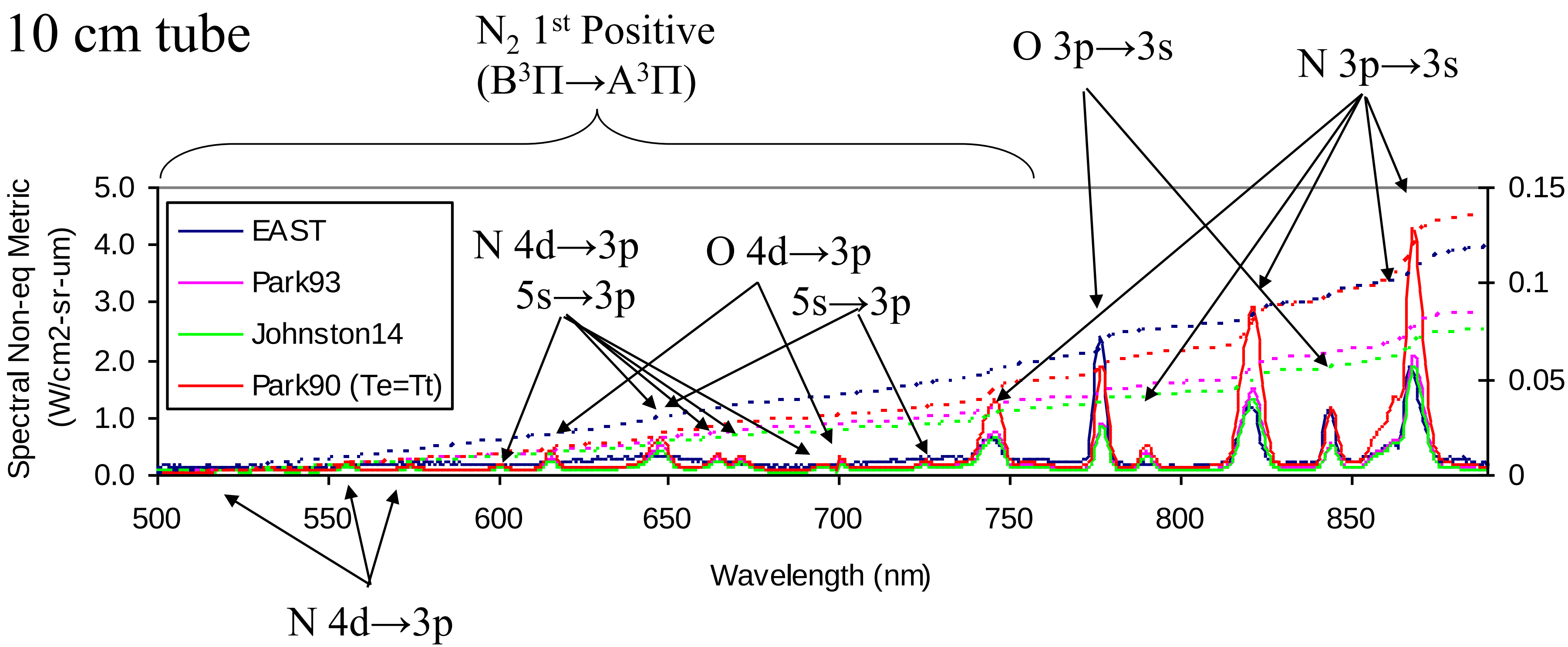
- **Broad features due to N_2 1st Positive still absent**
- **High level (4d,5s) N and O lines overpredicted**
- **O 3p : matched by heritage model, underpredicted other models**
- **N 3p : overpredicted by heritage, matched other models**

Non-equilibrium – 500-890 nm (0.30 Torr, 8.1 km/s)



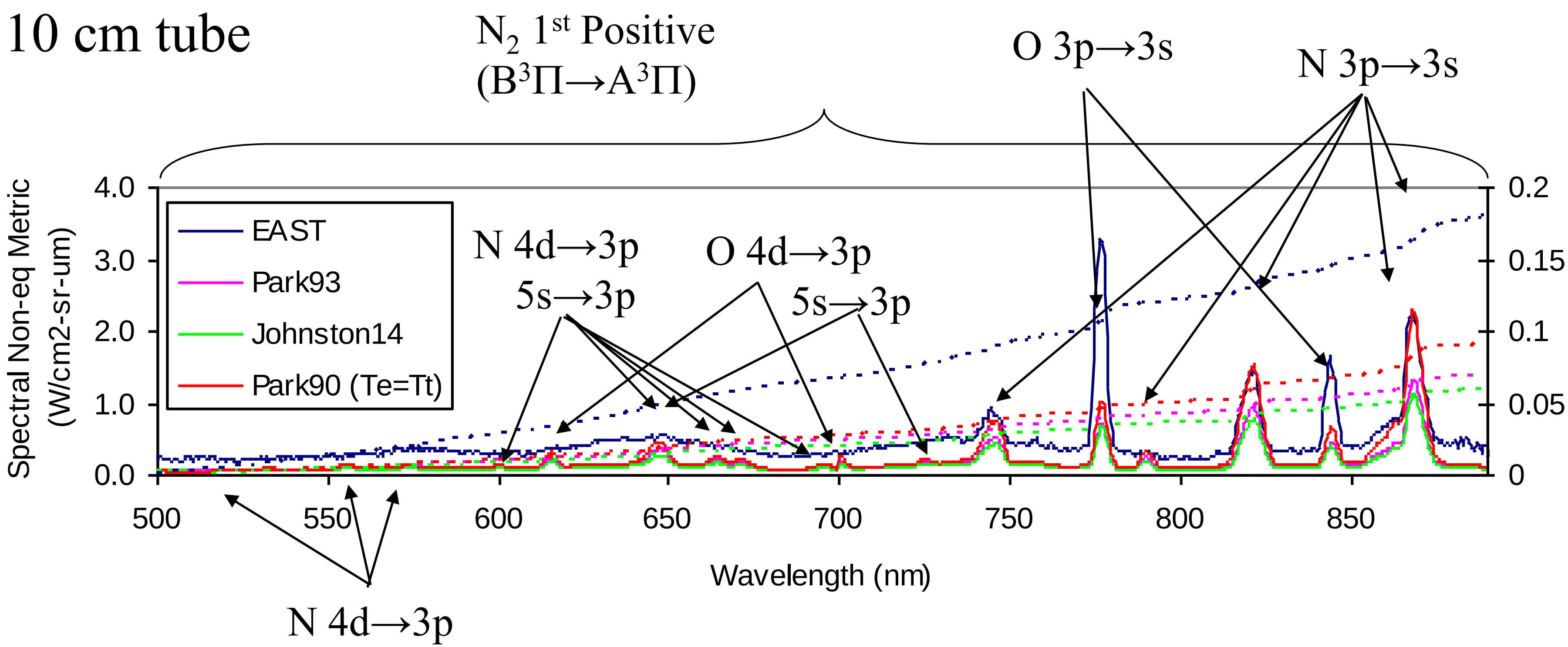
- **Broad features due to N_2 1st Positive still absent**
- **High level (4d,5s) N and O lines overpredicted, but less significantly**
- **O 3p : matched by heritage model, underpredicted other models**
- **N 3p : further overpredicted by heritage, matched other models**

Non-equilibrium – 500-890 nm (0.50 Torr, 7.7 km/s)



- **Broad features due to N_2 1st Positive still absent**
- **High level (4d,5s) N and O lines overpredicted**
- **O 3p : matched by heritage model, underpredicted other models**
- **N 3p : overpredicted by heritage, matched other models**

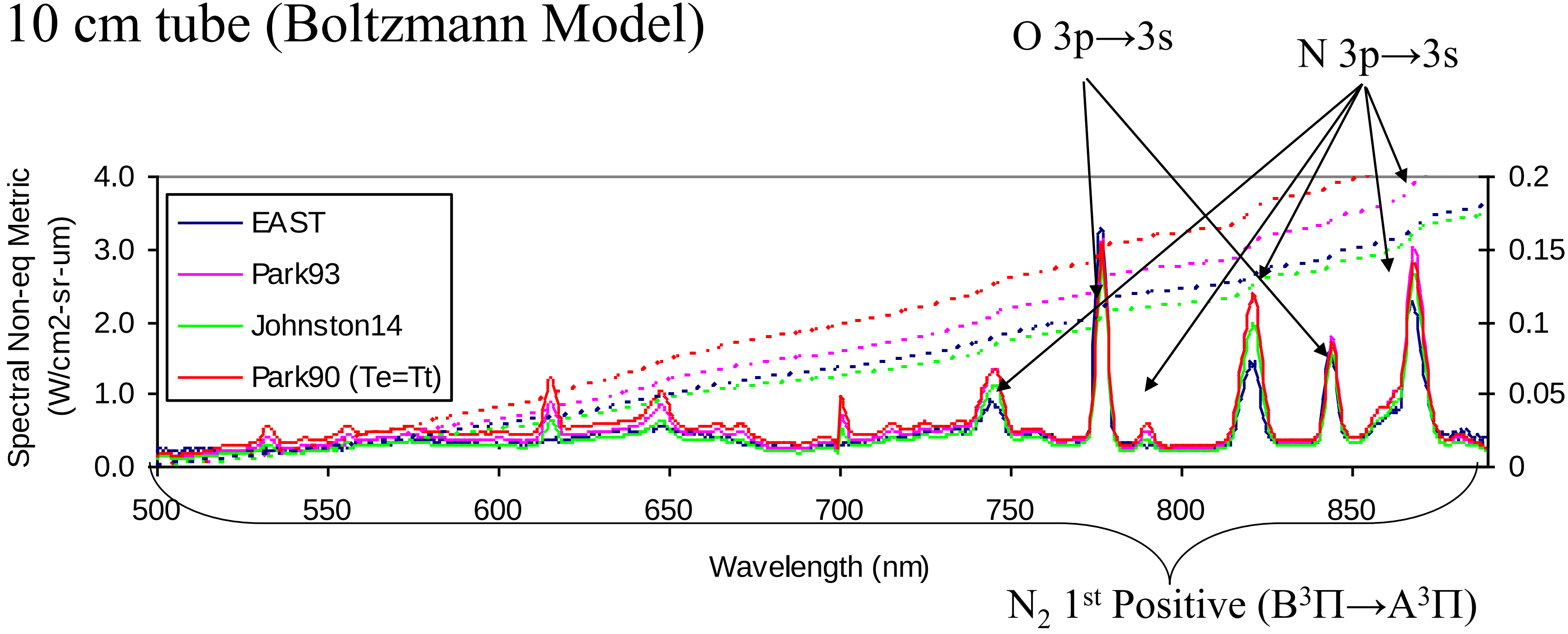
Non-equilibrium – 500-890 nm (0.70 Torr, 7.3 km/s)



- **Broad features due to N_2 1st Positive still absent**
- **High level (4d,5s) N and O lines overpredicted**
- **O 3p : underpredicted all models**
- **N 3p : overpredicted by heritage, matched other models**
  - **Apparent disagreement due to missing underlying N_2 radiation**

Non-equilibrium – 500-890 nm (0.70 Torr, 7.3 km/s)

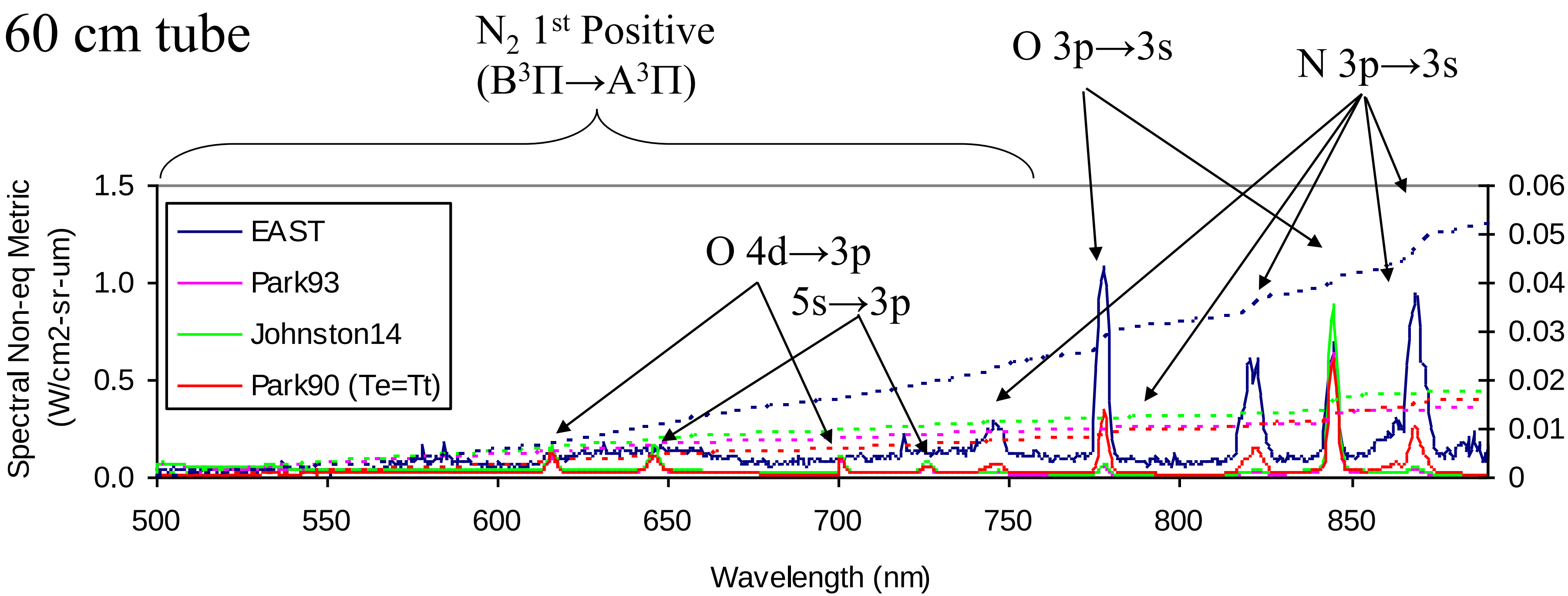
10 cm tube (Boltzmann Model)



- **Boltzmann matches N_2 1st Positive (Heritage slightly over)**
- **High level (4d,5s) N and O lines overpredicted by Boltzmann**
- **O 3p matched by Boltzmann (all models)**
- **N 3p : slightly overpredicted at Boltzmann**

Impact of Alternate N Atom Excitation Cross-section

60 cm tube



- **Huo excitation cross-sections**
  - **Eliminate spurious radiation from N 4d, 5s**
  - **Underpredict N 3p features**

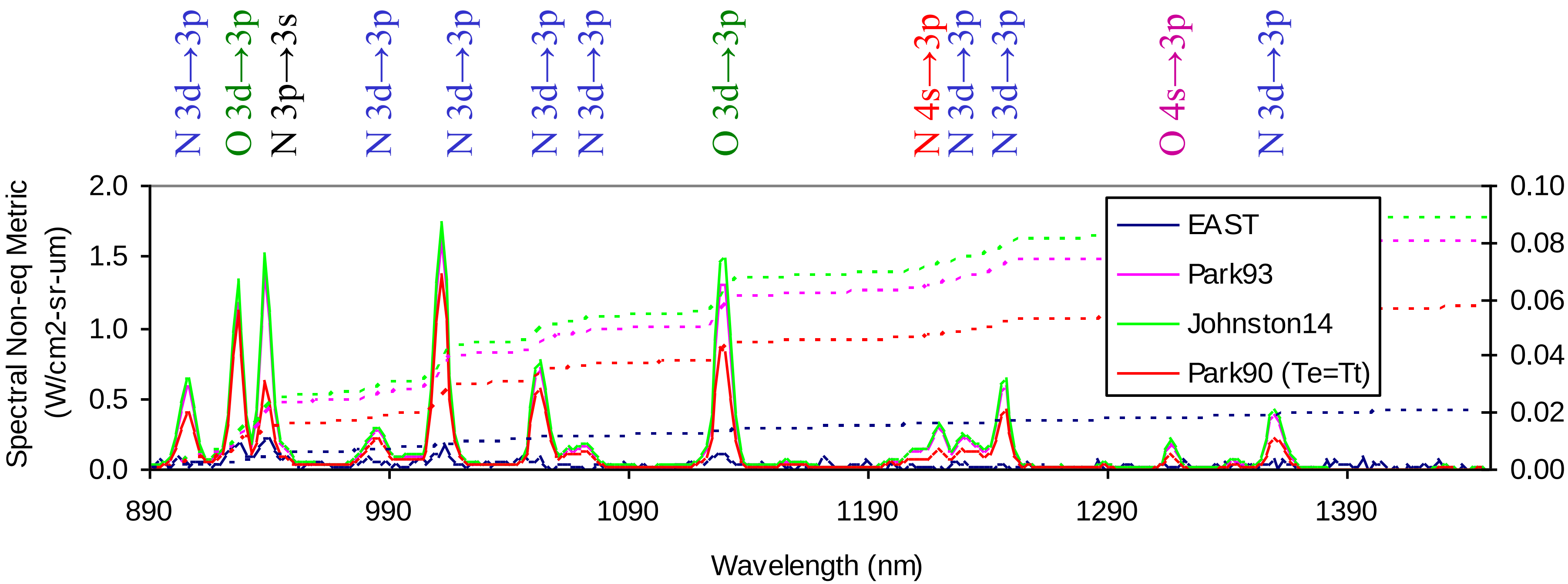
Summary 500-890 nm

- N_2 is always underpredicted
- Spurious N and O lines originating from 4d, 5s states
- N 3p lines
  - Matched by Park90 (Te=Tt) at 0.05 Torr, overpredicted elsewhere
  - Matched by Johnston at 0.14-0.7 Torr, overpredicted at lower pressure
  - Matched by Park93 at 0.05-0.7 Torr, overpredicted at lower pressure
- O 3p lines
  - Underpredicted by Park93/Johnston, except at 0.01 Torr
    - 845 nm line overpredicted at 0.01 Torr
  - Heritage approach
    - Nearly matches 845 nm line from 0.01-0.50 Torr
    - Underpredicts 777 nm line, but not badly

Non-equilibrium – 890-1450 nm (0.01 Torr, 8.6 km/s)

Entry Systems and Technology Division

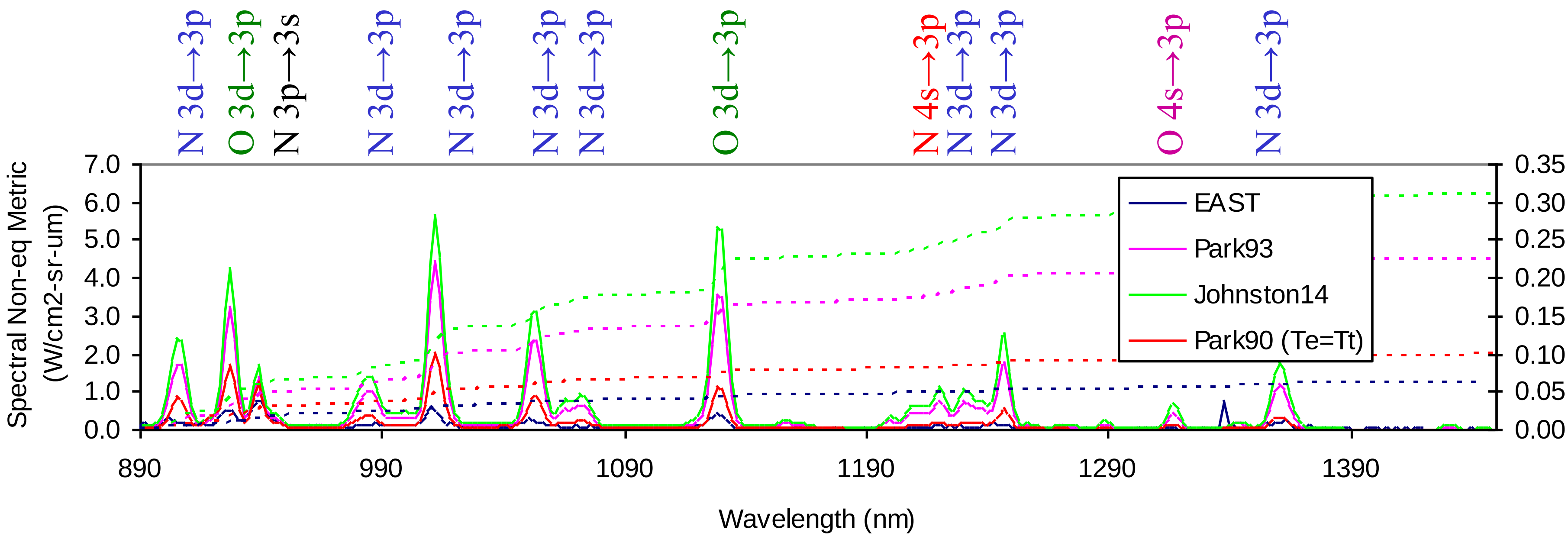
60 cm tube



- **All lines in this range overpredicted**

Non-equilibrium – 890-1450 nm (0.05 Torr, 8.9 km/s)

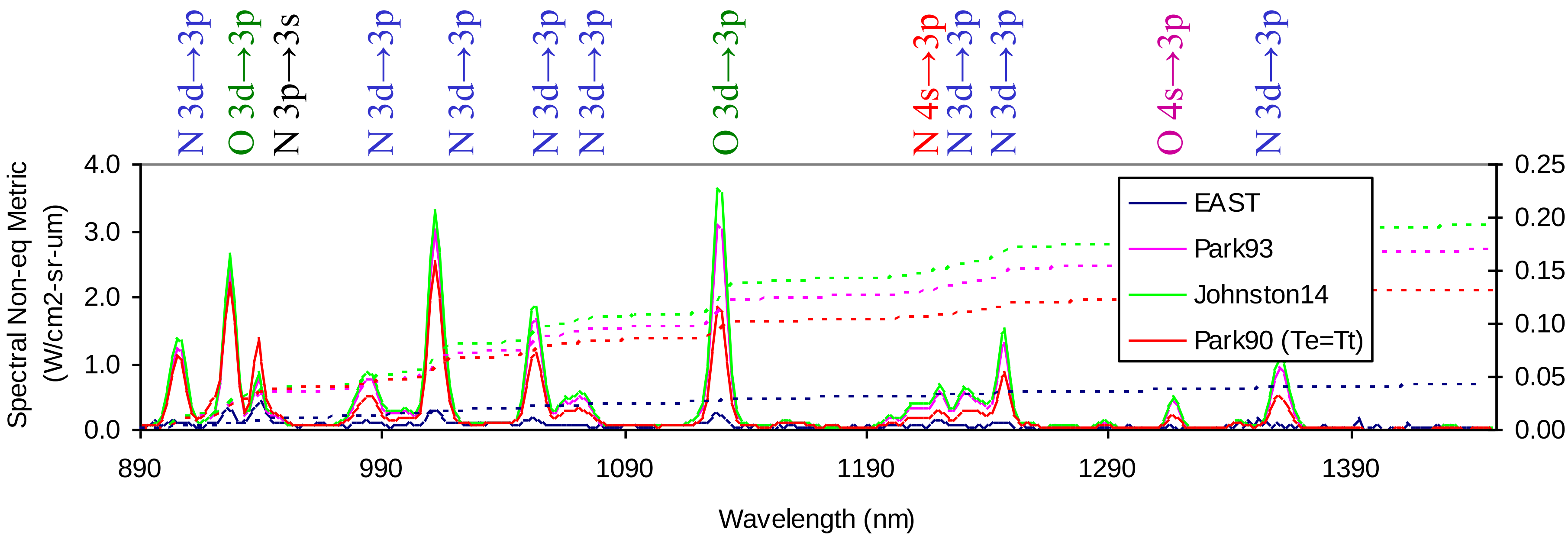
60 cm tube



- **Most lines overpredicted**
  - **Park90 matches 1362 nm line**
  - **N 3p line (939 nm) less overpredicted than others**

Non-equilibrium – 890-1450 nm (0.14 Torr, 8.4 km/s)

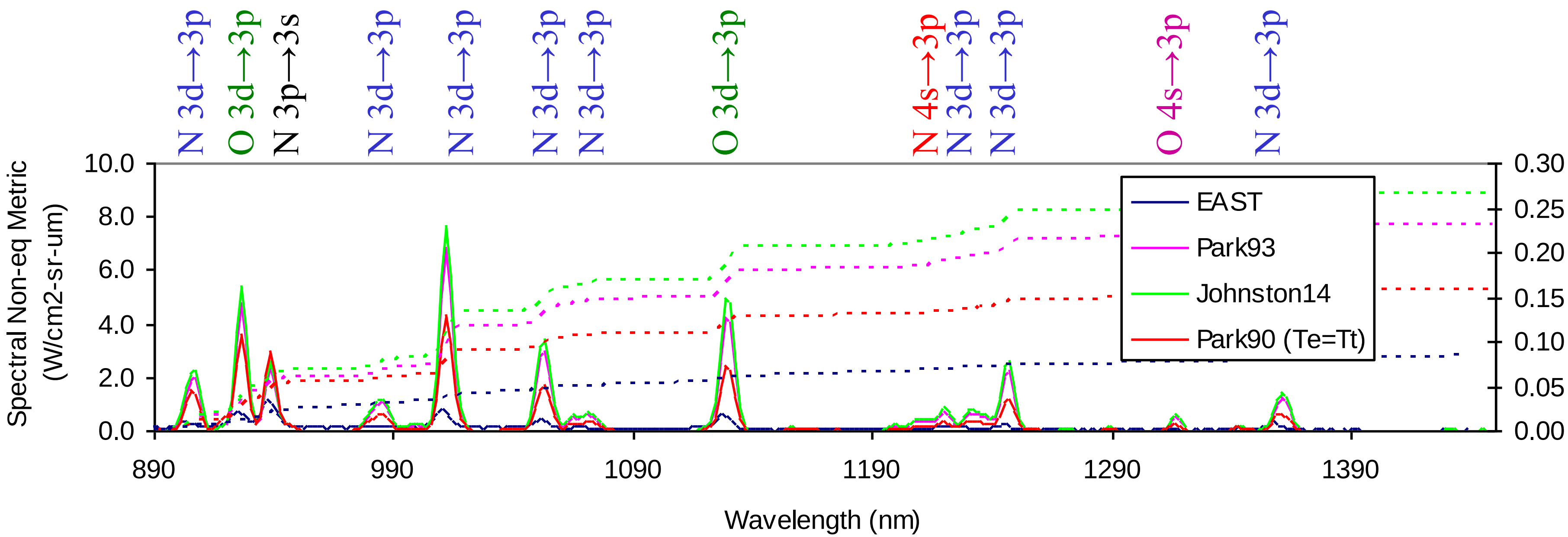
60 cm tube



- **All lines overpredicted**

Non-equilibrium – 890-1450 nm (0.14 Torr, 8.4 km/s)

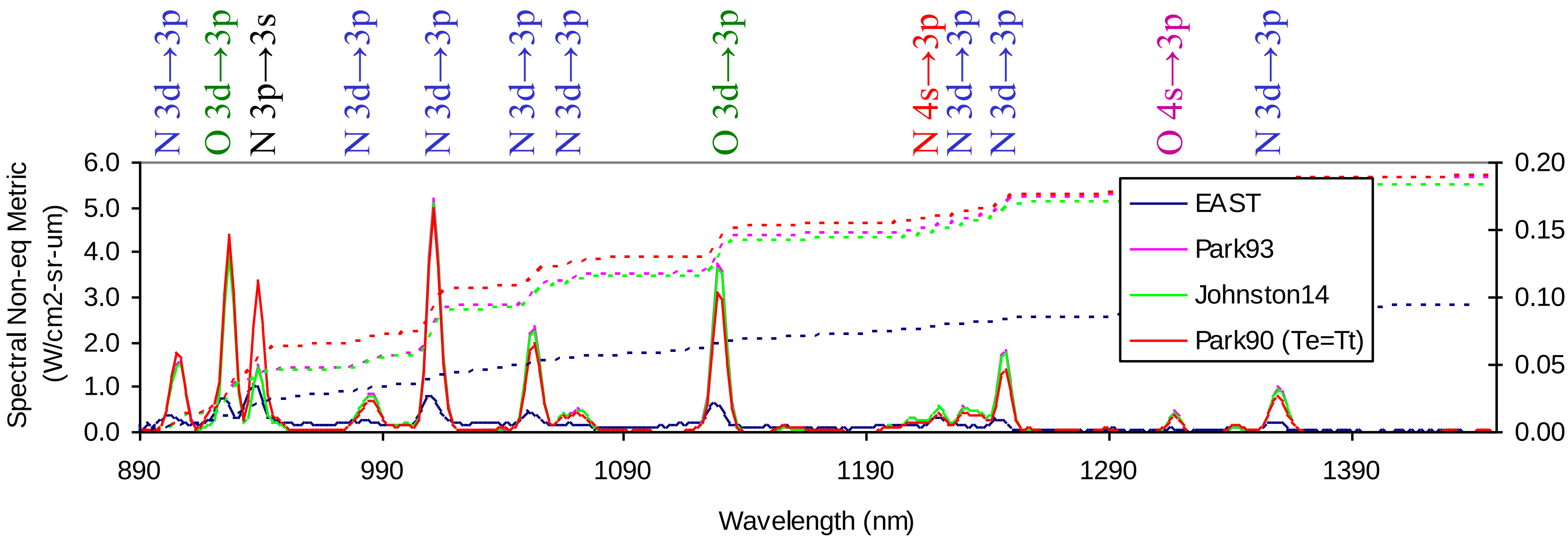
10 cm tube



- **All lines overpredicted**

Non-equilibrium – 890-1450 nm (0.30 Torr, 8.1 km/s)

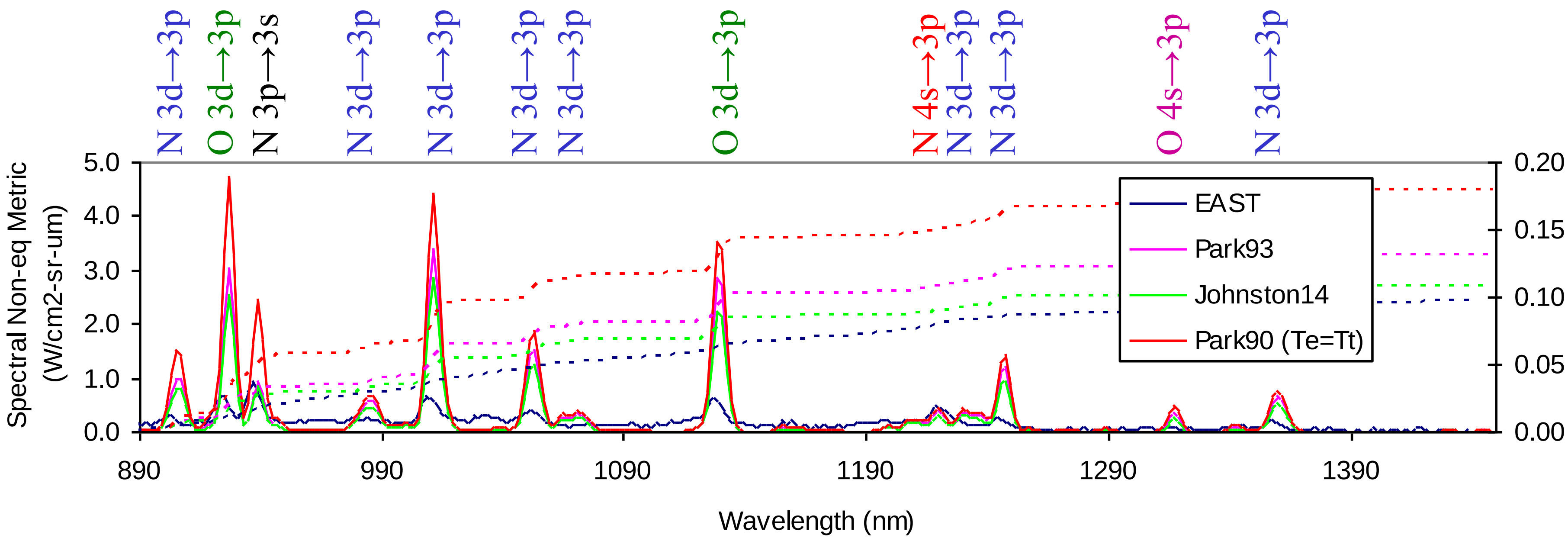
10 cm tube



- **All lines overpredicted**
- **N 3p line (939 nm) near match by Park93/Johnston**

Non-equilibrium – 890-1450 nm (0.50 Torr, 7.7 km/s)

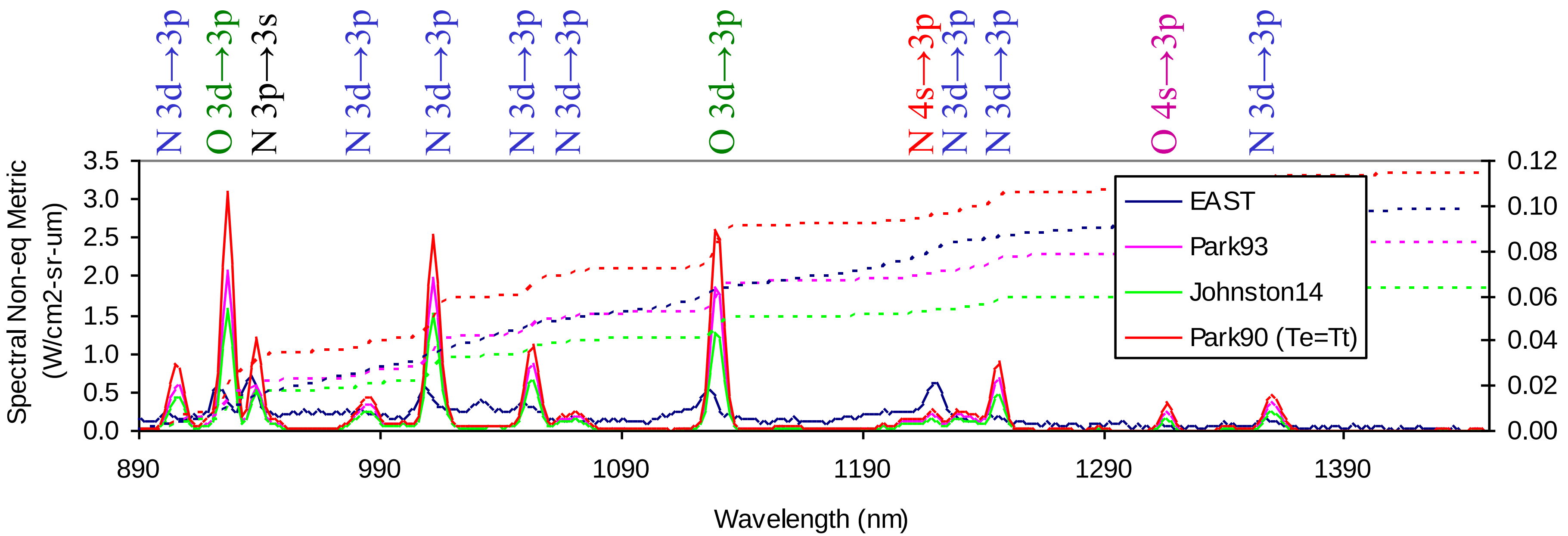
10 cm tube



- **Most lines overpredicted**
- **N 3p line (939 nm) matched by Park93/Johnston**

Non-equilibrium – 890-1450 nm (0.70 Torr, 7.3 km/s)

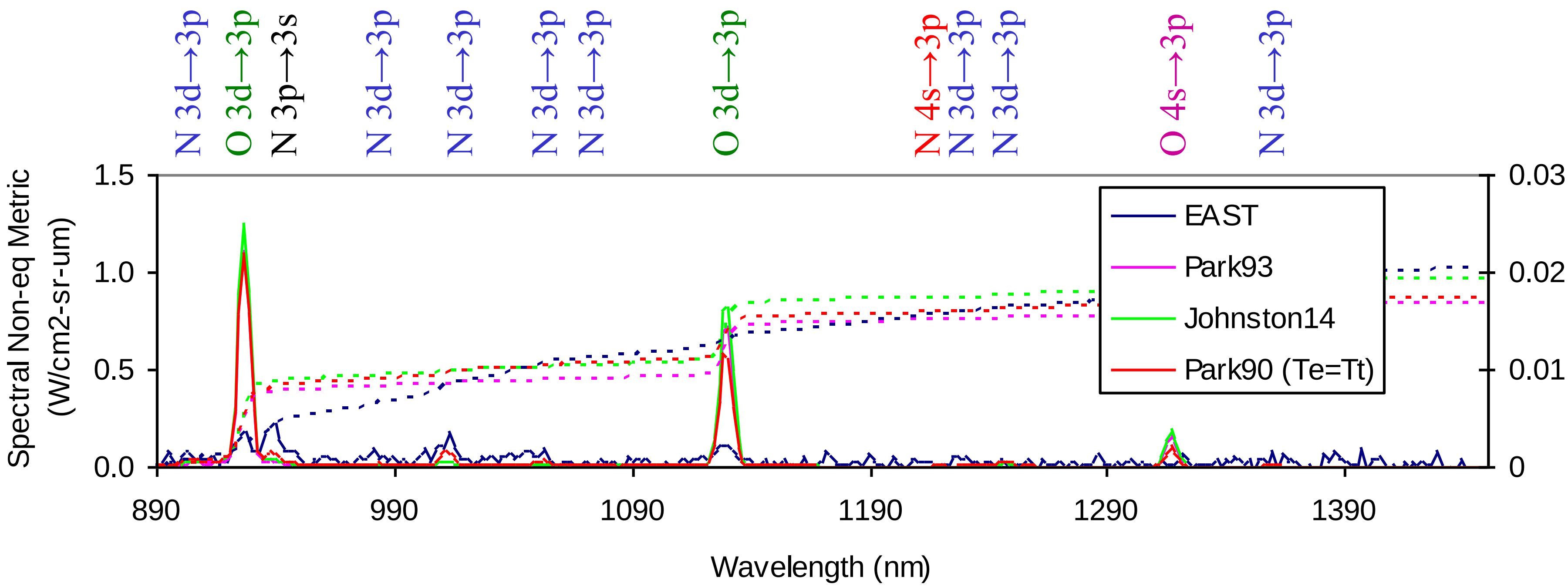
10 cm tube



- **Most lines overpredicted**
- **N 3p line (939 nm) matched by Park93/Johnston**
- **Continuum (N_2 Band) not predicted**

Alternate N Excitation Cross Sections

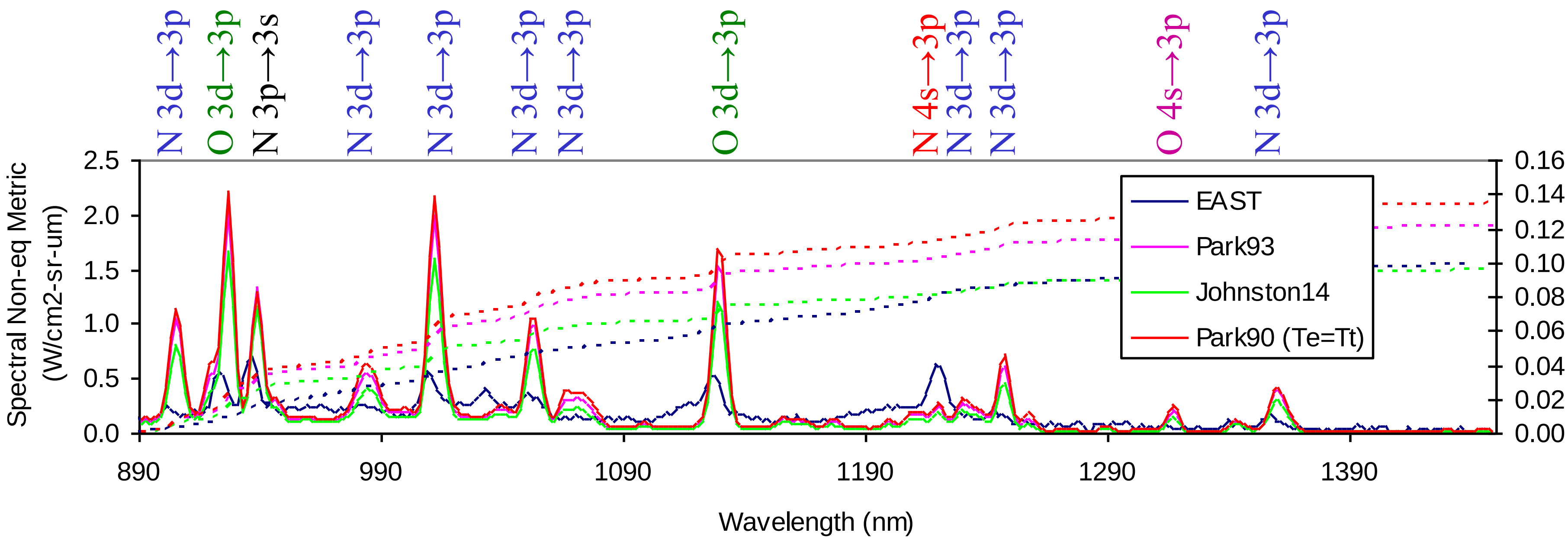
60 cm tube



- **Alternate cross-sections underpredict N 3p line**
- **Other lines near noise limit**
- **O atoms unchanged**

Non-equilibrium – 890-1450 nm (0.70 Torr, 7.3 km/s)

10 cm tube (Boltzmann)



- **Boltzmann improves background agreement, lines still too intense**

Summary 890-1450 nm

- **Atomic Lines originating from higher states generally over predicted**
- **One N 3p line is matched well by Park/Johnston from 0.3-0.7 Torr**
- **Molecular radiation at 0.7 Torr mostly matched under Boltzmann**

Predictive Summary

- **Agreement to Predictive (DPLR/NEQAIR) Model is mixed**
  - **Molecular radiation from N_2/NO is underpredicted**
    - **Boltzmann distribution takes up underprediction for N_2 B state and NO radiation**
    - **N_2 C state is overpredicted by Boltzmann**
  - **N_2^+ radiation prediction varies with pressure**
    - **At low pressure: overpredicted for T_e=T_v, matched by heritage model**
    - **Reasonably matched for intermediate pressure range**
    - **Underpedicted at high pressure**
  - **High lying N, O state radiation overpredicted**
  - **Radiation from 3p states of N predicted well, except at lowest pressure**
  - **Radiation from 3p states of O mostly underpredicted**
- **How does your model do?**

  https://data.nasa.gov/docs/datasets/aerothermodynamics/EAST/index.html

  (Test 59 - available soon)