Fire Spectral Characterization Experiment

Initial Data 'Look'

The **FIRES** Gang

Don Latham RMRS

Motivation, motivation….

- We need to understand the basic physical phenomena in a fire that govern the gross behavior
- We need to know what simplifications and assumptions can be made to ease calculations
- We need to be able to analyze and predict the emission of narrow spectral features from wildland fires
- We definitely need the emissivity and temperature of the flames to model a fire with *DIRSIG*

The general plan of attack….

- Describe the overall ‘picture’ and preliminary results of the study (today!)

- Describe the physical and chemical properties of a flame (soon)
  - Basic thermodynamics and atomic physics

- Present a more detailed model of line emission from a flame
  - More detailed atomic physics

What basic fire ‘processes’ produce unique spectral features?

1. Combustion temperatures are reached, organic materials volatilize and mix with air. Mixed fuel-air reacts and burns.
2. Volatile combustible materials disassociate, raising temperature of fire further and liberating alkali compounds.
3. Alakali compounds (halides) disassociate into alkali ions + (X) (~0.75 eV)
4. Alakalis are excited and ionize. (1.7 eV - 4.5 eV)
5. Excited states spontaneously decay to ground state, emitting narrow spectral lines. Ionized states pass through excited states decaying to ground state, emitting narrow spectral lines. (~1.5 eV)
6. Blackbody/greybody emission from uncombusted smoke particulates (incomplete combustion). Characteristic temperatures ~ 600 - 1000° C and down.
7. Other smoke products - H_2O, CO, CO_2 - emit strongly in the NIR to far IR.

Note: All of these processes are exceedingly complex

We will model the emission as a surface flux from an opaque uniform volume source

- The governing equation is trivial:

Power (E/s) = number of atoms (n) * atoms excited(%) * probability of de-excitation per unit time(1/s) * energy per de-excitation (E)

or in equation form:

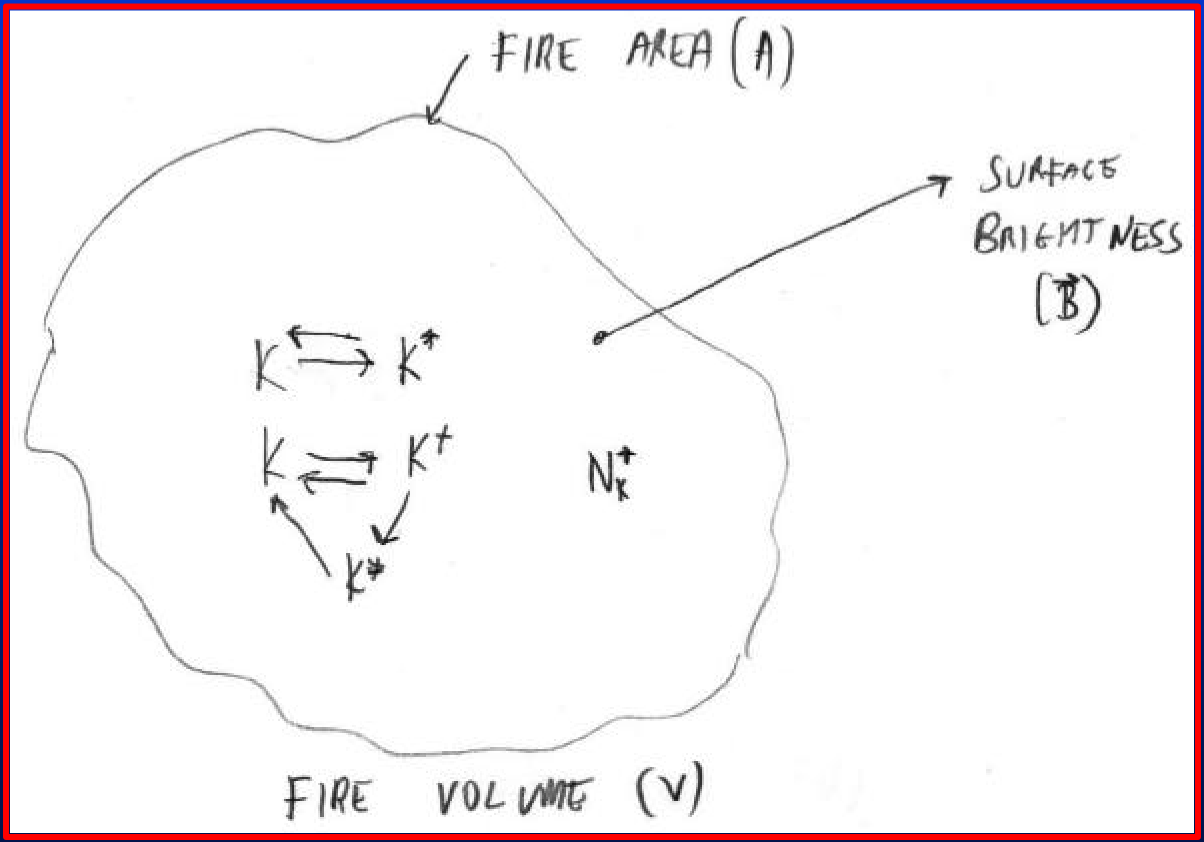
$$I = n_k\ f\ A\ E \qquad (1)$$

Notes:

- Local thermodynamic equilibrium (LTE) is assumed
- n_k is obtained from the elemental abundance of the species in the biomass and total amount of biomass burned.
- f is governed by Saha-Boltzmann statistics
- A is the Einstein spontaneous decay (A_{ul}) coefficient
- Is the opacity low? (No!)
- Self absorption effects?

We will model the emission as a surface flux from a uniform volume source with low opacity (2)

- The details of the geometry will be ignored. We assume spherical symmetry.

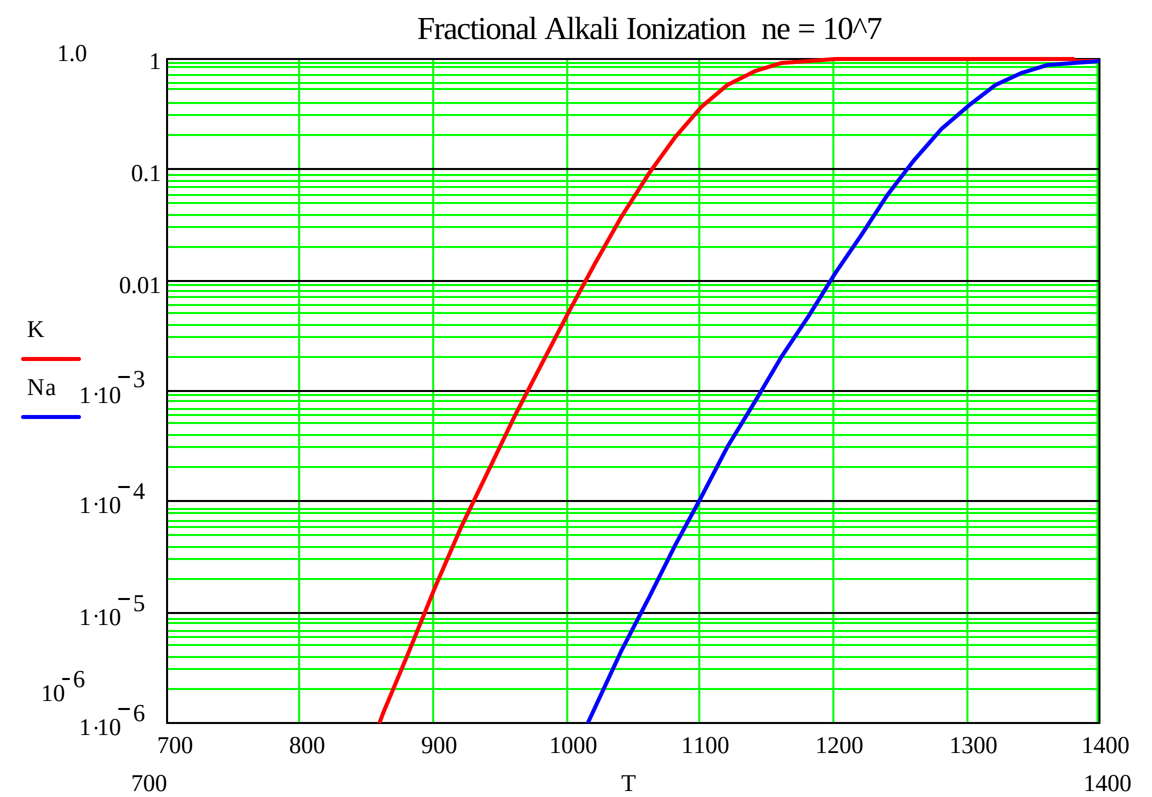


The Saha equation governs the distribution of atomic excited states in the system

- Assumption of LTE allows specification of the ensemble by statistical parameters

$$I_{i,n} := 4.83 \cdot 10^{21} \cdot \left(T_i\right)^{\frac{3}{2}} \cdot \frac{g2}{\left(g1 \cdot ne_n\right)} \cdot e^{\frac{-(E1)}{k \cdot T_i}}$$

$$K_{i,n} := \frac{I_{i,n}}{\left(1 + I_{i,n}\right)}$$



T in Kº

Potassium excitation interrogates the hottest parts of the fire

- About 1 in 500 atoms are in an excited state at normal fire temperatures (1000 K)

- We need to find sets of lines, blackbody emission, etc. that form self-consistent sets with shared unknowns. Are there any?

- We expect that the blackbody-emissive carbon particulates to be lower temperature because they have cooled from the flame front. We can model the cooling rates making assumptions about the particulates (carbon?)

Let’s do a back-of-the-envelope calculation of the emitted power from a ‘sensible’ source

- Parameters for potassium (single channel, excited state only):
  - E = energy / decay = 1.7 eV = 2.7 X 10^{-19} J
  - a = decay rate = 2.6 X 10^{-8} /s
  - f = fraction of excited states ~ 10^{-3} (at 950 K)
  - n = Total number of atoms (per Kg):

1% potassium by weight

-> 10 gm potassium per kg

-> 10/40 *A_g = 1.6 X 10^{23} K atoms per kg

Substituting:

I = 1.1 X 10^{-6} W / kg burned in a spectral line < 10A (10^{-3} mm) wide.

Assume that the density of wood is 0.33 (when burning?) so the volume of a 1 kg spherical mass is: 3000 cm^3 --> 9 cm -> surface area = 1000 cm^2, 10 A= 10^{-3} mm .

So:

F = 1.1 X 10^{-2} W/m^2- mm

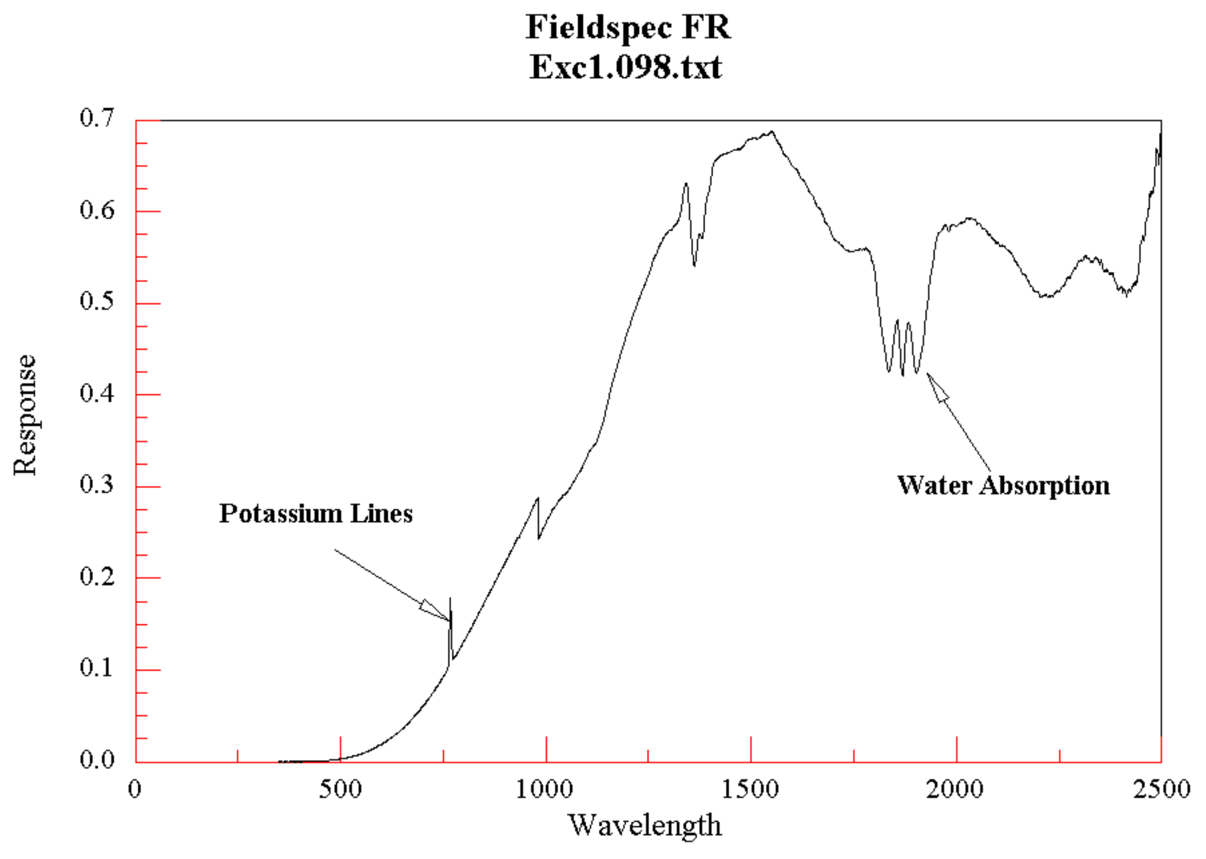
How do the thermal and line emission flux densities compare?

- Back of the envelope says:

  K exitance: 1.1 X 10^{-2}

  1000 K Blackbody (e = 1): 2.5 X 10^{-1}

  So the K signal should be smaller than the fire, but this is not the case!



Is it possible to determine the emissivity of the flame from the available data?

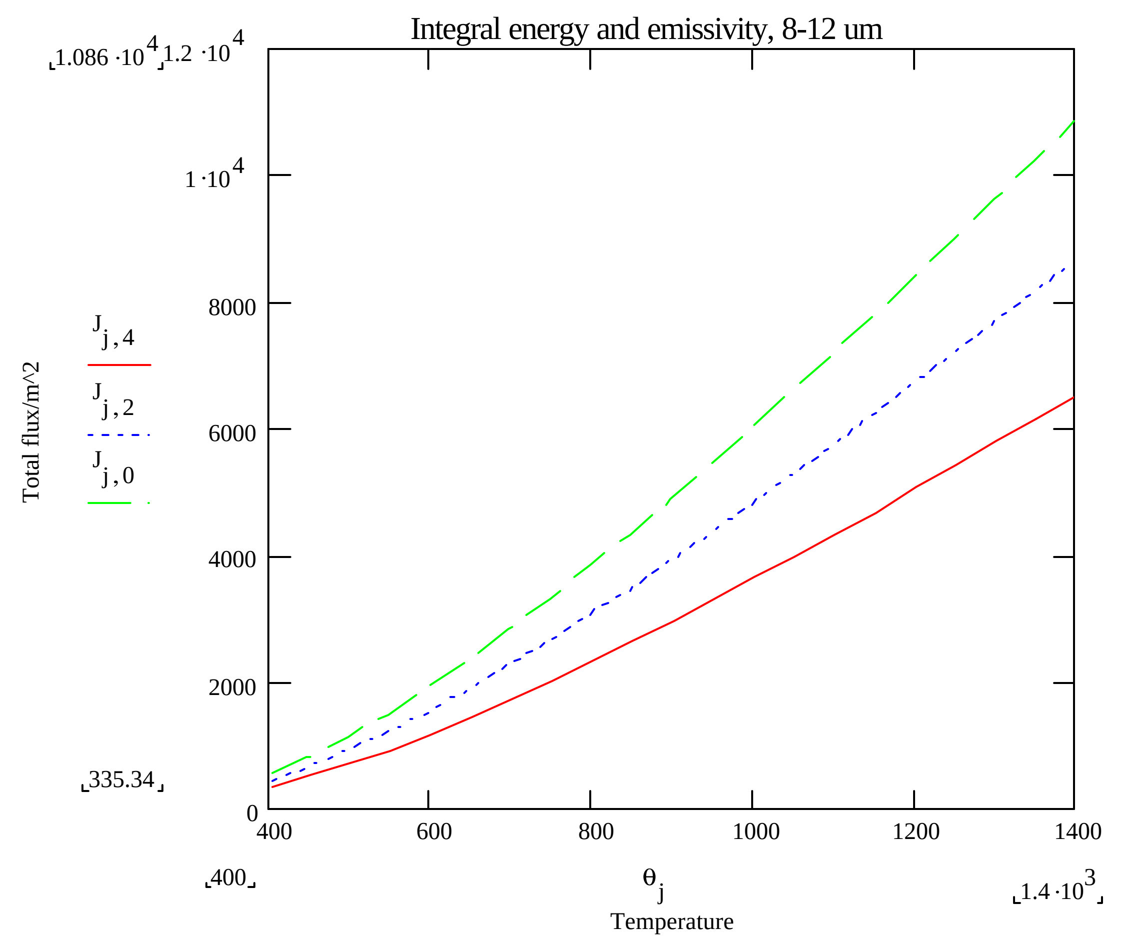
- We have spectral shape from ASD and Ocean Optics. The peak can be fit to determine the temperature. The leading edge can also be fit, and we have better data there. The spectra will be dominated in energy and (the lead edge will rise first) from the hottest portion of the flame. Remember σT^4!

- We have absolute flux in the 8 - 12 μm band from the Heitronics radiometer. The Heitronics presents a temperature, but measures flux * f(emissivity)

- The Asd and Heitronics look at (maybe) the same part of the flame at the same time. They should both measure the same temperature.

How do we measure the emissivity of the fire?

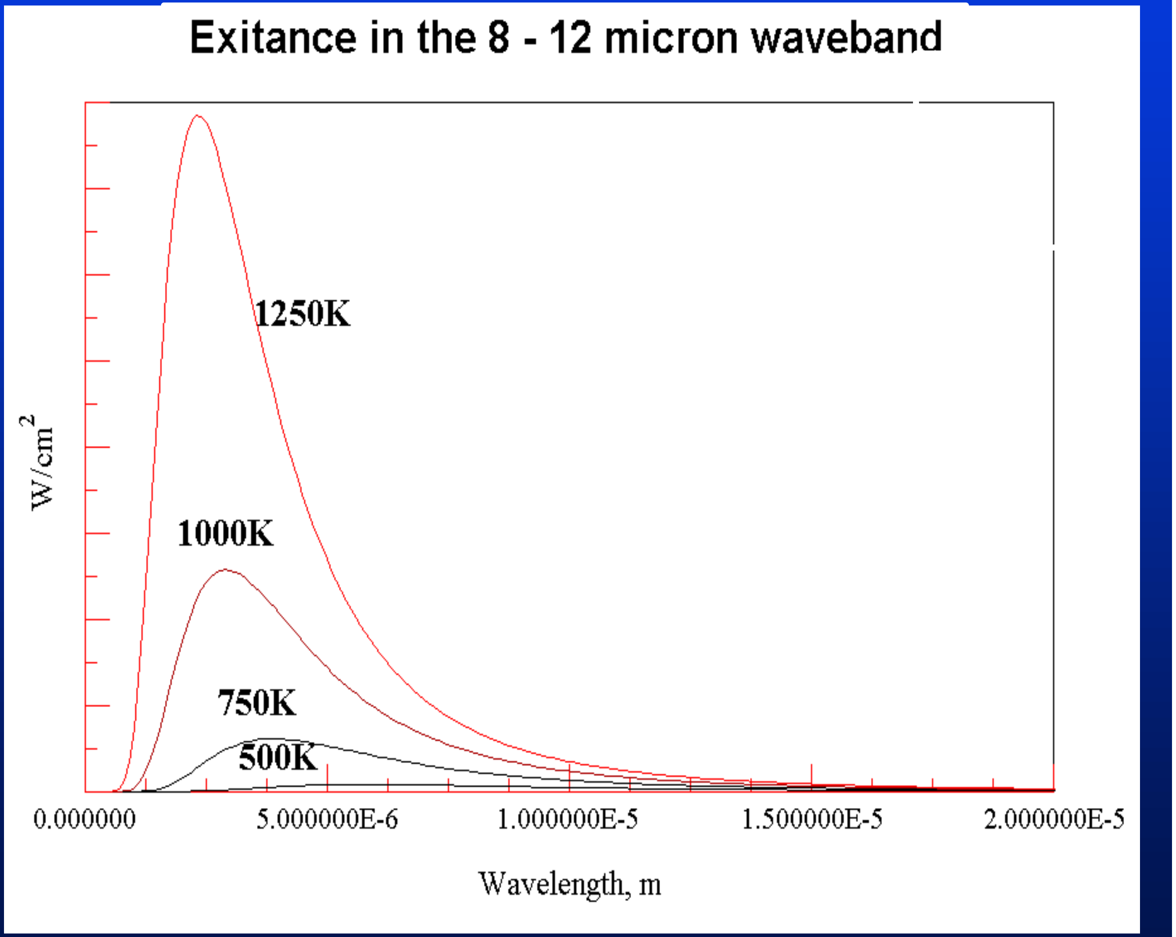
- Emissivity as a function of wavelength is required for *DIRSIG* modeling
- Emissivity is an elusive parameter!!!
- Might be able to use RMRS spectrometer as absolute measure for other bands/emissivity



Calculated for **e** = 1

We should be able to determine the highest blackbody temperature

- Fit to the leading edge
- Make the simplifying assumption that the emissivity is constant over the 8 - 12 μm waveband
- We did this with other ASD data and got reasonable, unambiguous results.
- We can then calculate an emissivity which will produce the same temperature as the fit with the Heitronics flux


Exitance in the 8 - 12 micron waveband

What next?

- Try to characterize the emission spectra from the longer wavelength portion of the spectrum.
- Lots of emission lines in the spectra. Some of these are atmospheric absorption lines (H_20, CO_2) Are these lines broadened? Are and properties of these lines useful?
- Continue to look at wealth of data