Outline

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History of Color Ratio Pyrometry

- First reportedly used in 1994 using infrared-sensitive pixel array to resolve temperature profiles of filaments [1].
- Shown to be achievable using consumer color cameras for temperatures of 800-2500C with an error of 50C [2].
- Extensively used on filament, soot, and direct injection spark ignition engines [3-8].
- Densmore et al. has used color ratio pyrometry to probe burn characteristics of C-4 charges, fireballs, impact combustion, and thermite burn tubes [9-12].

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Advantages and Complements to Spectrometry

SPECTROMETER	CAMERA
• Large areas focused onto optic cable and average temperature is calculated. • Small point source of light used to measure temperature.	• Bayer filter array separates incoming light into multiple channels onto a metal sensor. • Sensitive to wider range of wavelengths.
• Temperature determined through Planck's Law. • Allow for selective removal of channels with high elemental emission.	• Temperature determined by taking ratios in channel intensities. • Demosaicing algorithm applied to recorded pixels. • Unable to selectively remove wavelengths.

• Advantages:
  • Faster temporal resolution.
  • Higher sensitivity when using PMT.
	• Advantages:
	  • Can be used to identify inhomogeneities in material and view spatiotemporal dynamics.

• Disadvantages:
  • Unable to resolve space.
	• Disadvantages:
	  • Slower for larger areas and many assumptions.

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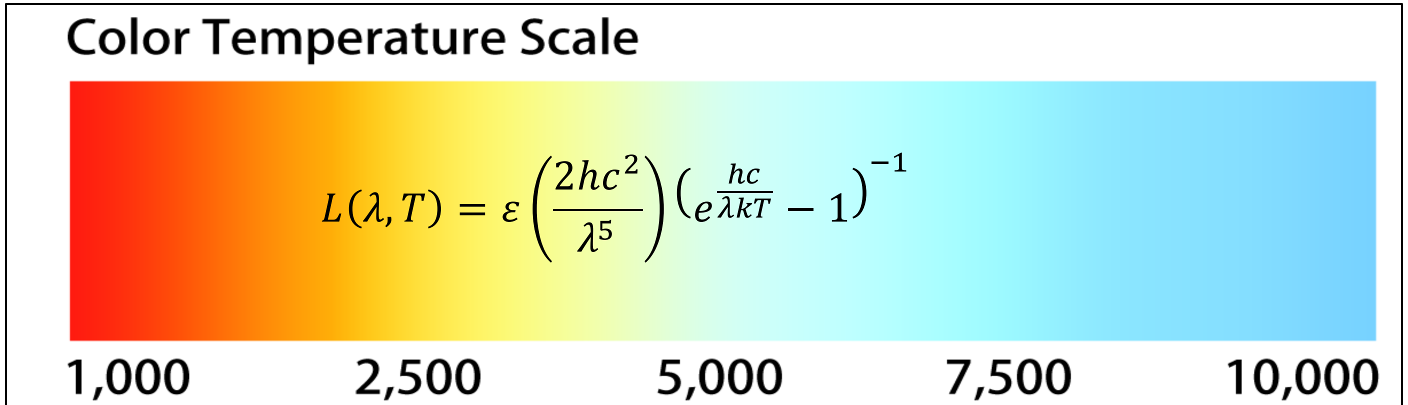
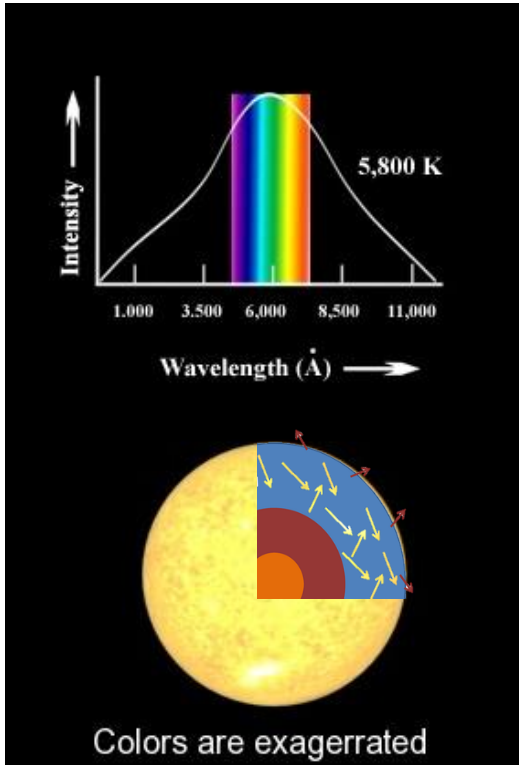
Blackbody Radiation

- Used to model stars, as energy escaping the surface is immediately replaced by hot core [13].
  - Same physical principle can be applied to hot nanoparticles.
- Perfect emissivity across all wavelengths (ε = 1) [14].
  - Temperature can be easily calculated by linearizing Planck's Law.



$$L(\lambda, T) = \varepsilon\left(\frac{2hc^2}{\lambda^5}\right)\left(e^{\frac{hc}{\lambda kT}} - 1\right)^{-1}$$

http://4.bp.blogspot.com/-dzCPCiP3BiA/Tyl7QgDTF1I/AAAAAAAAAkY/Pt-QseLWuOg/s1600/Color-Temperature.png



https://docs.kde.org/stable5/en/kdeedu/kstars/star_colors.png

Theory and Assumptions –

Camera Operation

- Digital color camera build:
  - Light passes through lenses attached to camera.
  - Mosaic color filter array serves as bandpass for wavelengths, with peak transmittance for wavelengths corresponding to the name (red/green/blue).
  - Light passed through filter array strikes metal sensor which generates electrical signal based on intensity.
- Spectral response to color is specific to every camera based on the sensor and color filter array.
  - Vision Research Phantom Miro M110 response curve can be seen to the right.

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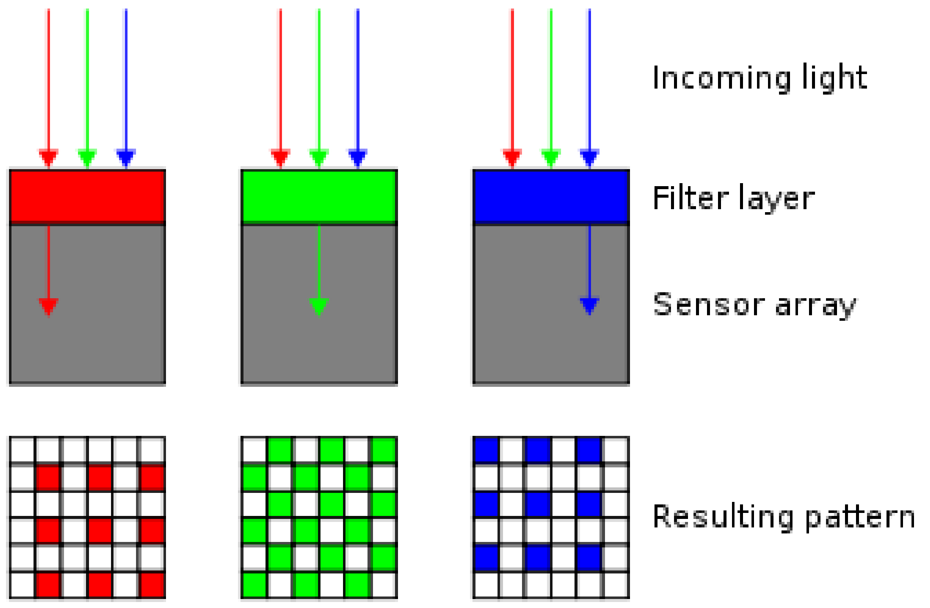
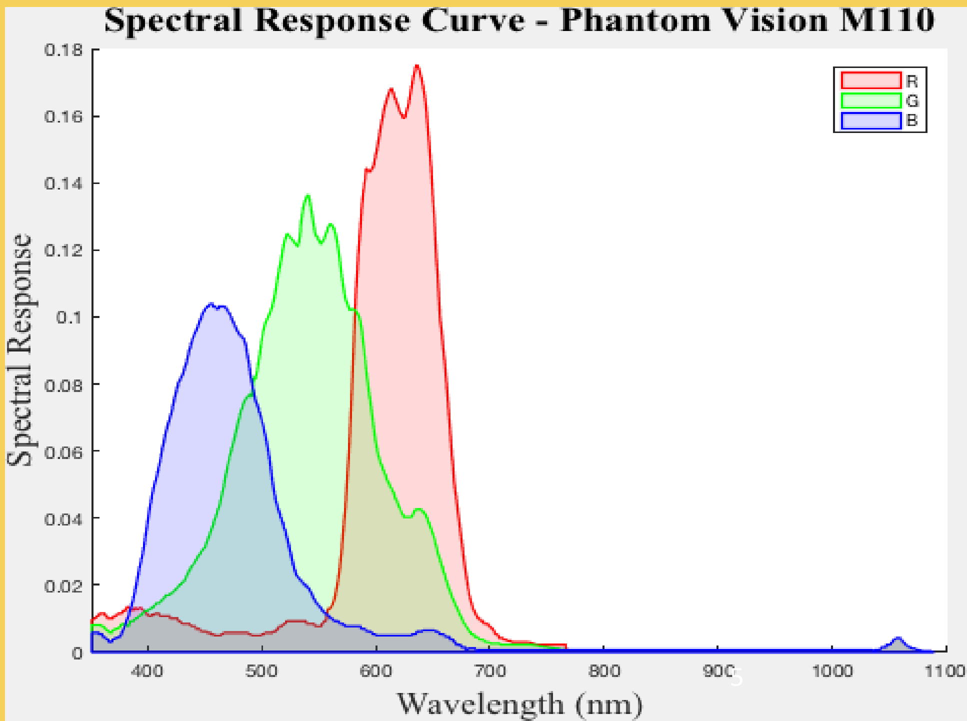


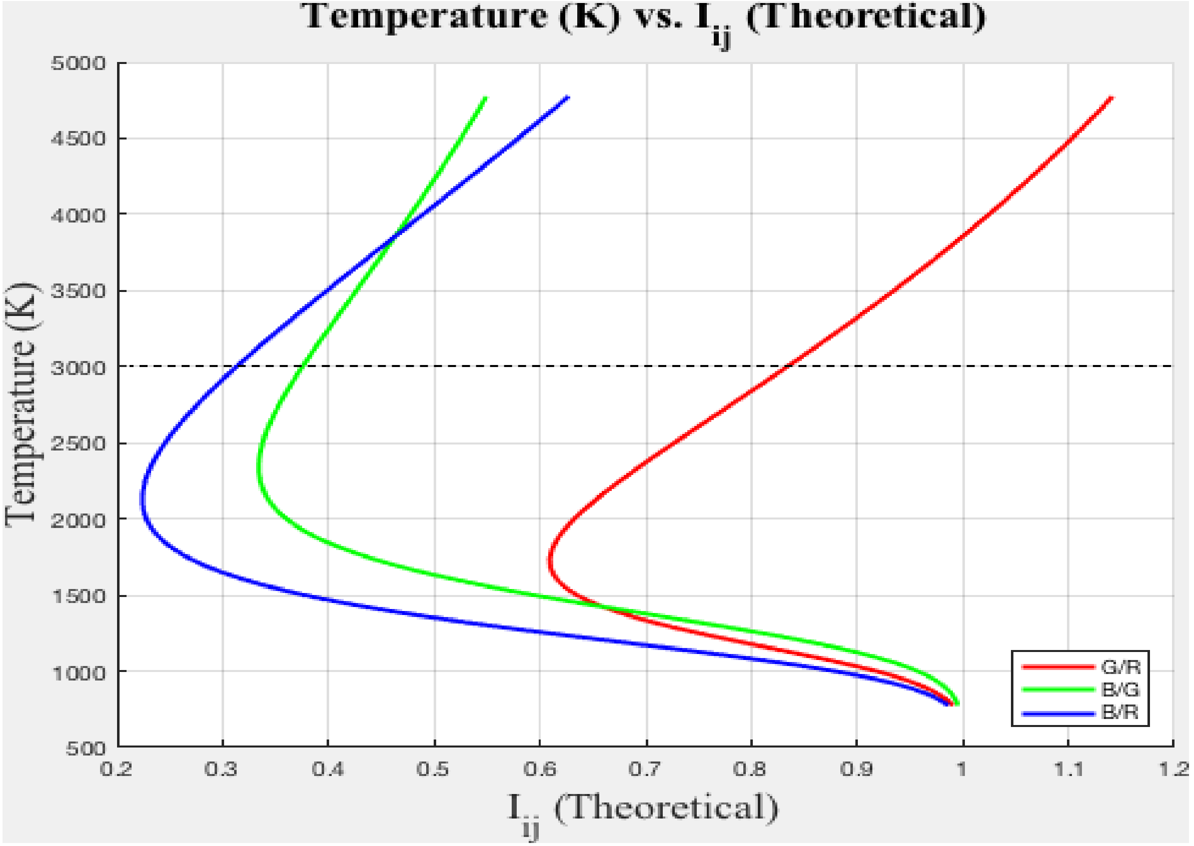
https://upload.wikimedia.org/wikipedia/commons/thumb/1/1c/Bayer_pattern_on_sensor_profile.svg/350px-Bayer_pattern_on_sensor_profile.svg.png



Theory and Assumptions –

Graybody and Color Ratio Pyrometry

- Graybody assumption: although emissivity is unknown, it is constant across the entire spectrum ($\varepsilon \neq \varepsilon(\lambda)$).
- Color Ratio Pyrometry (CRP)
  - Intensity of light reported by channel is a function of the channel gain (ψ), the integrated product of Planck's Law, and camera spectral response.
  - Emissivity of particles cancel out when taking ratios between channels..
  - Theoretical ratios of channels can be calculated for different temperatures (I_{ij}).



Experimental Setup –
Calibration

- Standardized blackbody heat source with known temperature recorded with color camera and contiguous center raw pixel values are extracted.
  - Newport Blackbody source and Avantes Avalight HAL-CAL light source both used to replicate spectra.
- Demosaicing algorithm applied to area in MATLAB using color filter array configuration.
- Observed ratios between channels at known temperatures are compared to theoretical values to generate a calibration factor for the camera (ratio of channel gains).

$$\left(\frac{I_i}{I_j}\right) = C_{ij}\left(\frac{I_i}{I_j}\right)_0$$

$$C_{ij} = \frac{\psi_i}{\psi_j}$$

Lens	C_{gr}	C_{bg}	C_{br}
Wide Angle	1.007	0.966	0.972
Macro	0.952	0.888	0.847

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Experimental Setup–

Calculations & Processing

Record video

(up to 440000pps).

Extract raw pixel values and package for MATLAB interpretation.

- Black/saturation thresholding.
- Temperature calculations & analysis.
- Video creation.
- Efficient data packaging of summary file.

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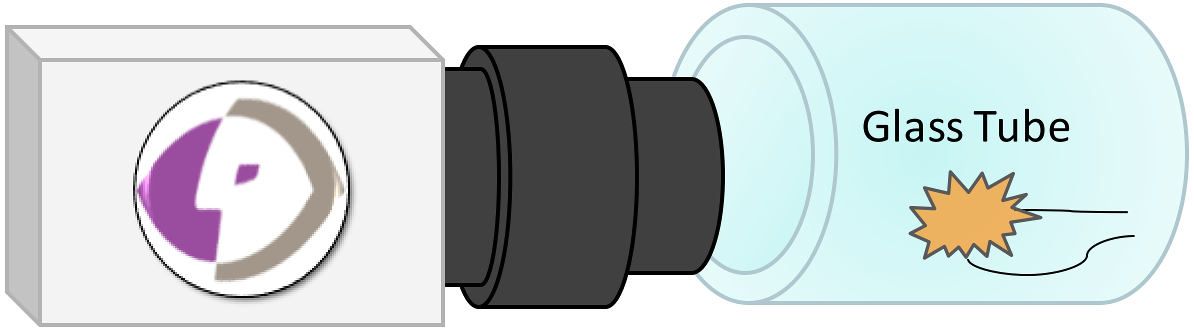
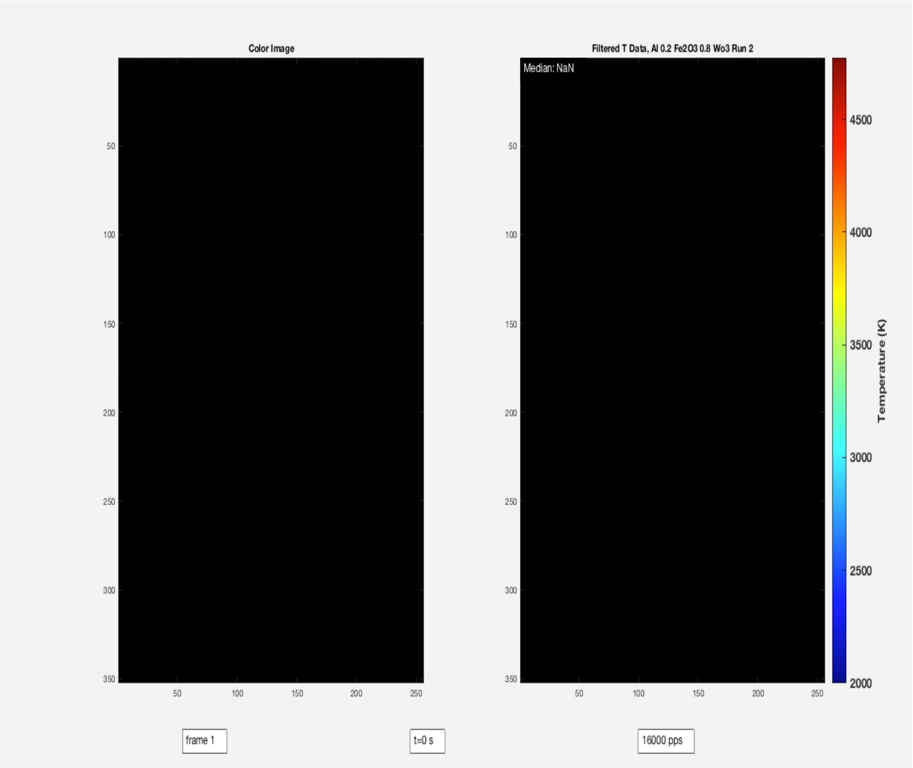
Example Videos –

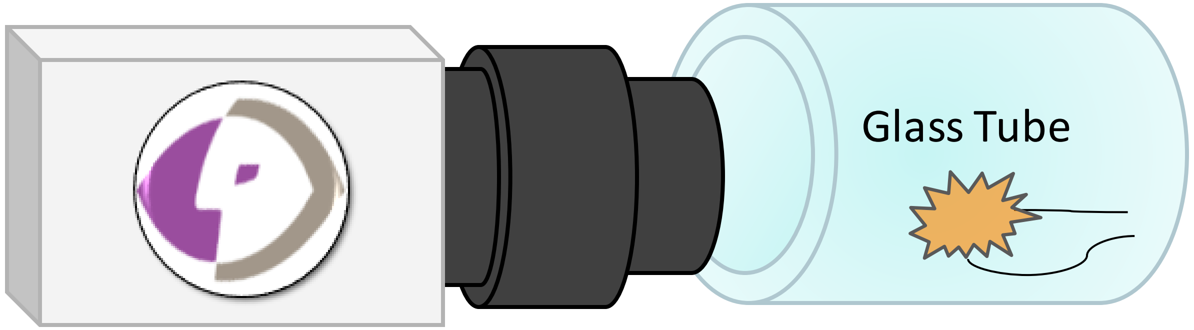
Thermite Reactions in Air (Al 0.4 Fe_2O_3/0.6 WO_3)

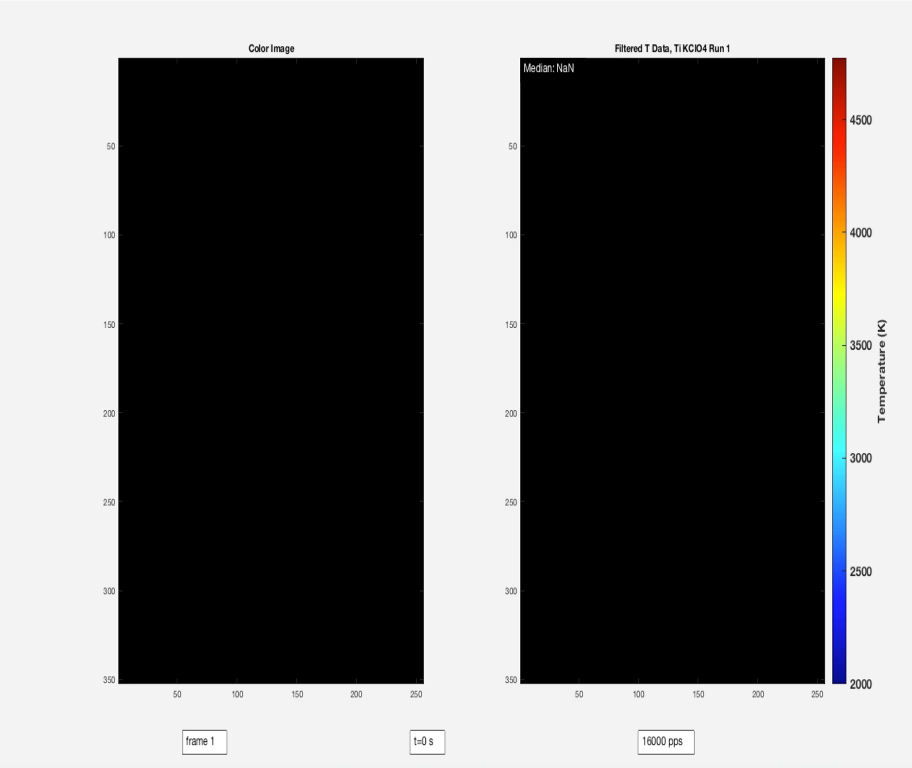




Example Videos –

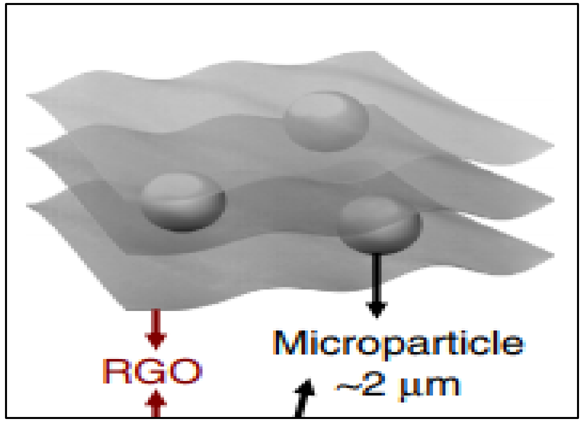
Thermite Reactions in Air (Ti $KClO_4$)



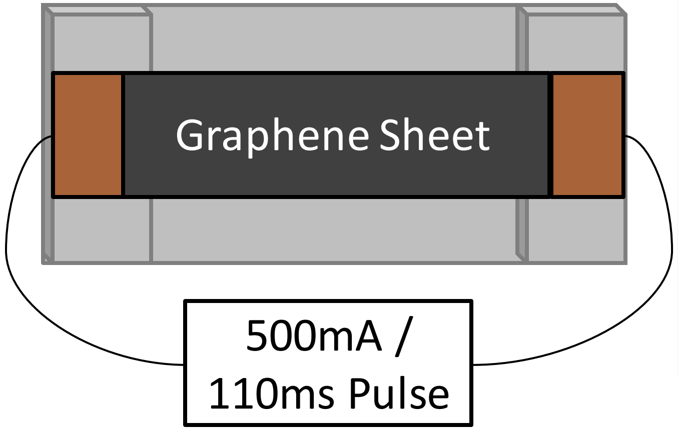


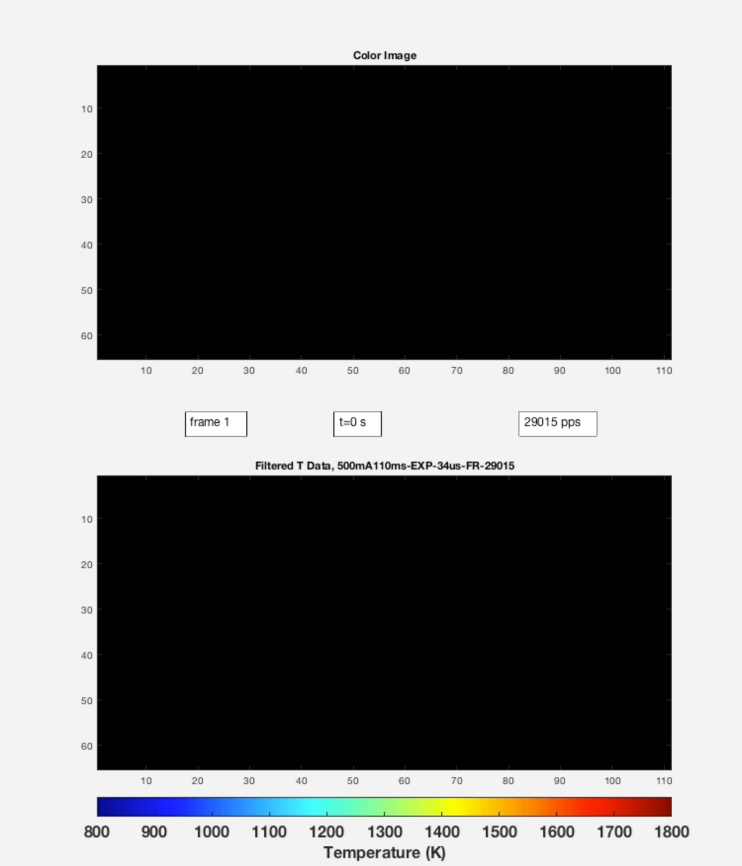
Example Videos –

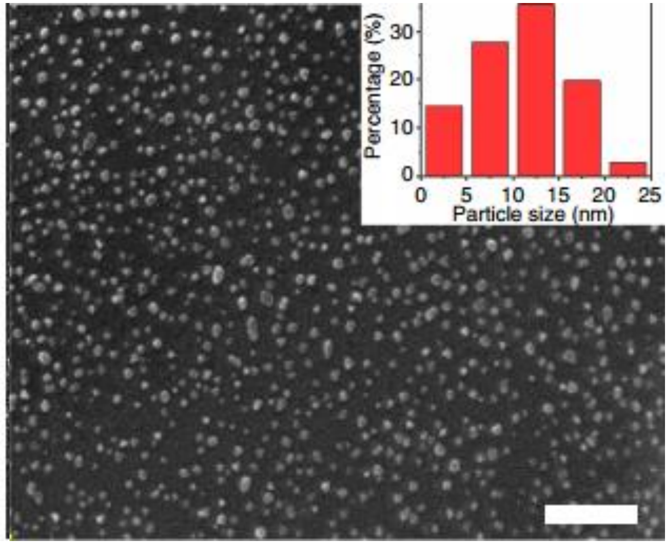
Thermal Shock of µAl in Graphene



Chen, Egan, Wan, et al. DOI: 10.1038/ncomms12332. 2016.

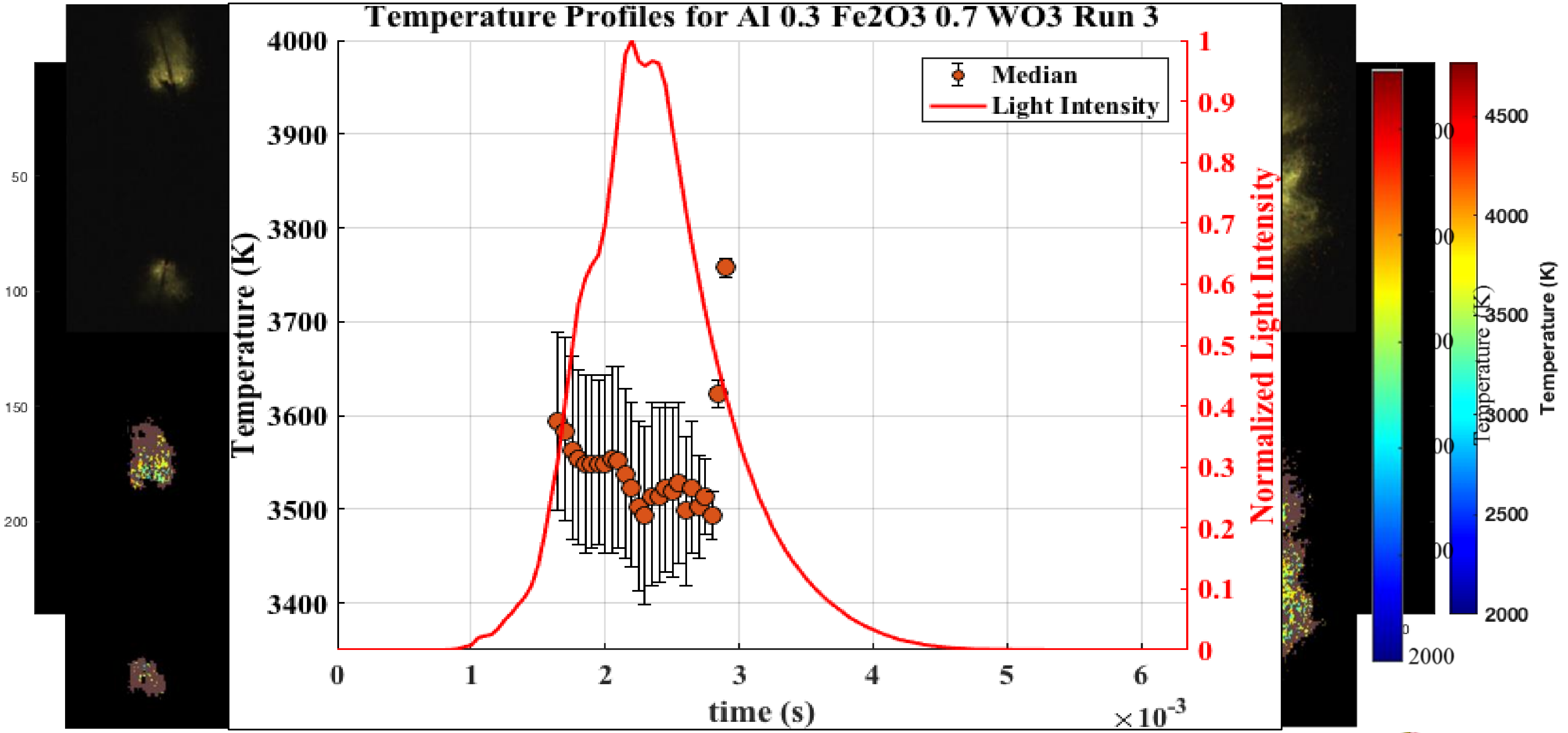






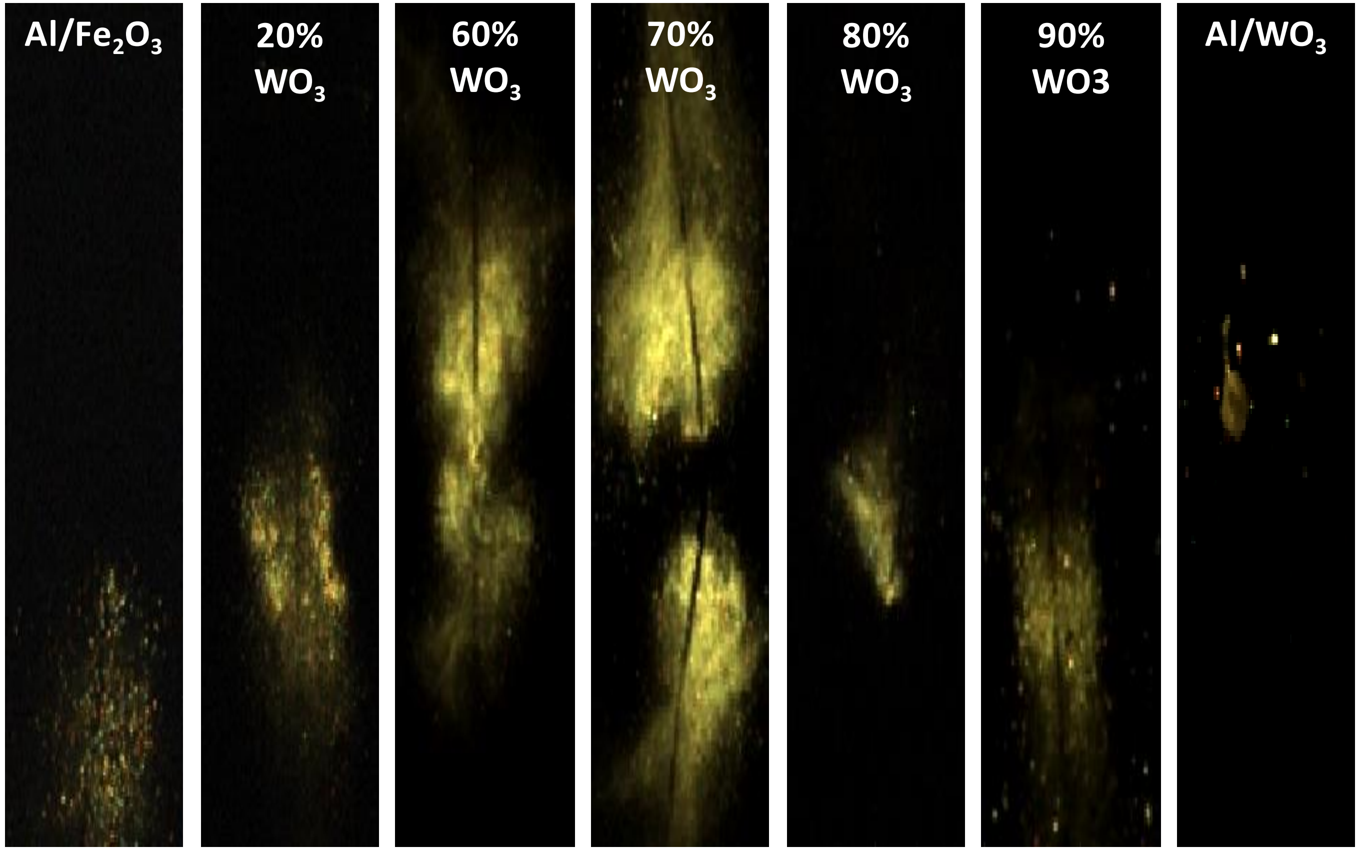
Chen, Egan, Wan, et al. DOI: 10.1038/ncomms12332. 2016.

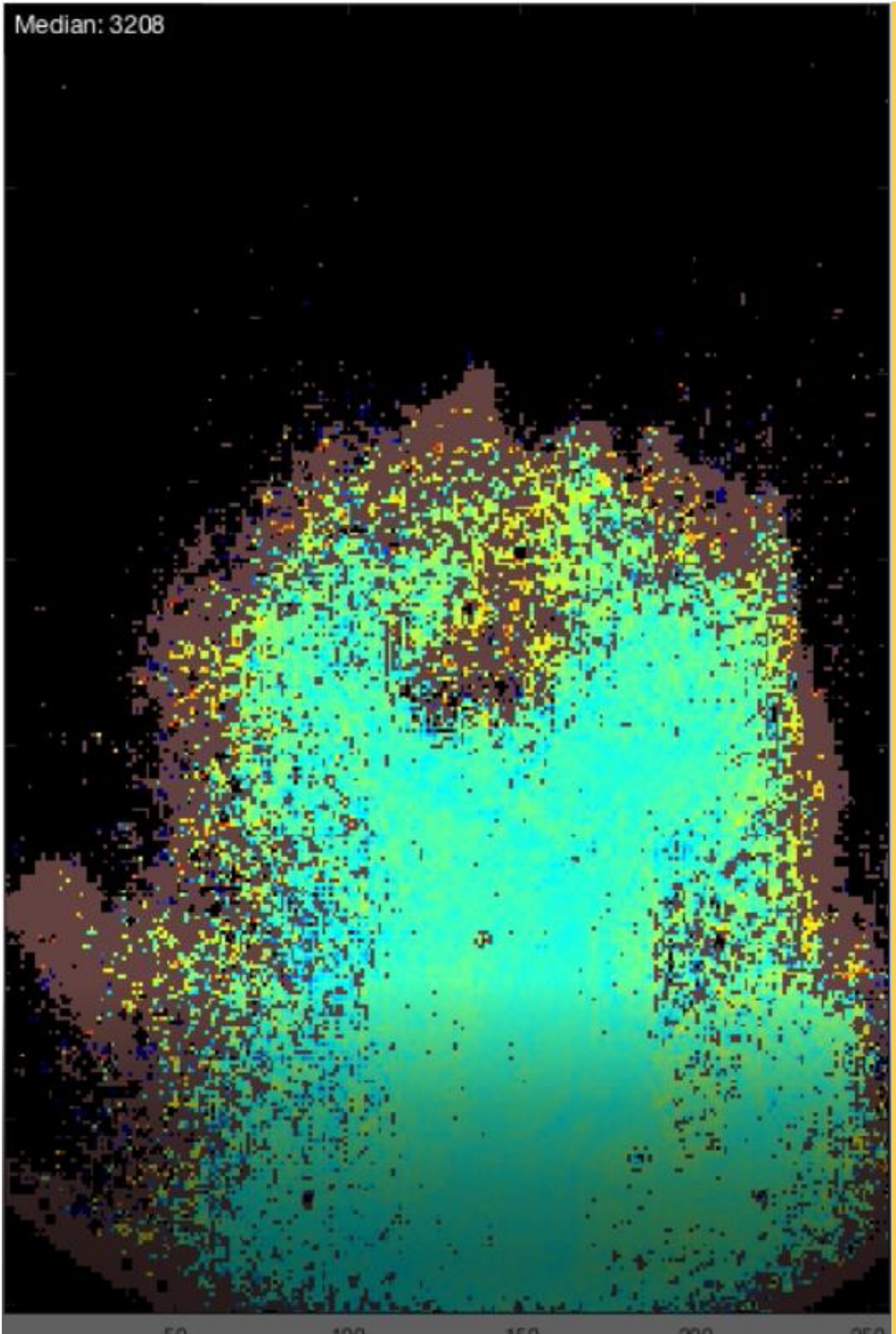
Example Videos –
T-Jump Thermite in Ar (Al 0.3 Fe_2O_3/0.7 WO_3)



Results and Trends

- Mean and median temperatures are usually higher than those reported by spectroscopic measurements.
  - Sodium emission.
  - Data reduction techniques.
- Provides more insight on possible mechanisms of reaction.
- Trends in temperature between experiments are similar.





Future Work and Conclusions

- Color ratio pyrometry is a new tool that can be used to probe spatiotemporal burn characteristics of experiments.
  - Can be used to observe dynamics of reaction with an error up to 110C.
  - Can be used as a complement to or independently from a spectrometer.
- Color ratio pyrometry is still in its infancy.
  - Light scattering and emissions are still a large source of error.
    - Corrections have been proposed for emissivity such that $\varepsilon \sim 1/\lambda$ in thin flame fronts [15].
  - Assumptions made in formulation may lead to high error in temperature measurements.
  - Fidelity of calculations are heavily dependent on quality of video recorded.

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- Rohit J. Jacob – countless hours of guidance in experimental design and mentorship over the past 6 months.
- Phil M. Guerieri – optimization of MATLAB code developed for temperature measurements (cut down calculation time from 30 minutes to <30 seconds for 200+ frame videos).
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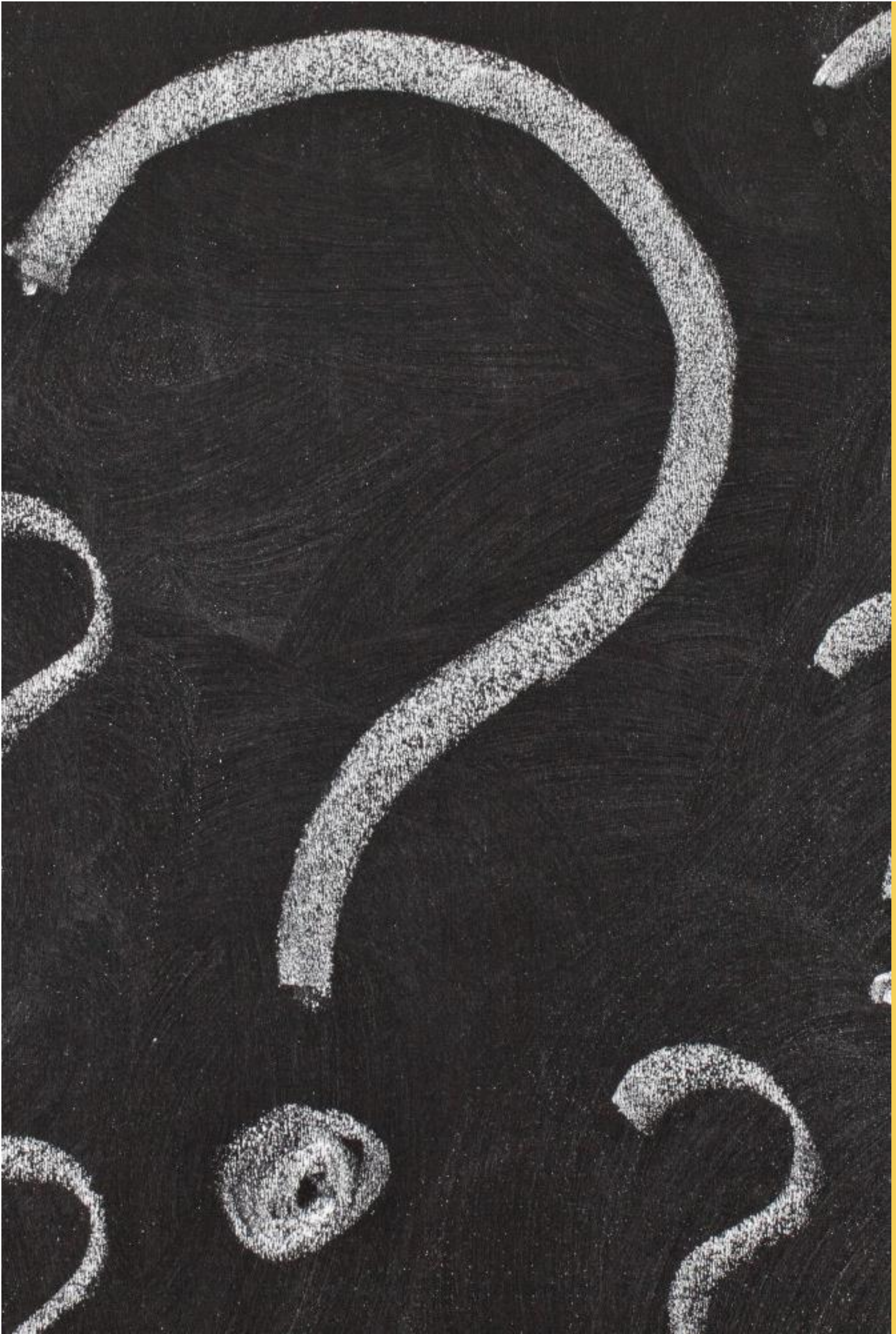

Questions?

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