

Spectral Features of Biomass Fires

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Why study forest fires and build remote sensing fire satellites?



- Destruction of ‘exploitable assets’ like timber (wildlife) can be minimized by rapid response of fire-fighting team.
- Fire towers are undermanned and flight time is expensive.
- **Particulate matter, CO, CO₂, methane, evolved water alter atmospheric transport of solar energy.**
- **Atmospheric gaseous composition is incredibly important to energy balance - and *life on Earth*:**

Radiation

Absorbtion

$$4 \pi r^2 \sigma T_e^4 := \pi a^2 S(1 - a)$$

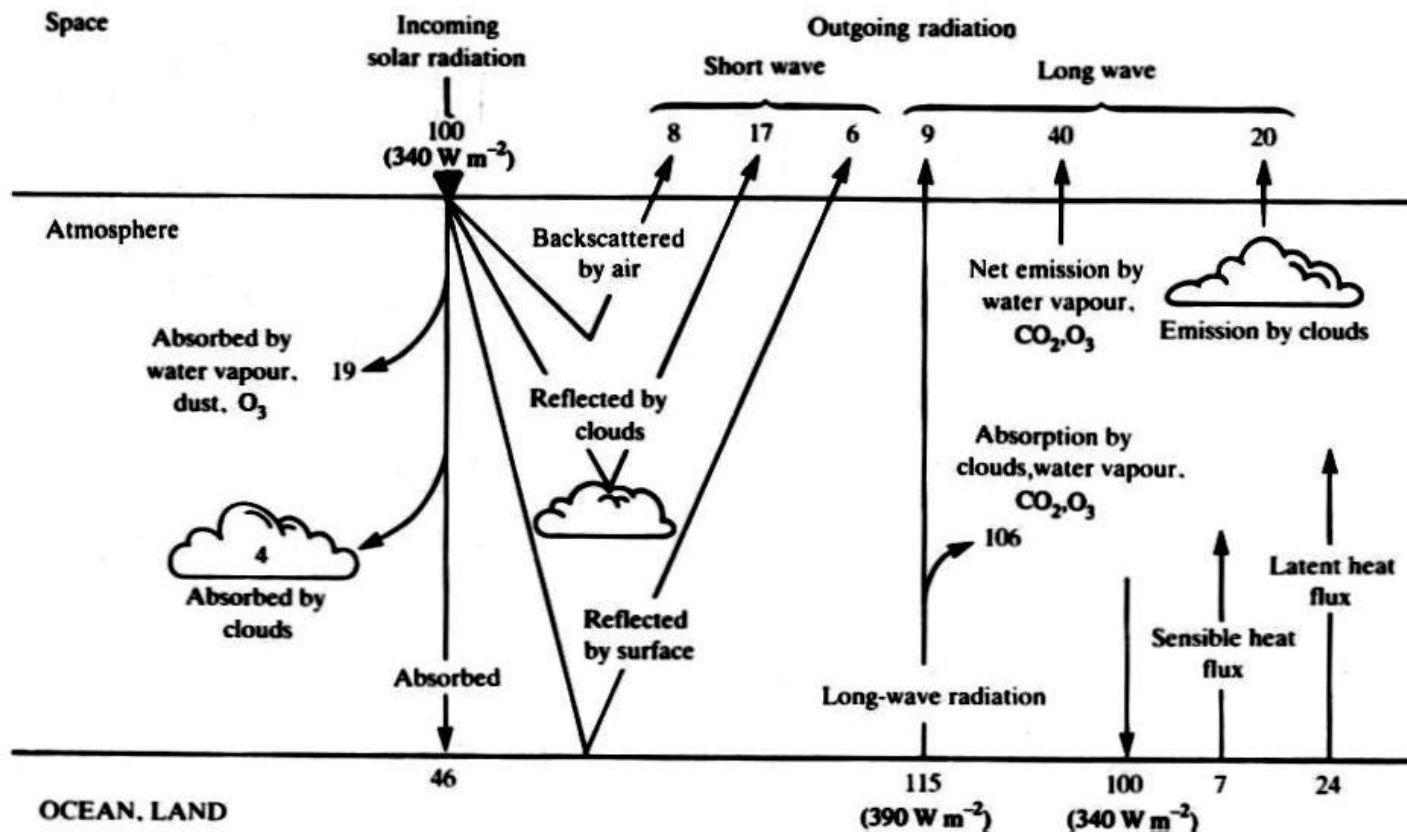
$$T_e := \left[\frac{S \cdot (1 - a)}{4 \cdot \sigma} \right]^{\frac{1}{4}}$$

$$T_e = 253.622$$

Can forest fires alter the radiation balance of the earth?



- Antarctic ice samples (and other evidence) show long term increase in several greenhouse gases



Forest fires have been detected in the past using IR signatures



- Thermal emission spectra from 1200K fire peaks at (Wein displacement law)

$$\lambda = 0.29/T \text{ (cm)} = 2.4 \text{ mm}$$

- Multi-band IR measurements allow approximate determination of temperature of scene
- Long wavelength IR (8 - 12 mm) can detect fire scars and 'hot' ground (if large enough in area)
- Very large dynamic range necessary for MWIR (2.5 - 5 mm) detectors to avoid saturation
- Likelihood for false alarms is very high if only one waveband is

used

IR detection of fires presents difficulties when using simple systems



- IR detectors typically not as sensitive (on any measure) as visible (silicon) devices
- IR detectors need cooling, in general (bolometers a possible exception)
- Small fires may be important as precursors to larger burns and as predictors of fire spread.
- **Small fires, which are in general sub-pixel events in a small satellite, are indistinguishable from specular reflections.**
- A detector only measures the *total incident power*. For a particular pixel, in a given waveband, the same power can be obtained from a large area high reflectivity warm surface (false alarm) or a cold background + fire (“true” alarm).
- Distinguishing a fire needs a discriminating condition - which could be obtained by comparison with adjacent pixels, etc.
- A large, hot fire will saturate a detector designed to look at Earth-ambient temperatures (300K)

Vegetative biomass is primarily composed of just a few elements



- As expected, most of the mass is H,C,O and N (by weight):
 - C: 45%
 - H: 5.5%
 - O: 41%
 - N: 3.5%
- But there are large (and varied) weight percentages of ‘trace’ elements:
 - K: up to 7% ← Candidates for fire detection
 - Na: 0.1% ←
 - P: up to 1%
 - Ca: up to 5%
- *Some of these elements have unique spectral properties in a fire*

The physical properties of the alkali metals make them ideal narrow line spectral sources



- The alkalis have a filled shell core which electrostatically shields the outer electron from the attractive positive nucleus.
- Because of this ‘screening’ the ionization potential (I_p) of the alkalis is very low, and the spectral is simple (‘hydrogen-like’):
 $I_p = 3.89 \text{ eV}$ for Cesium and 5.39 eV for Lithium.
- The alkalis are very reactive, form strong ionic compounds often bound to halogens, and are the ‘ion-pumps’ for many cellular processes.
- Ubiquitous in living material.
- All alkalis have very strong resonance transition doublets from the first excited state to the ground state.
- For potassium:
 - $^2P_{3/2} - ^2S_{1/2}$, $^2P_{1/2} - ^2S_{1/2}$
 - Wavelengths: 766.5 and 769.9 nanometers (near IR)

What happens to the alkali compounds in a fire?

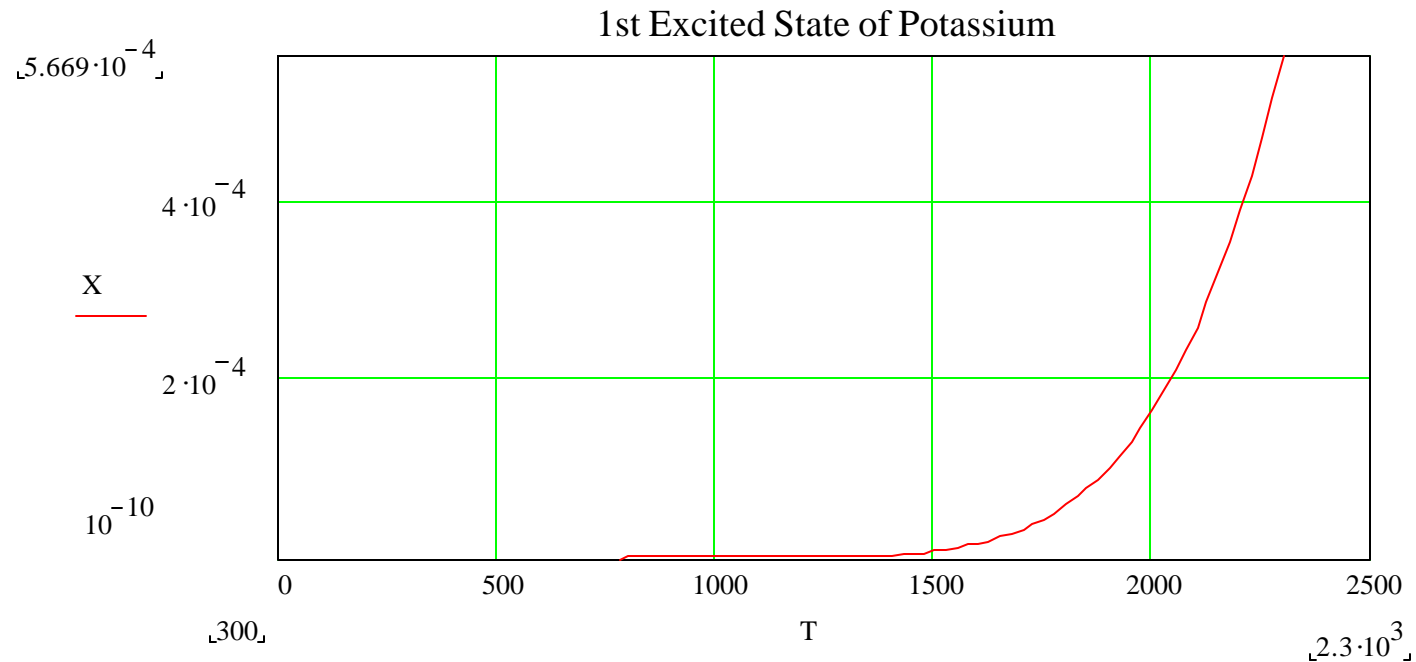


- Alkalis as halides or other ionic compound dissociate into $A + X$
- Some alkali atoms directly thermally excite to first excited state. These de-excite and produce strong emission lines.
- Relatively more alkali atoms ionize (after dissociation). These recombine with their own and other ionized atoms. The recombination cascade passes through the resonance state, producing strong emission lines.
- These processes are strongly dependent (Boltzman factor, $e^{-E/kT}$) on temperature, total electron number density, ionization potential and first excited state level.
 - For potassium:
 $E_{\text{ion}} = 4.32 \text{ eV}$
 $E_{\text{1st ex}} = 1.69 \text{ eV}$
 e^- number density in a flame $\sim 10^5 / \text{cm}^3$ or less (near neutral)

Most of the potassium is in the ground state in a fire



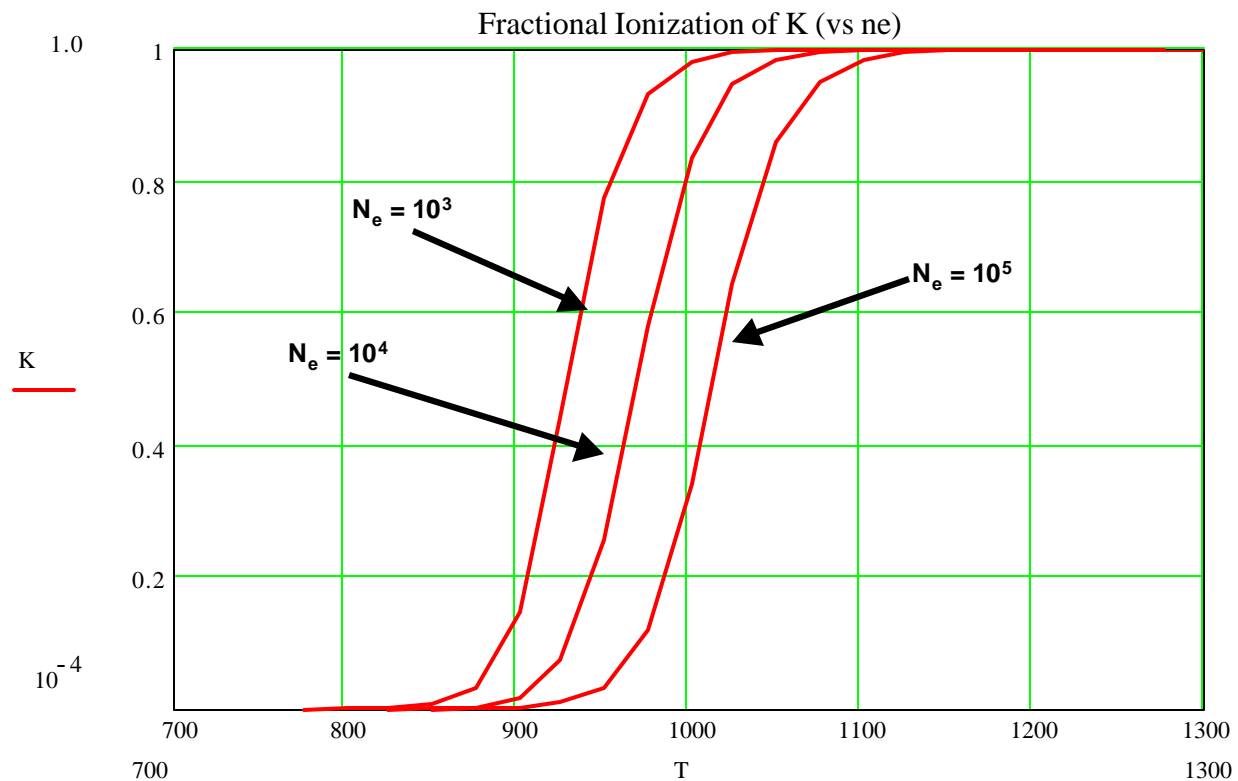
- Use Boltzmann equation to determine number in upper state
- No significant excitation until $kT_{\text{fire}} \sim$ energy of first excited state



But, there is a high degree of ionization at fire temperatures



- Strength of lines is determined by the fraction of *all atoms* that are in the first excited state (Saha equation) (curves are parameterized by electron density, n_e in the flame)



Ionized alkalis can make transitions resulting in very strong emission lines



- However, the 766.5 and 769.9 nm lines are near the oxygen 'A' band. A MODTRAN atmospheric transmission simulation was performed to verify feasibility.

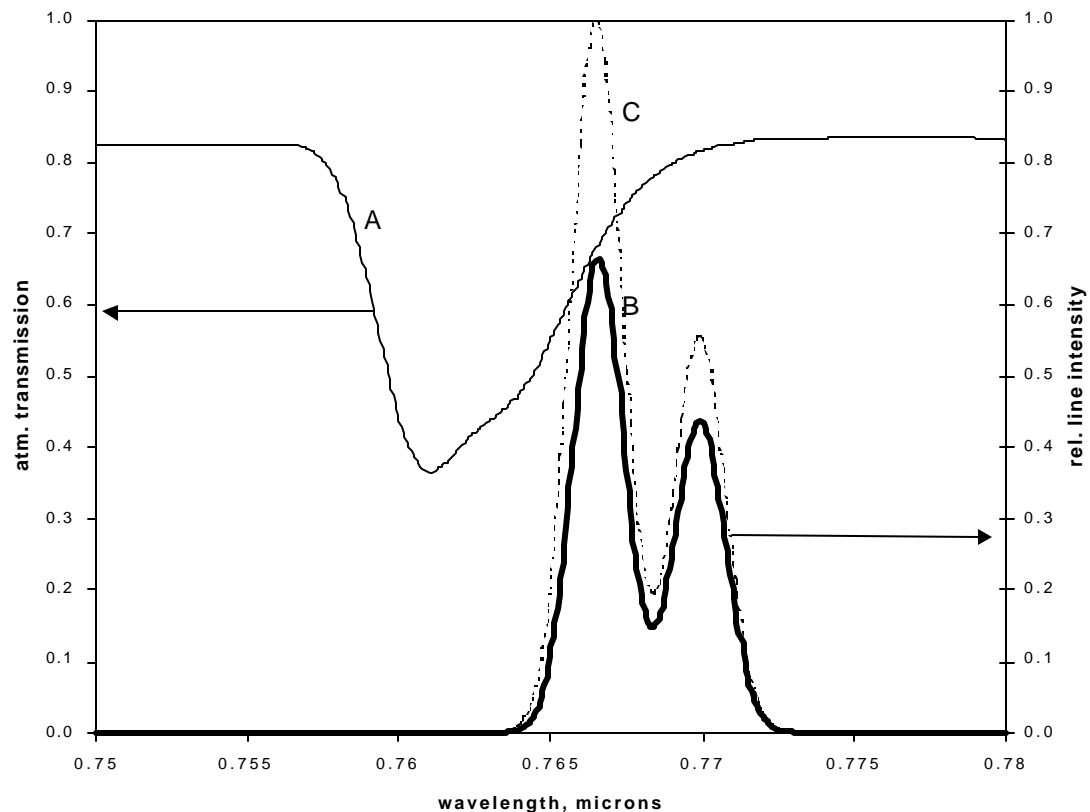
A - MODTRAN atmospheric transmission model, at 3 nm resolution

B - K line pair, convolved with 3 nm instrument response, after atmospheric transmission

C - Expected K line emission

Results:

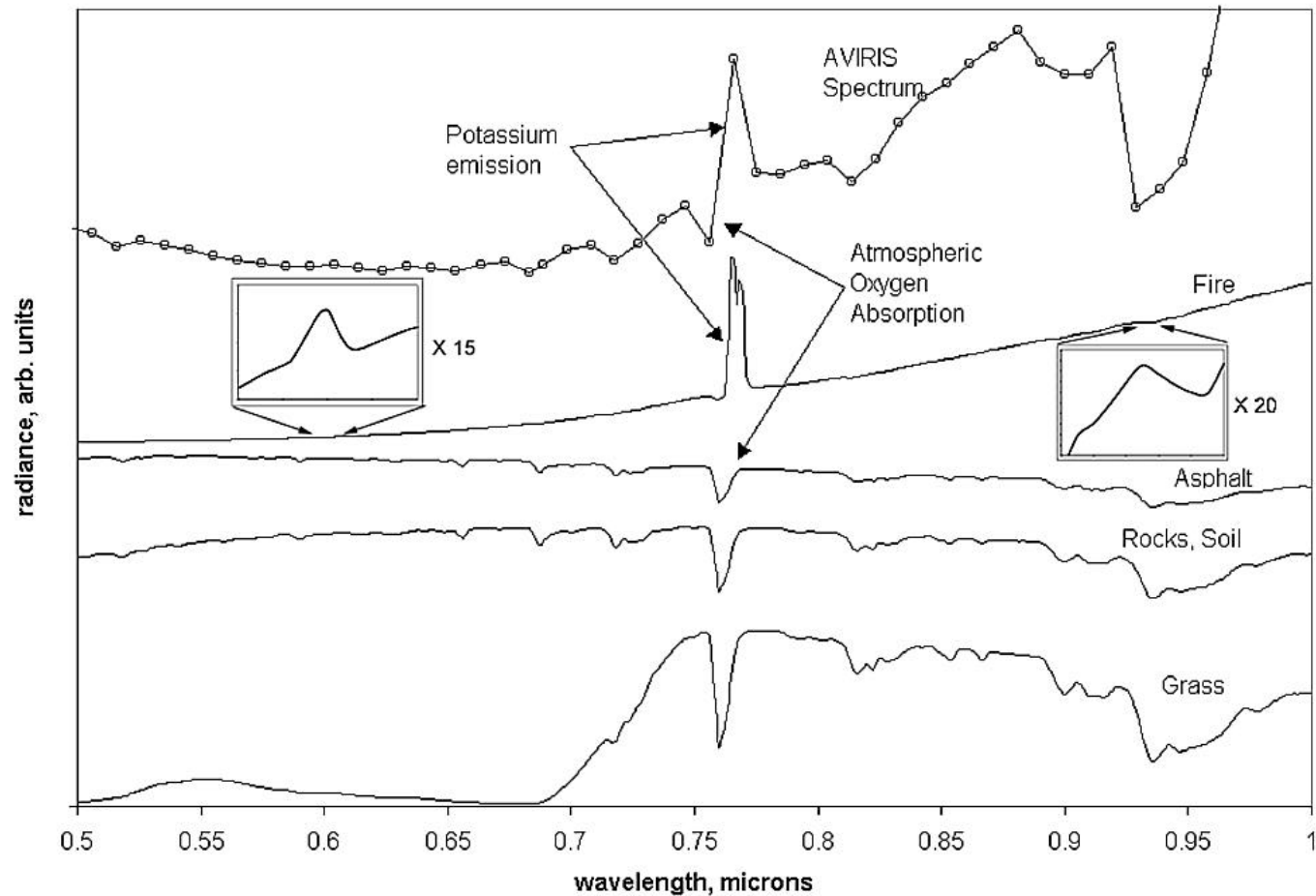
Intensity decreases, line ratios altered



We observed ionized alkalis and other low-ionization level elements in test biomass fire



A controlled burn performed to investigate spectra ASD spectrometer in radiance mode used for data collection.



Because the spectral energy density is very high in these emission lines, signal to noise can be very high



Data from ASD was fit with sloping linear background and instrument response.

Free parameters - center wavelength, amplitudes, background slope and intercept, instrumental FWHM

Results:

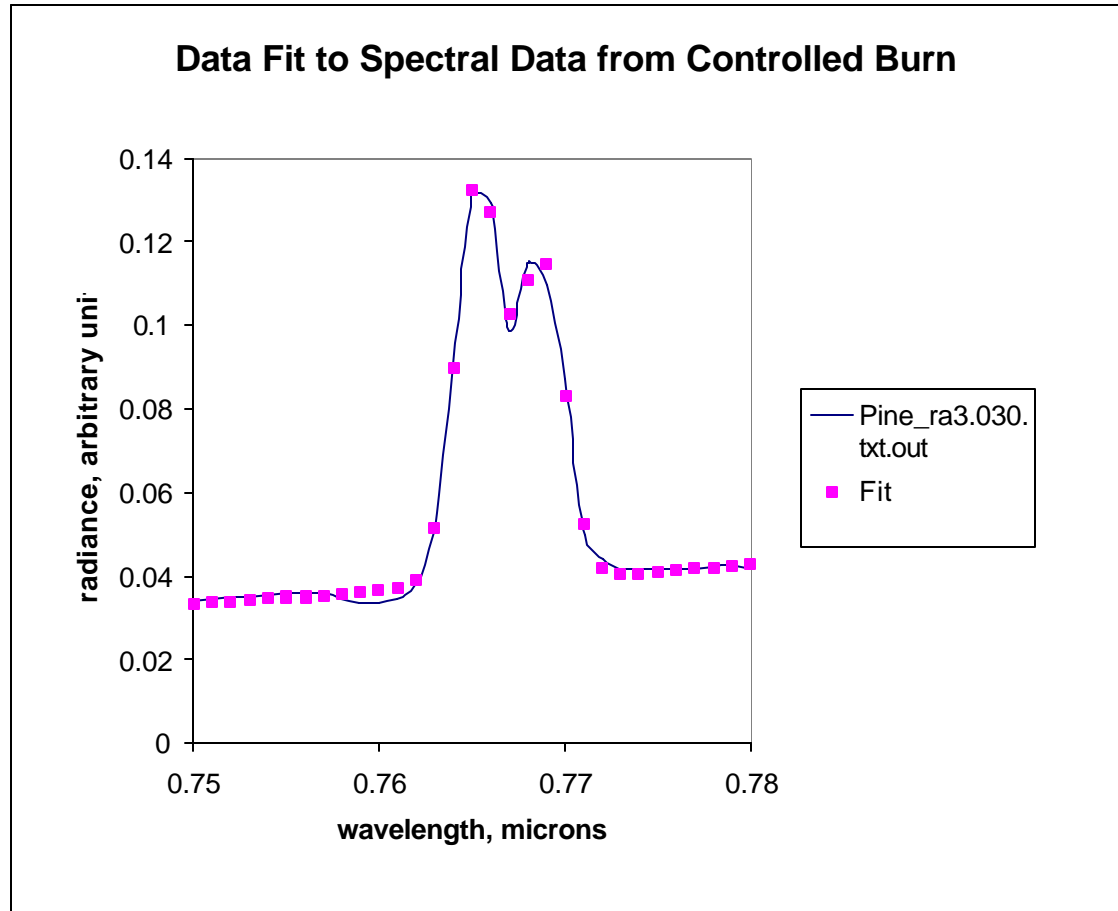
Line ratio: 1.3

Expected: 1.8 (?)

Wavelength: both

-1.2nm from 'true'

Instrument: 2.81 nm



High signal to noise and unique spectral signature reduces false alarms

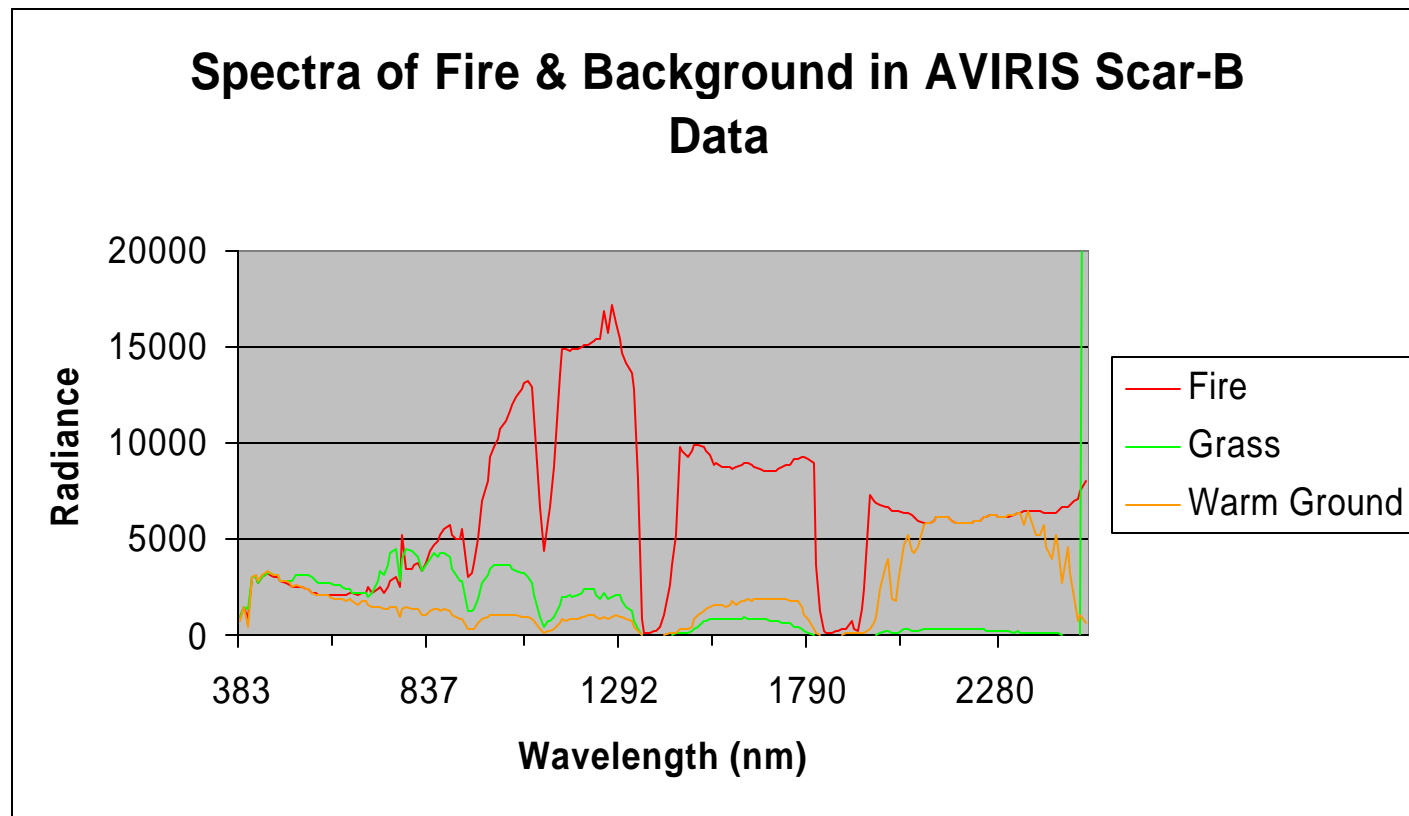


- Extremely narrow (~angstroms) lines allow reducing optical bandwidth. The spectral energy density of specular reflections and blackbody emission is too low to detect in a narrow band.
- Because K emission is specific to flaming combustion, if it is observed in conjunction with the sensing of blackbody emission, which detects warm or hot spots, there is the potential to separate smoldering from flaming vegetation.
- Separating smoldering from flaming vegetation is important to quantifying the release of gases and aerosols from biomass burning that impact atmospheric chemistry because some important gases (CO_2 , NO_x , SO_2 , N_2O) are released primarily during the flaming stage and others (CO , CH_4 , other hydrocarbons) are released during the smoldering stage.

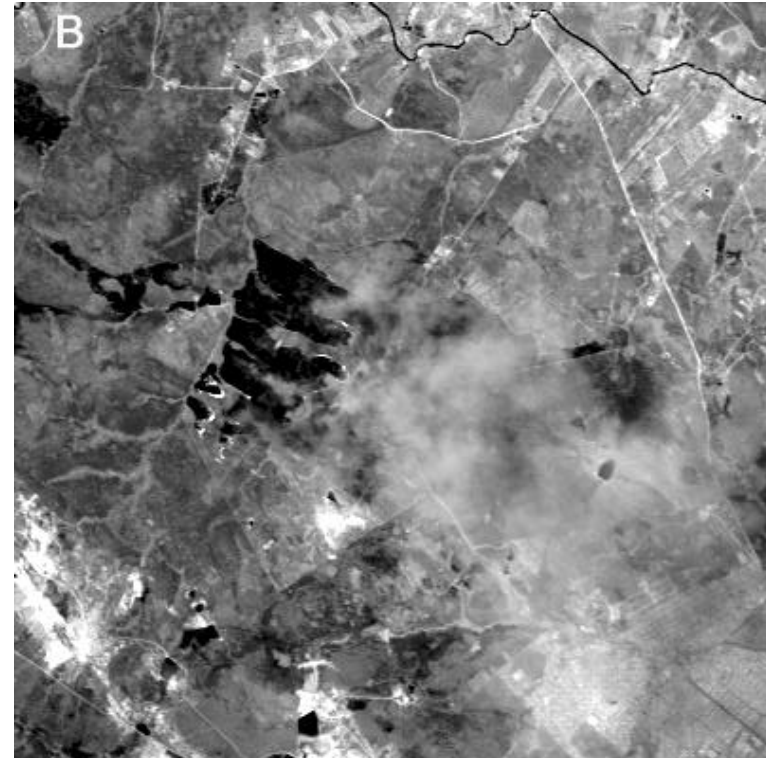
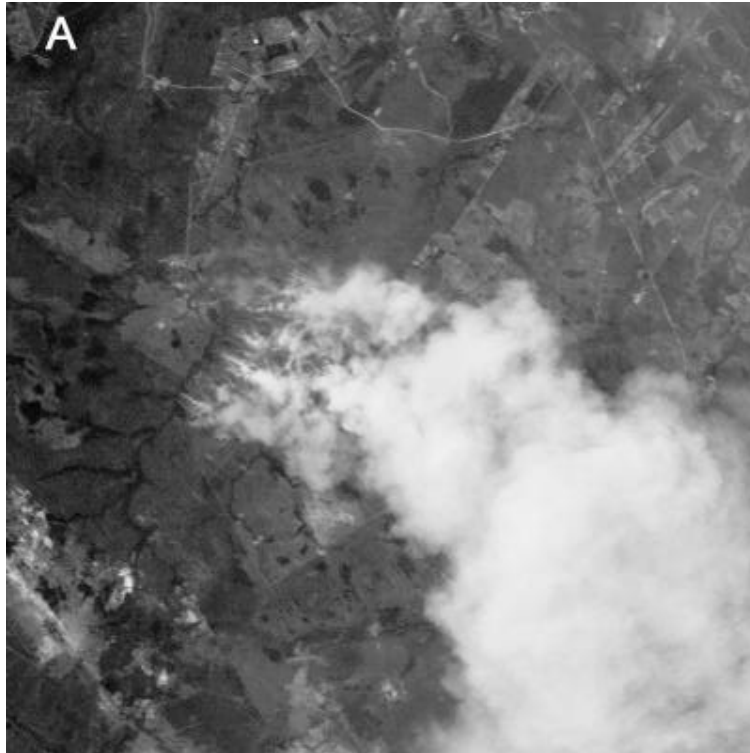
We have analyzed an AVIRIS fire data sets in several wavebands (Cuiaba, BZ)



- Individual pixels of this data show strong potassium lines
- Some IR channels saturated

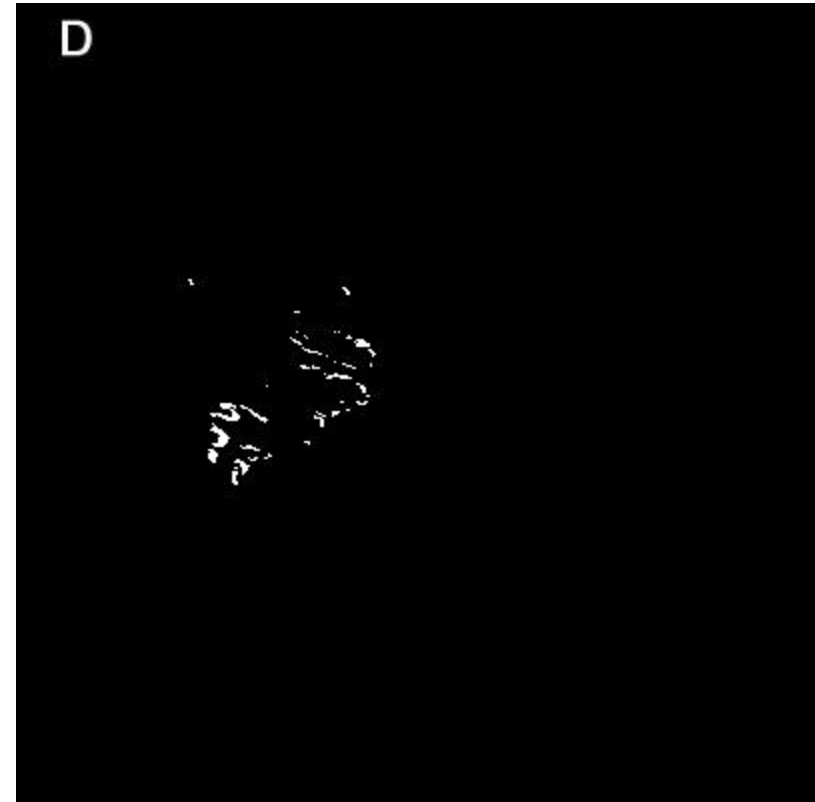
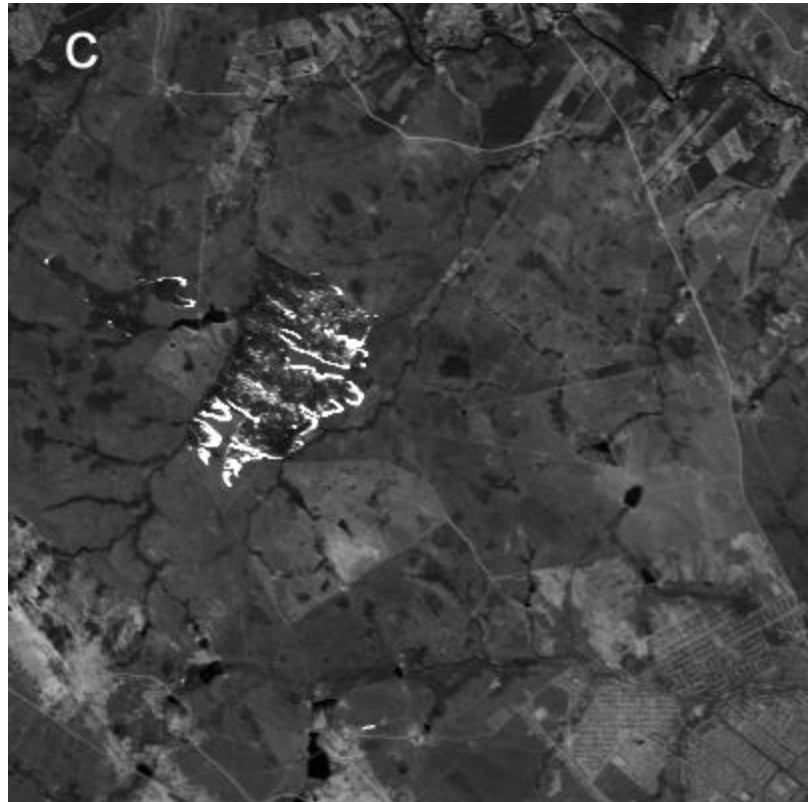


We have analyzed an AVIRIS fire data sets in several wavebands (Cuiaba, BZ) (2)



- A - 589 nm - no smoke penetration
- B - 770 nm - smoke penetration, bright active fire fronts visible

We have analyzed an AVIRIS fire data sets in several wavebands (Cuiaba, BZ) (3)



- C - 1500 nm (smoke penetration, fire fronts)
- D - Band ratio, 769 nm / 779 nm thresholded to 6 s

Other operational advantages may be possible using potassium detection



- The waveband of interest (770 nm) is accessible by Si detectors or photomultipliers.
- Because of high QE and low D^* , these detectors typically do not require cooling.
- False alarm rate can be calculated a priori knowing only a few parameters (WIP)
- An estimation of the mass and temperature of the burning material may be possible using the strength of the line (WIP)