# ASTR 421

## Stellar Observations and Theory

# Lecture 09
# Line Profiles: II

Prof. James Davenport (UW)

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# Today

- Details of line broadening mechanisms
- Ca II HK
- Revisiting other line profiles (P Cygni)

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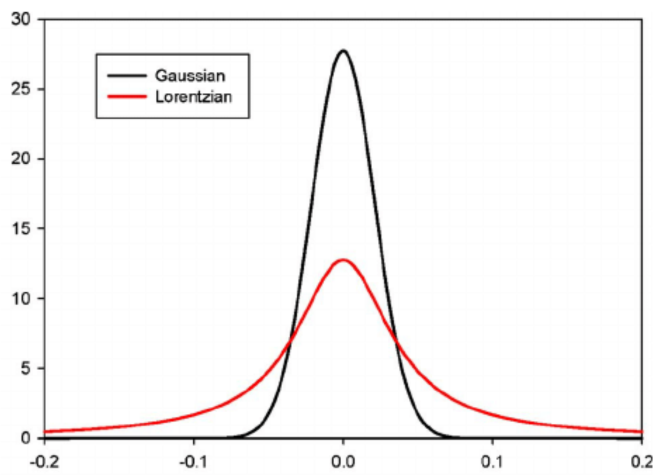
# Overview of Line Broadening

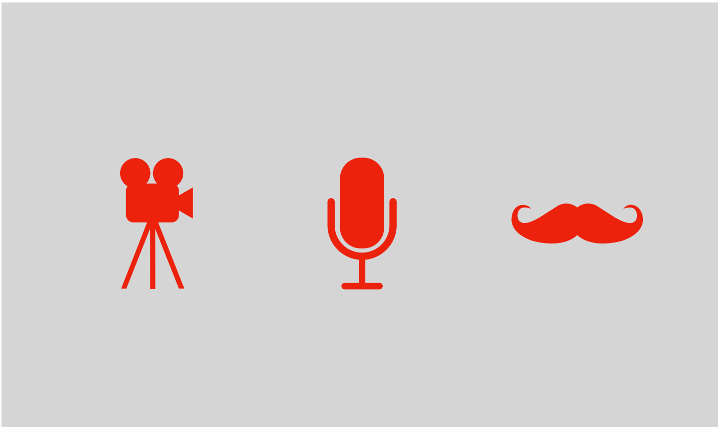
Many things can impact “doppler broadening”, anything w/ gas velocities

- **Doppler broadening** (thermal motions)
- **Natural broadening** (Heisenberg uncertainty)
- **Pressure broadening** (a few kinds)

**Gaussian profile**

**Lorentzian profile**

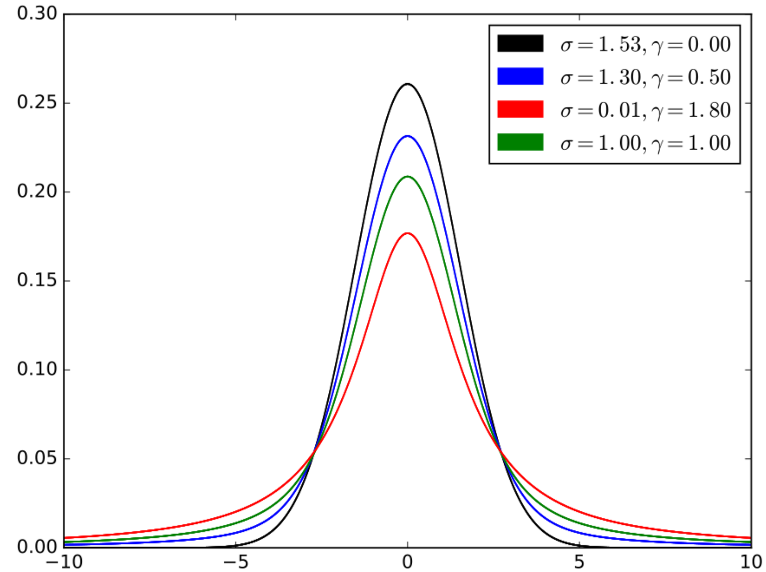


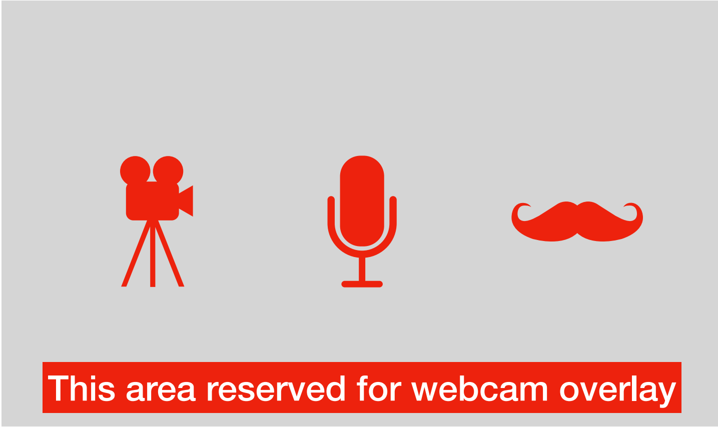



# The Voigt Profile

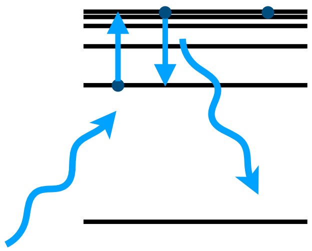
- A *convolution* of Gaussian & Lorentzian profiles
- This the classic line profile equation we use in most cases
    - Core: mostly Gaussian shape
    - Wings: mostly Lorentz shape
- **Useful for constraining physics behind both thermal & pressure broadening in a line!**

$$V(x;\sigma,\gamma) = \int_{-\infty}^{\infty} G(x';\sigma)L(x-x';\gamma)\,dx'$$



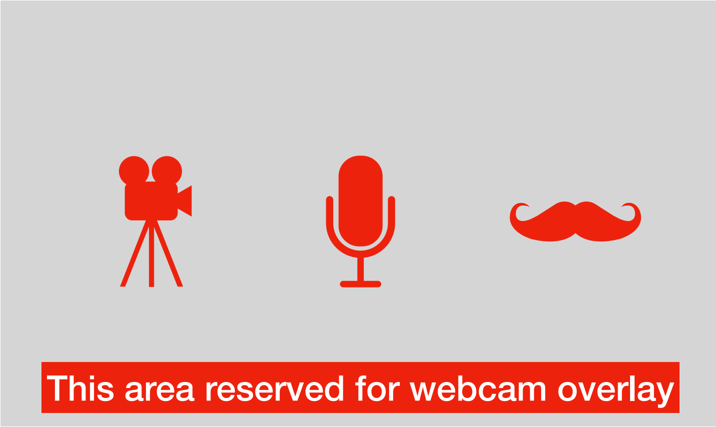
# Natural broadening



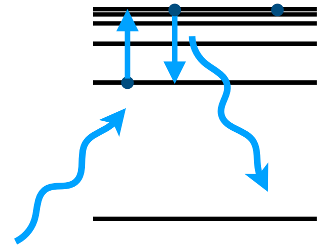
- Arises due to Heisenberg uncertainty principle
  $\Delta E \; \Delta t \approx \hbar$
- Time electron spends in excited state is finite… the photon *does* get emitted!
- Plugging in the classic $E = hc/\lambda$ for photon…
- BOB gives estimate of the line width for natural broadening of:

$$FWHM = \frac{\lambda^2}{\pi c \Delta t} \quad \text{(eqn 9.61)}$$

- Example for $H\alpha$: FWHM $\sim 2 \times 10^{-5}$nm (!)
  - **TYPICALLY VERY SMALL**

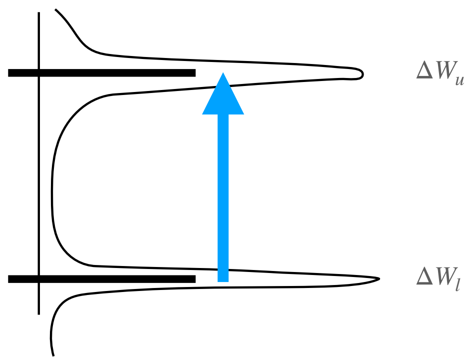


# Natural broadening

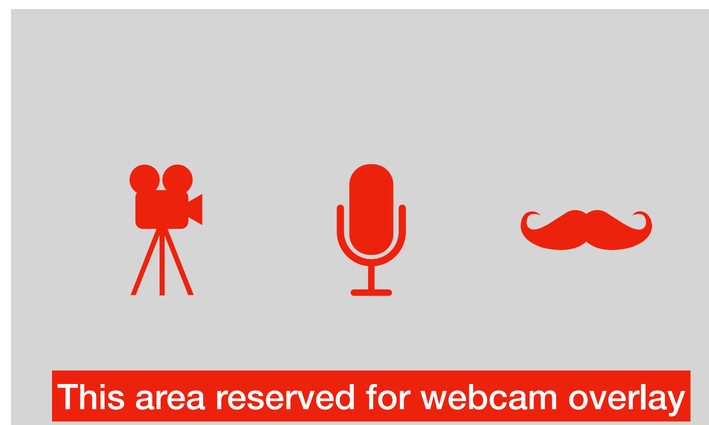


- Arises due to Heisenberg uncertainty principle
  $\Delta E \, \Delta t \approx \hbar$

- Another way to think about this is the *location* of the energy levels cannot be precisely determined at any given moment.

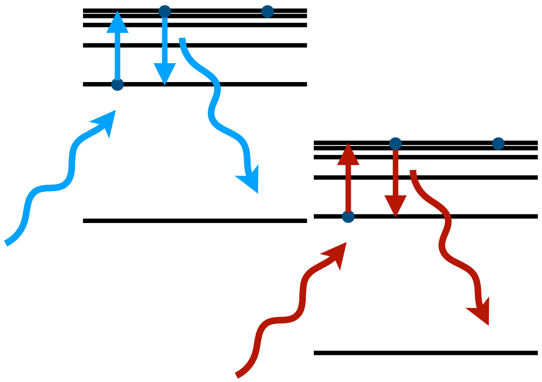


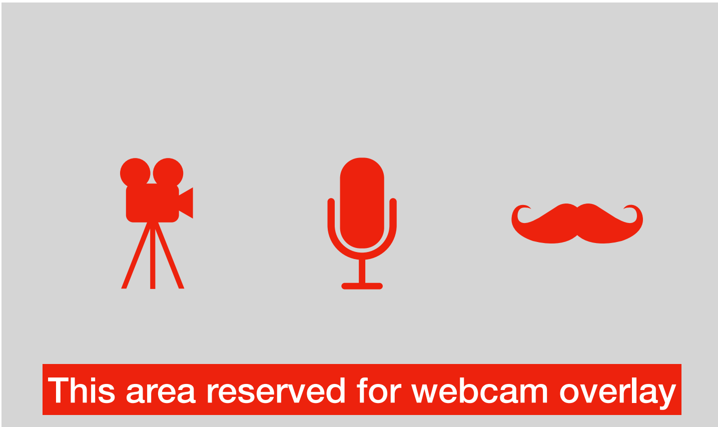

Gray, Fig 11.1



# Thermal (Doppler) broadening

- Arises due to atoms *moving around* in the medium
- Each transition (absorption or emission) is blue/red shifted due to simple doppler velocity shift
- **The line width is therefore determined by the velocity distribution**

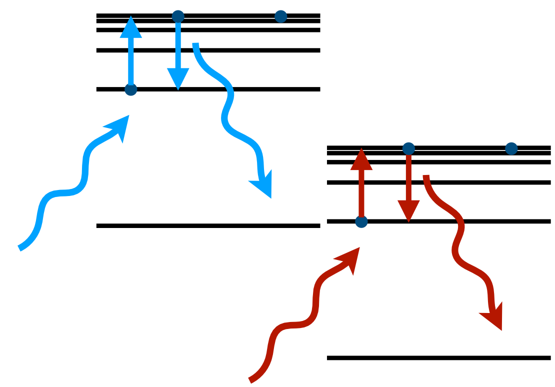




# Thermal (Doppler) broadening

- Thankfully we have a good model for velocity distribution of an ideal gas… our friend once again, the Maxwell-Boltzmann distribution, which classically gives

$$v_{peak} = \sqrt{2kT/m}$$

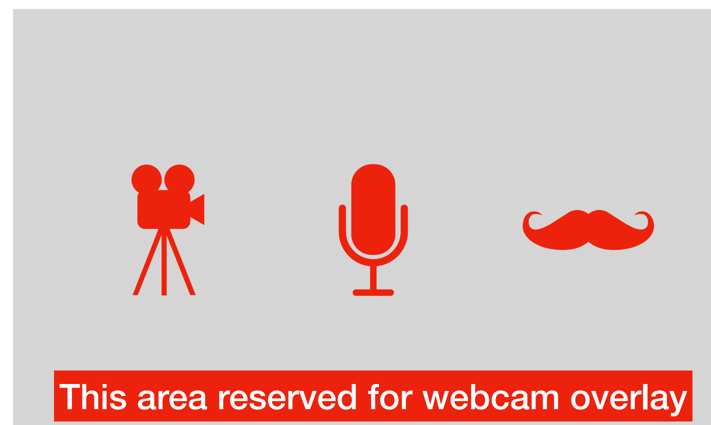


- A handy reminder for Doppler shift: $\dfrac{\Delta\lambda}{\lambda} = \dfrac{v}{c}$

  (in non-relativistic limit)

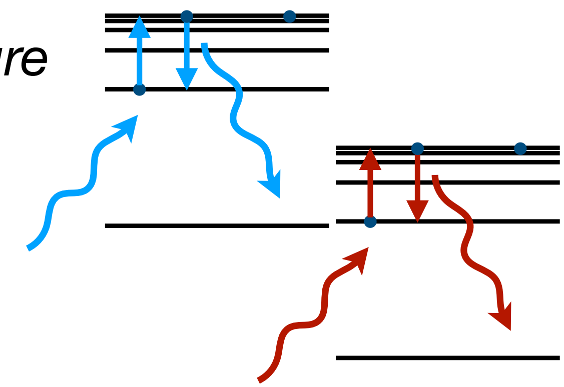
- This yields good approximation of:

$$\Delta\lambda \approx \frac{2\lambda}{c}\sqrt{\frac{2kT}{m}}$$

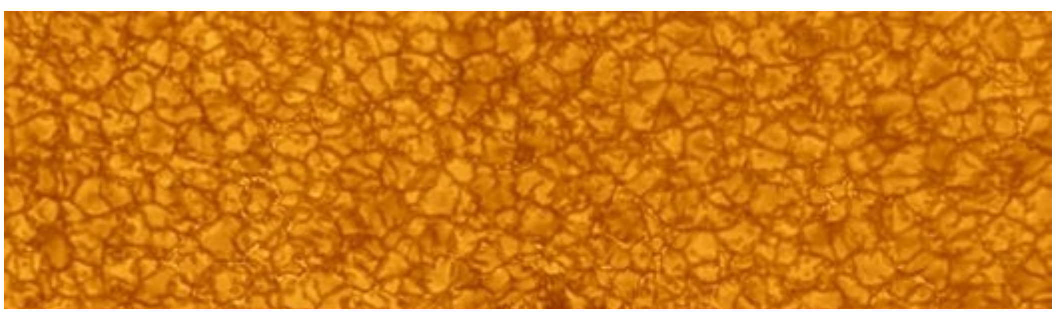


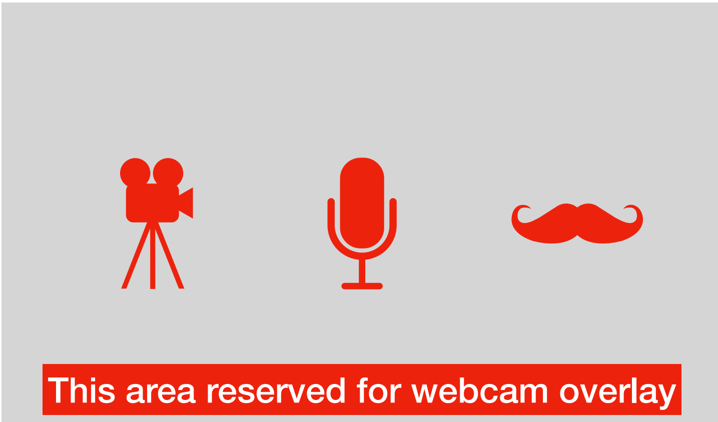
$$\Delta\lambda \approx \frac{2\lambda}{c}\sqrt{\frac{2kT}{m}}$$

# Thermal (Doppler) broadening



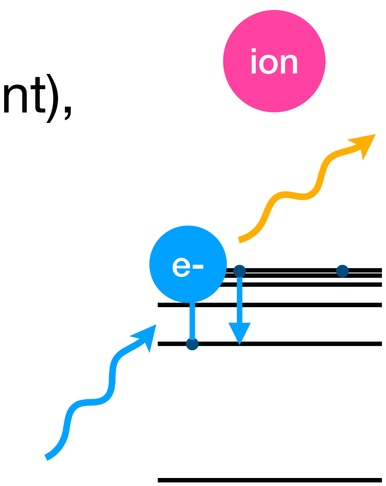
- For $H\alpha$ on (above?) the Sun, we expect just the *temperature* to cause $\Delta\lambda \approx 0.04$nm
  - MUCH LARGER than Natural Broadening…
- Other velocity motions can cause Doppler broadening i.e. not explicitly *thermal* behavior
- e.g. microturbulence, especially due to convective motions of gas

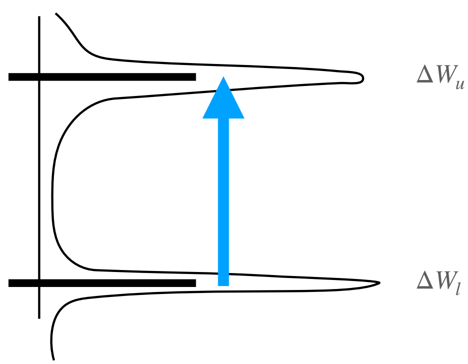


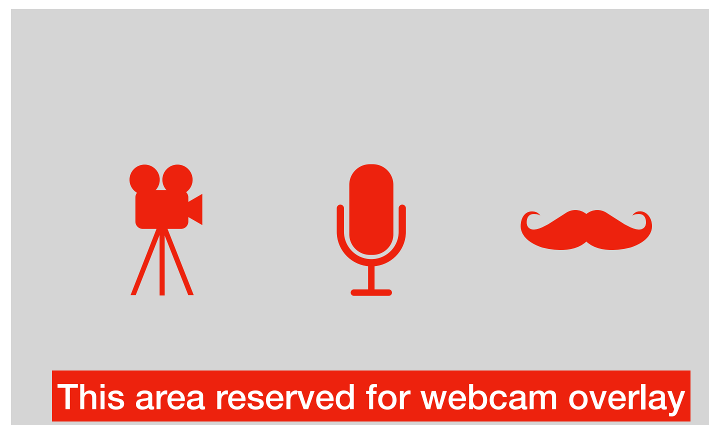


# Pressure broadening

- Collisional interaction between atoms (of the same type or different), ions, e-… even molecules in some cases.
- These interactions can blur the locations of the energy levels
- Again, due to Heisenberg, this results in line broadening



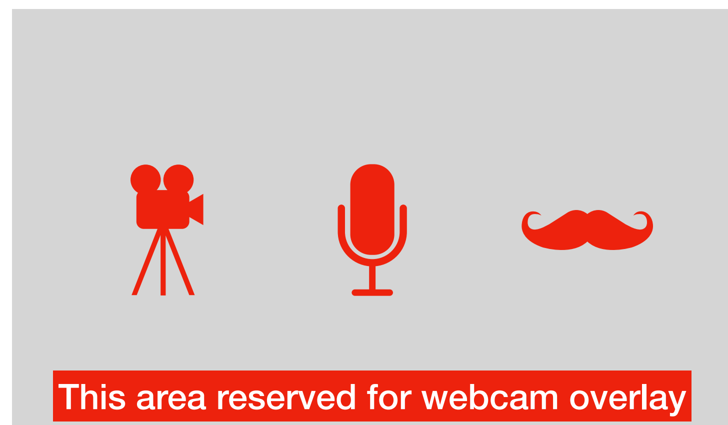



# Pressure broadening

- Collisions more frequent when pressure (and density) is high in the gas
- If we use our intuition from natural broadening, where $\Delta t$ is now the typical time between collisions $$FWHM = \frac{\lambda^2}{\pi c \Delta t}$$
- Assume a typical velocity from the thermal motion (i.e. Doppler broadening)
- These combine to give a useful estimate:

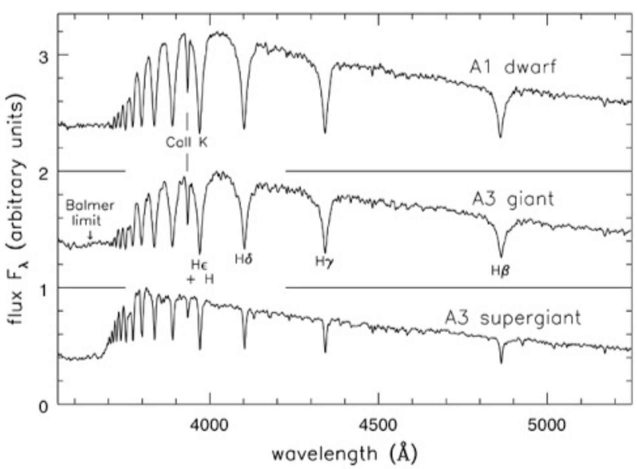
$$\Delta\lambda \approx \frac{\lambda^2\, n\sigma}{\pi c}\sqrt{\frac{2kT}{m}}$$

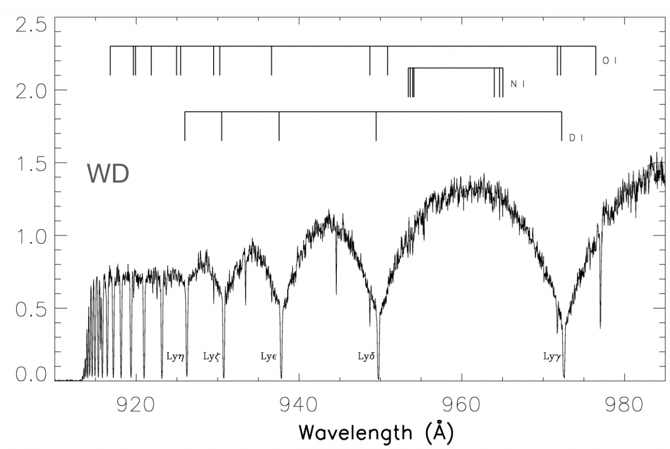


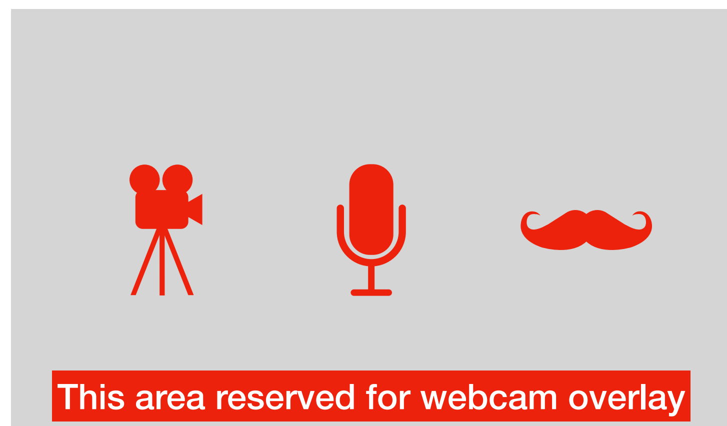
# Pressure broadening

$$\Delta\lambda \approx \frac{\lambda^2 n\sigma}{\pi c}\sqrt{\frac{2kT}{m}}$$

- Line width due to temperature, but also density of material!
- Thus Pressure broadening is the indicator of surface gravity (mean density)
- For dwarf stars, this is often small (e.g. for $H\alpha$), but can be VERY large for high surface gravity!



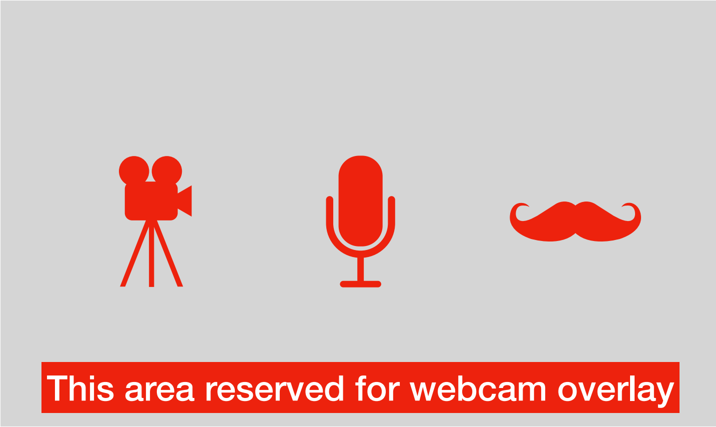
# Pressure broadening

$$\Delta\lambda \approx \frac{\lambda^2\, n\sigma}{\pi c}\sqrt{\frac{2kT}{m}}$$

STARK EFFECT

- Various physics creating these collisions:
  - **Linear Stark Effect** (mostly for H lines, impacting Protons & e-)
  - **Quadratic Stark** (most lines in hot stars, impacting ions & e-)
  - **van der Waals** (most lines in cool stars, impacting neutral H)

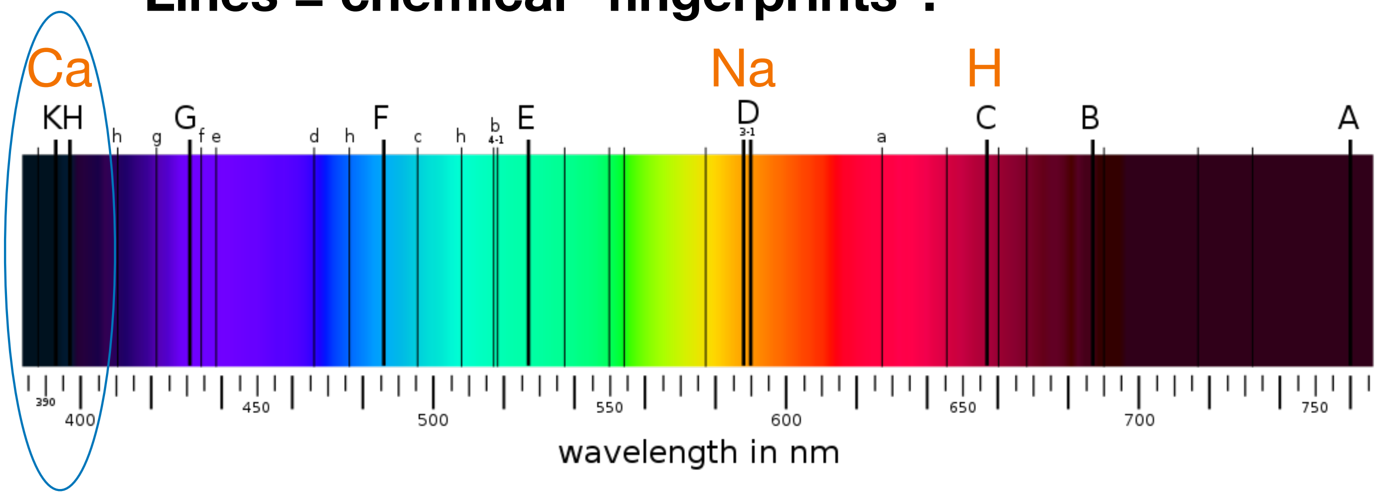
- Can be VERY broad, esp. for strong dipoles (e.g. H)

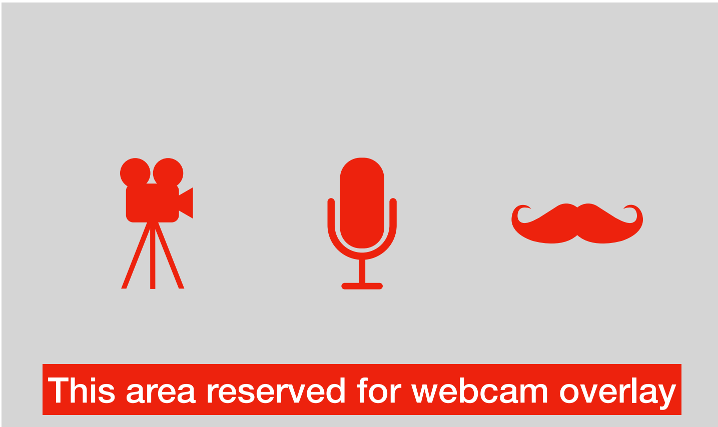


From: Lecture 04

# Fraunhofer lines

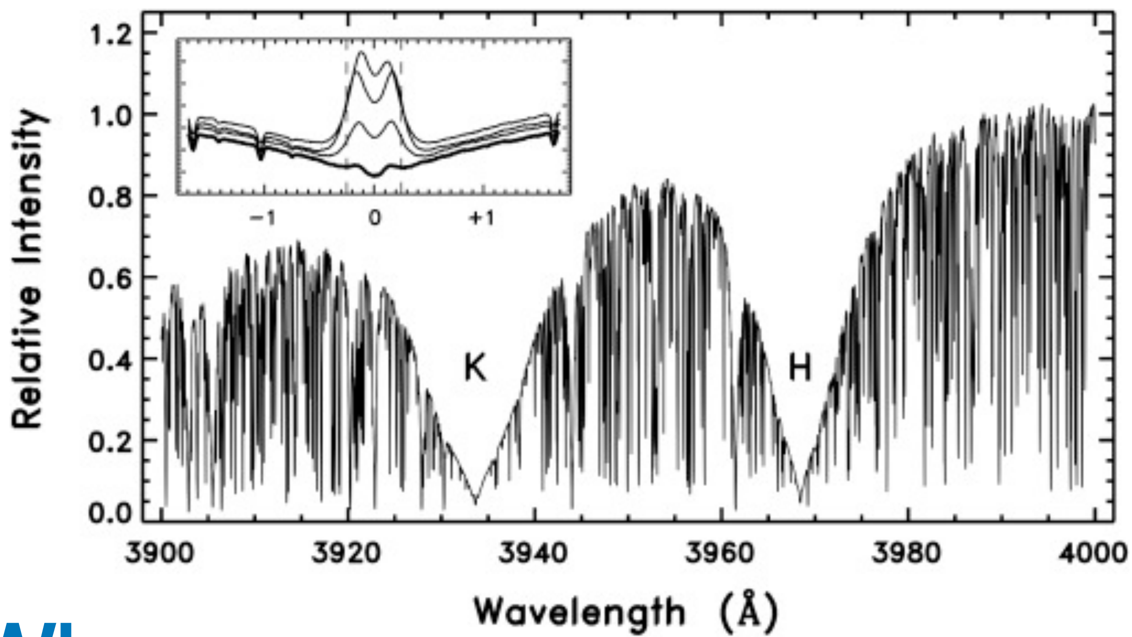
- Cataloged in solar spectrum by Fraunhofer in 1814
- Seen in many other stars
- Kirchhoff & Bunsen noticed these == emission line from burning! (1859)
  **Lines = chemical “fingerprints”!**




https://en.wikipedia.org/wiki/Fraunhofer_lines

# Ca II (or Ca+) “HK”




Whoa…

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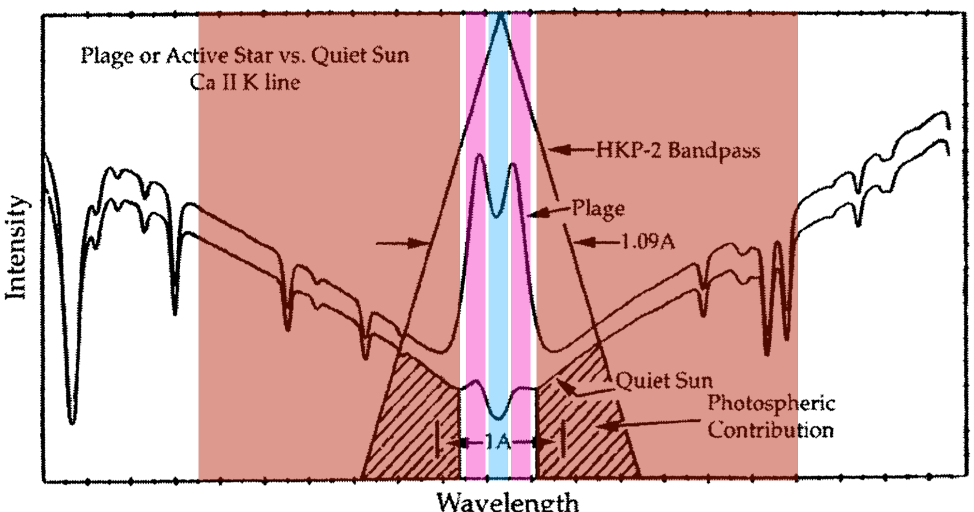
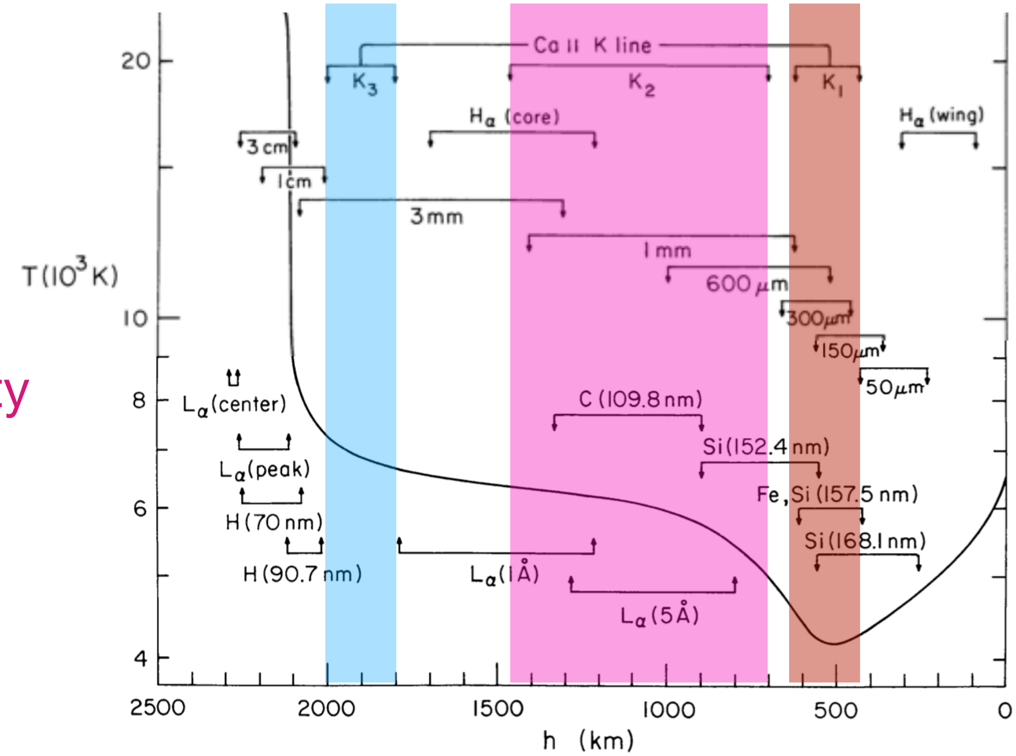
# Ca II (or Ca+) "HK"

Important tracer of chromospheric **B** activity




Duncan+1991, Baliunas+1998

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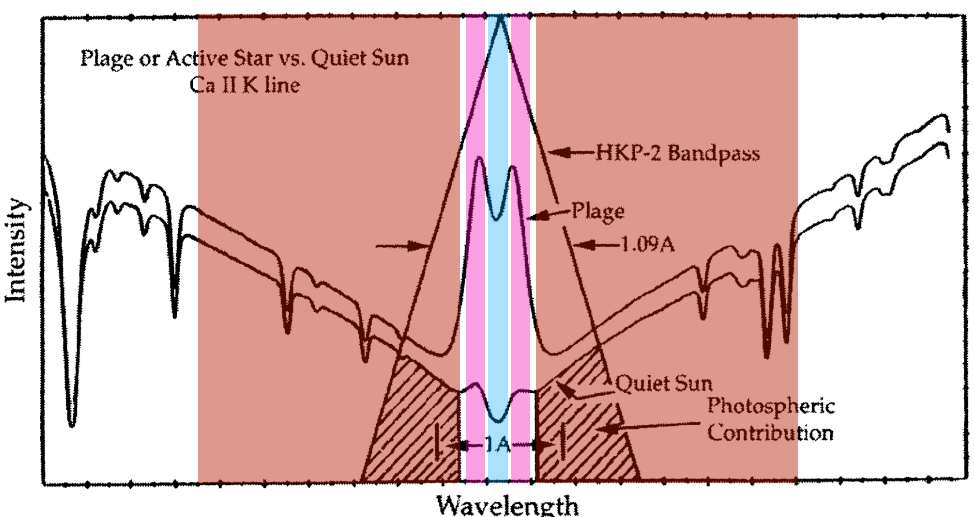
# Ca II (or Ca+) “HK”

- Wings formed at photosphere surface, driven by scattering
  (super broad Lorentzian profile)

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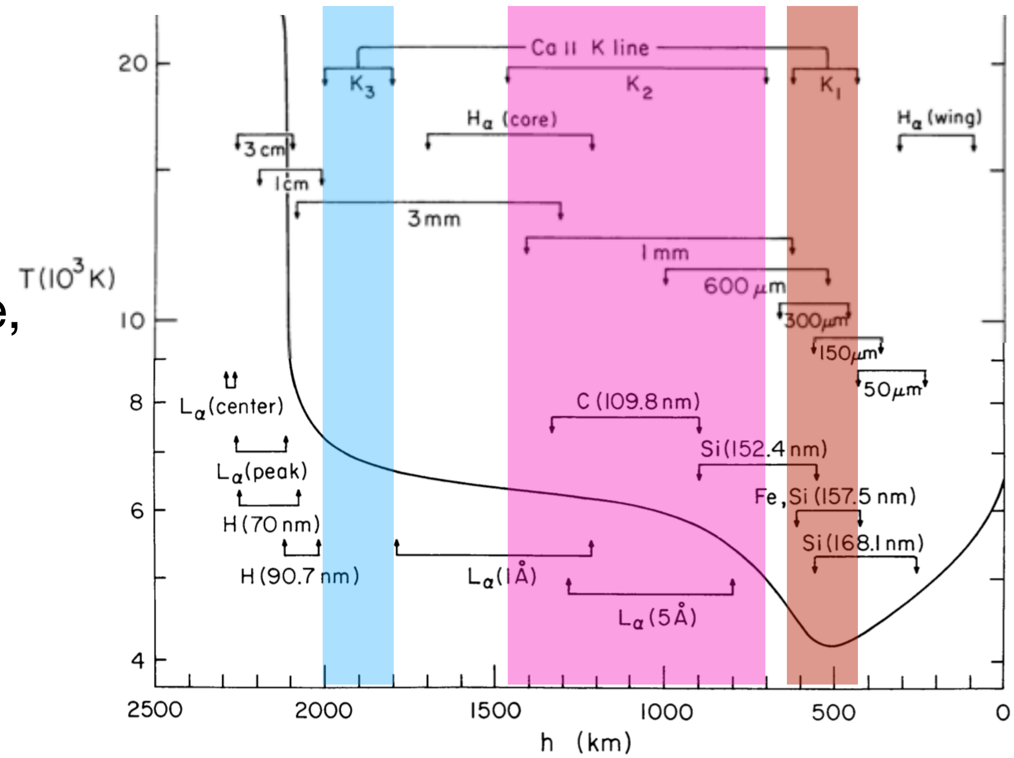


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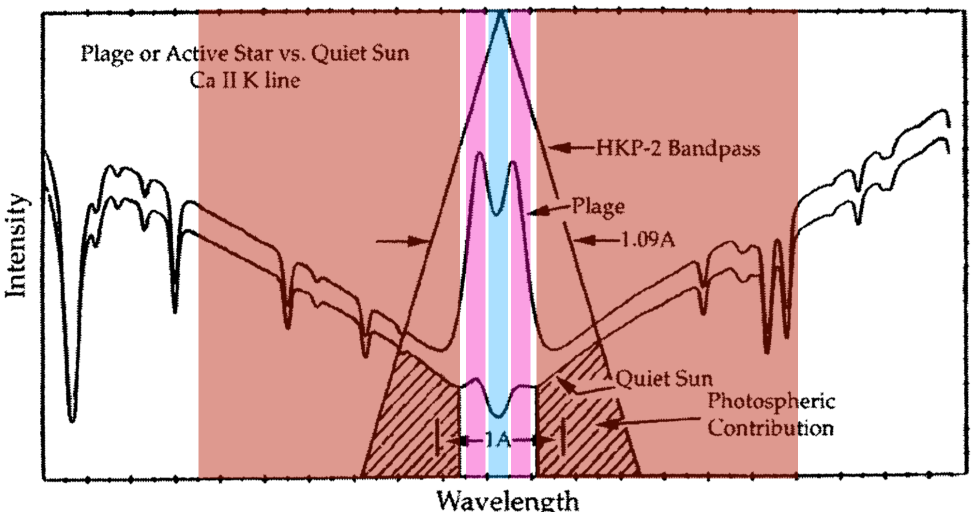
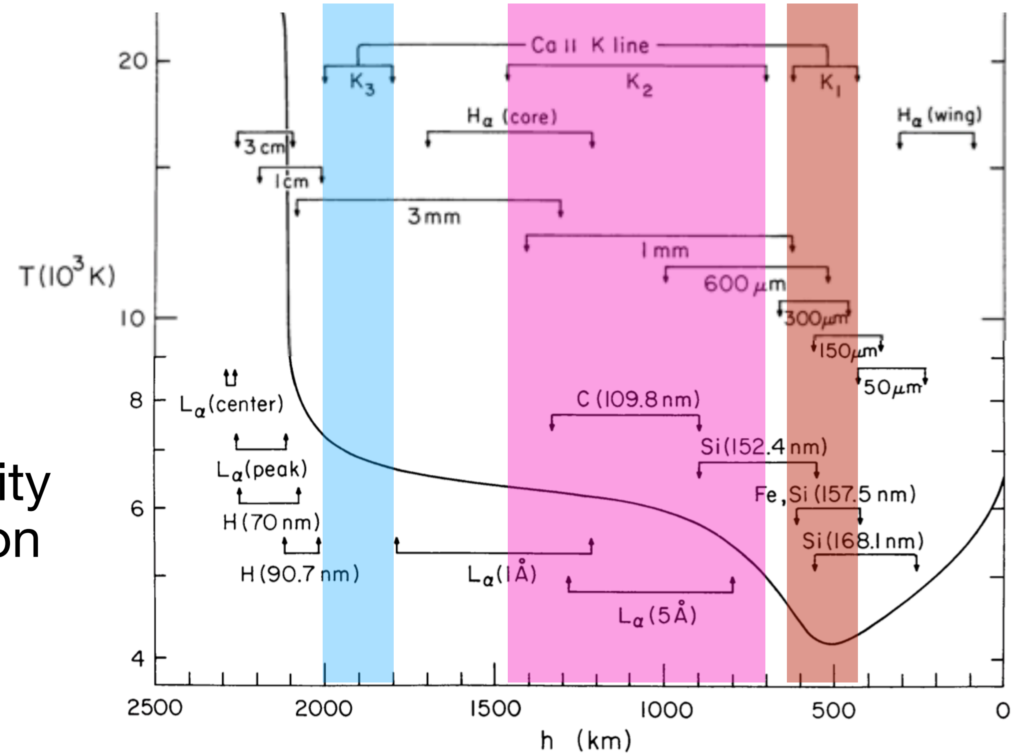
# Ca II (or Ca+) “HK”

- Peaks due to increased temperature in chromosphere (like $H\alpha$)
- Dip due to scattering, increases opacity again right before the Transition Region




Duncan+1991, Baliunas+1998

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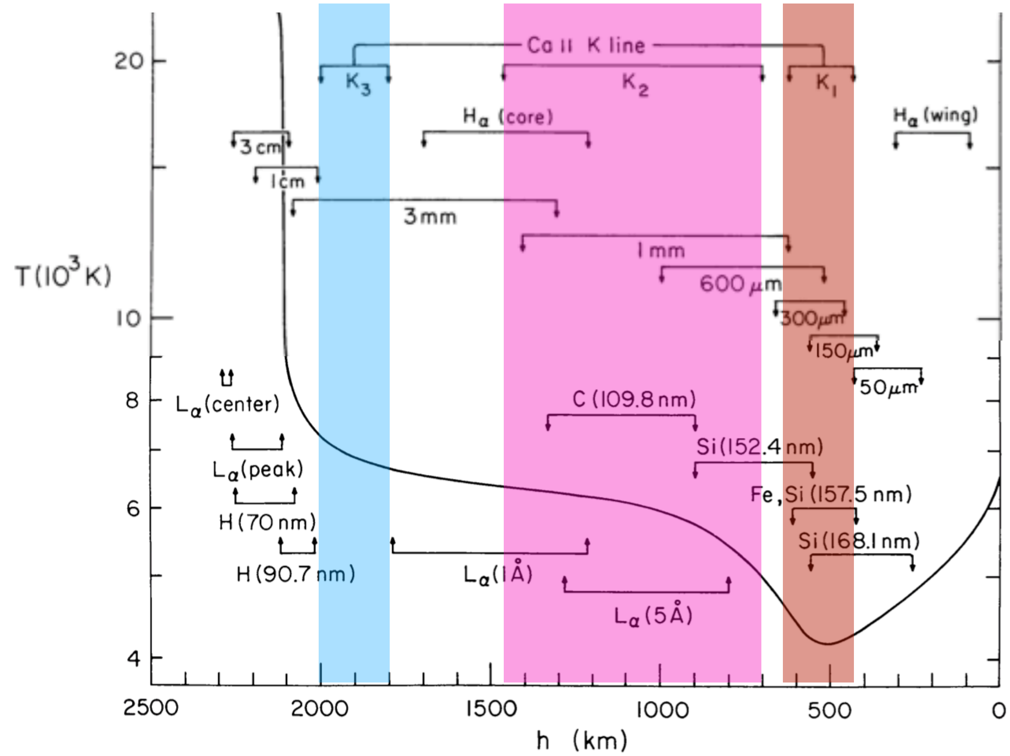
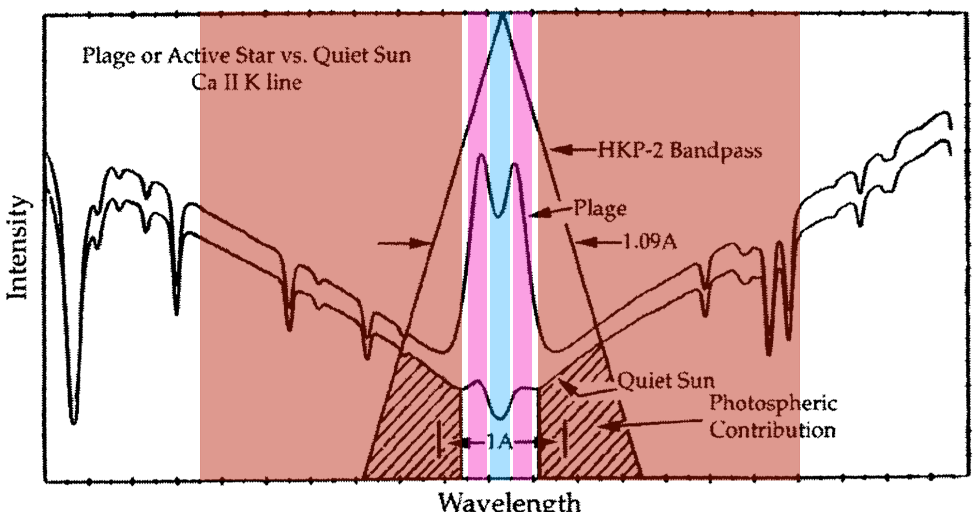
# Ca II (or Ca+) "HK"

- Interestingly, the dip can be offset from line center, due to motions of gas (Doppler shift) in the upper chromosphere

Bjørgen+2018




Duncan+1991, Baliunas+1998

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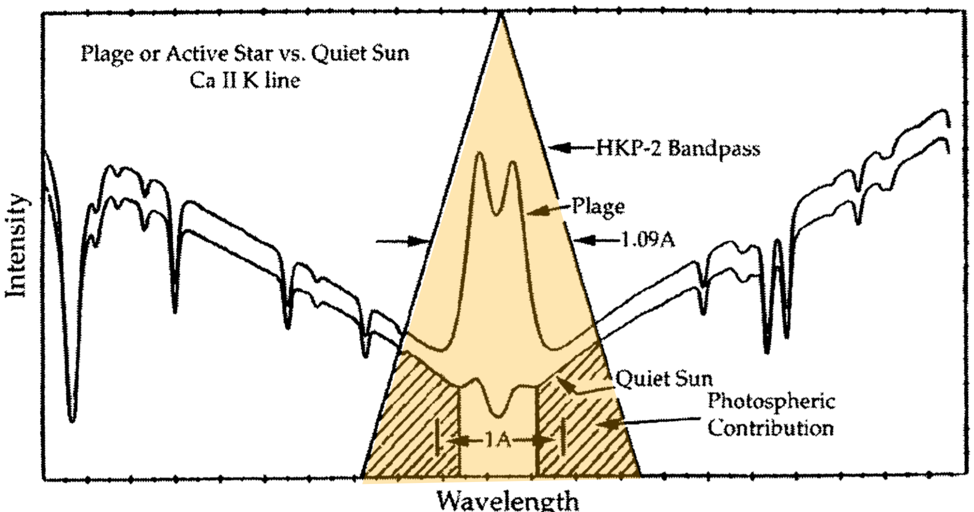
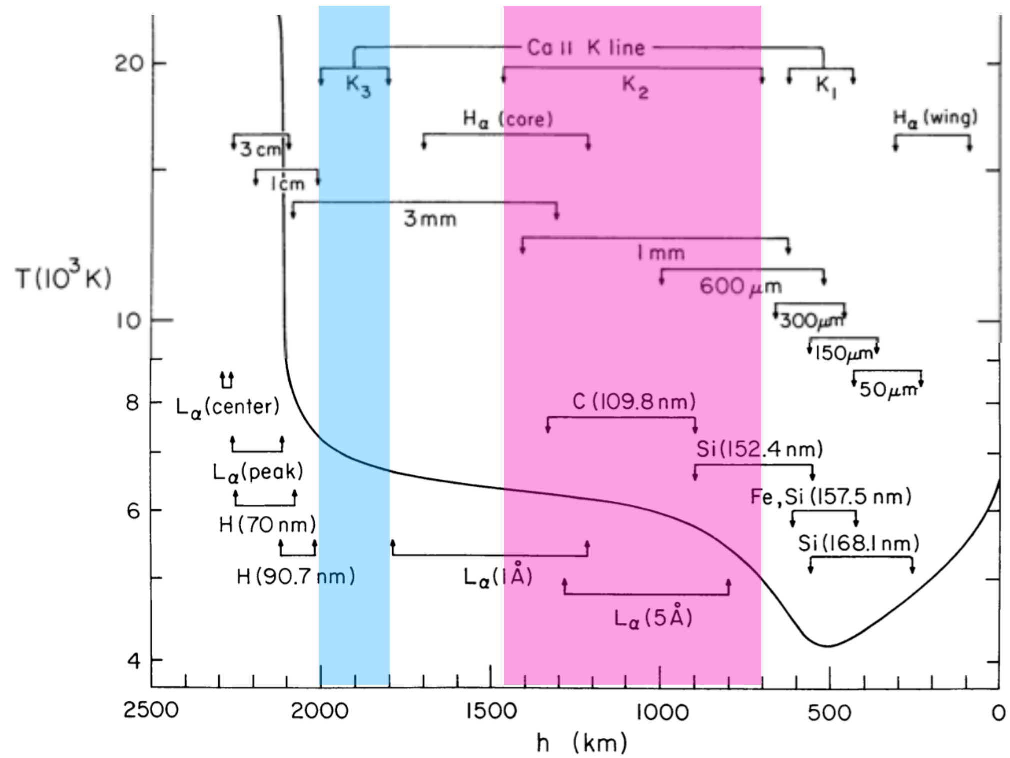
# Ca II (or Ca+) “HK”

- The core is the most “interesting” part historically
- Strongly dependent on **B** heating of the chromosphere!




Duncan+1991, Baliunas+1998

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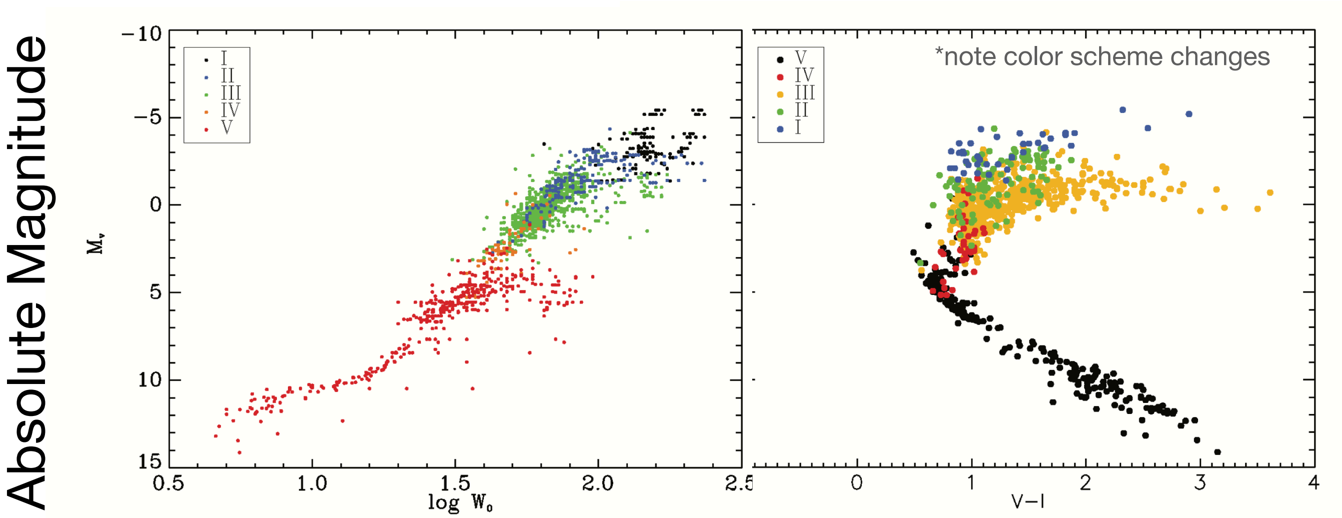
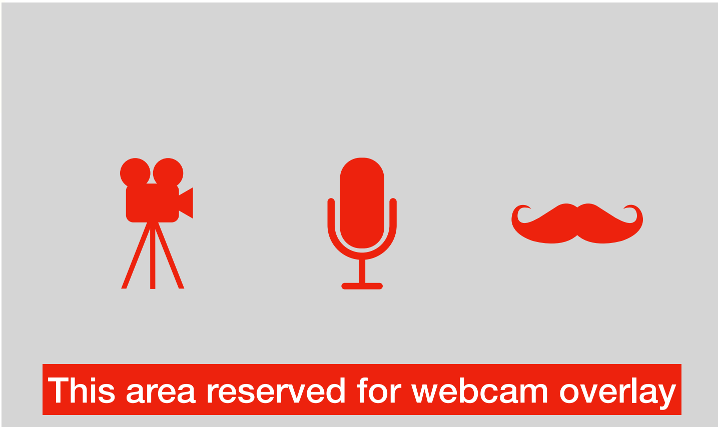
# Wilson-Bappu Effect

- Empirical connection between width of Ca II line core and a star's *luminosity*



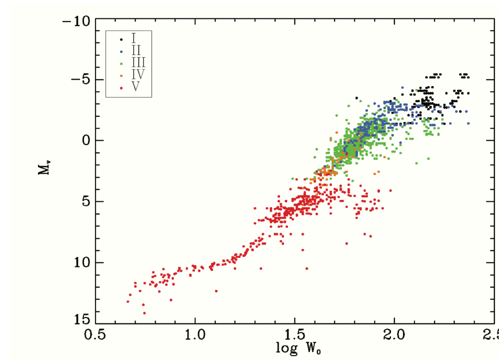

log(Width)



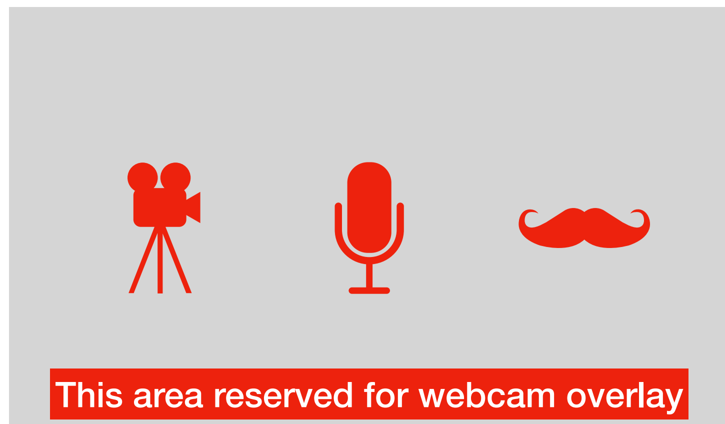

Gomez & Wallerstein (2011)

# Wilson-Bappu Effect

- Empirical connection between width of Ca II line core and a star's *luminosity*
- Since Ca II lines can be very broad, can be easier way to estimate luminosity (and thus distance) to a star…

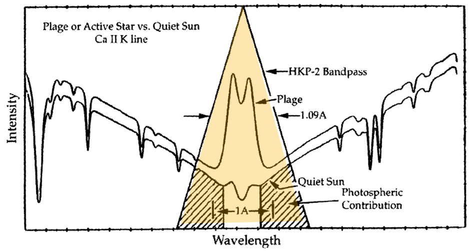



- Ca II line definition varies from author to author works best for dwarfs with chromospheres
- Sensitive to both gravity effects AND chromospheric activity…

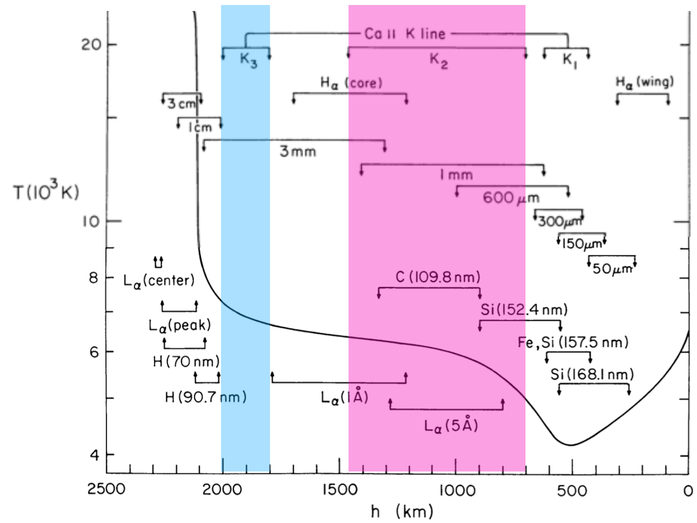



Gomez & Wallerstein (2011)

# Ca II HK




Duncan+1991, Baliunas+1998

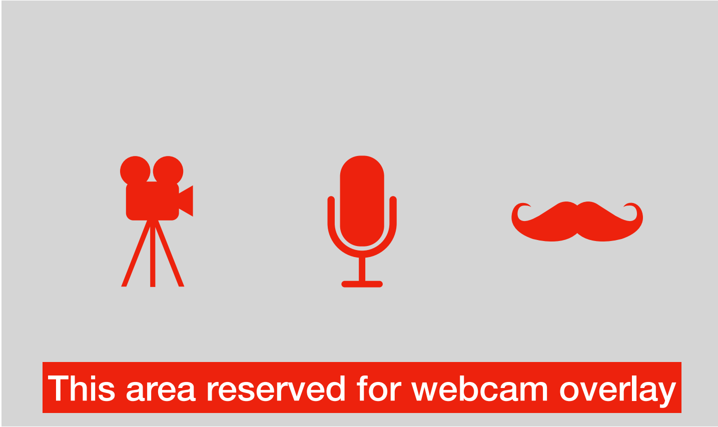



- Strongly dependent on **B** heating of the chromosphere!

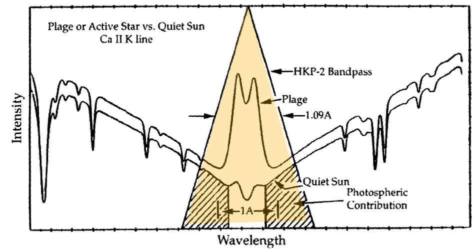
- This means chromospheric heating changes if the total **B** strength changes.

- Ca II HK (and $H\alpha$) the most widely used indicators of total surface **B** field
  e.g. see Hall (2008)

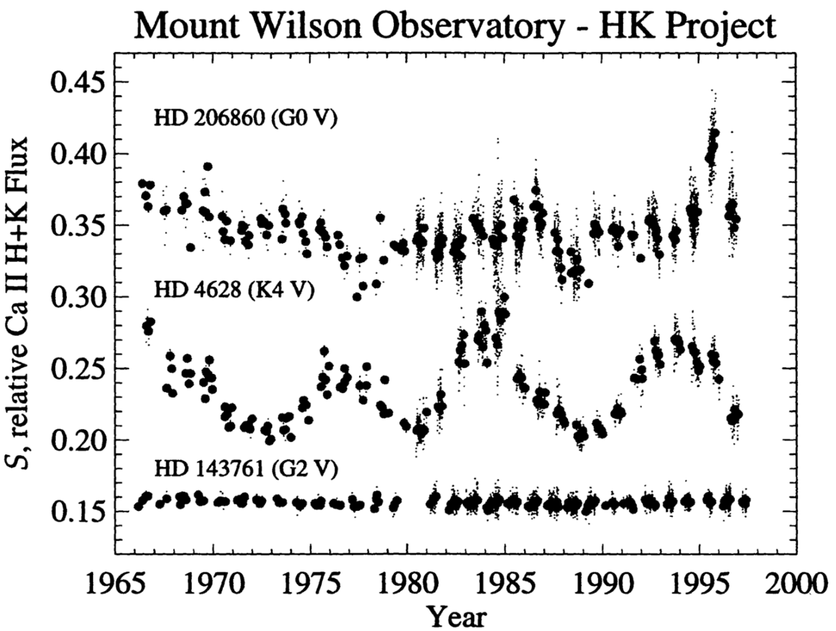
- **Activity cycles… a rich history!**



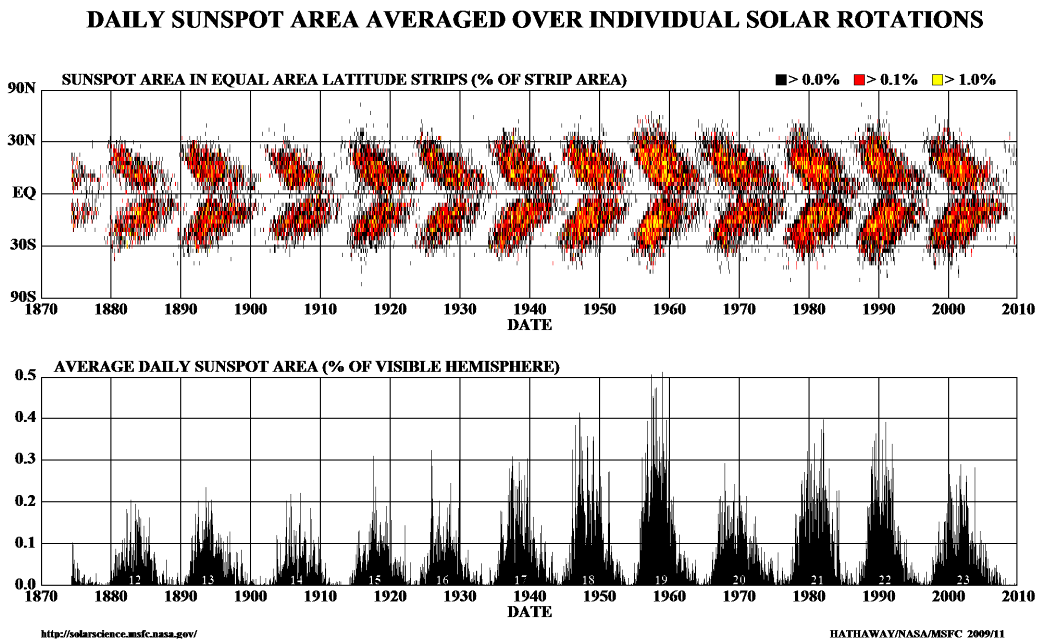
# Ca II HK

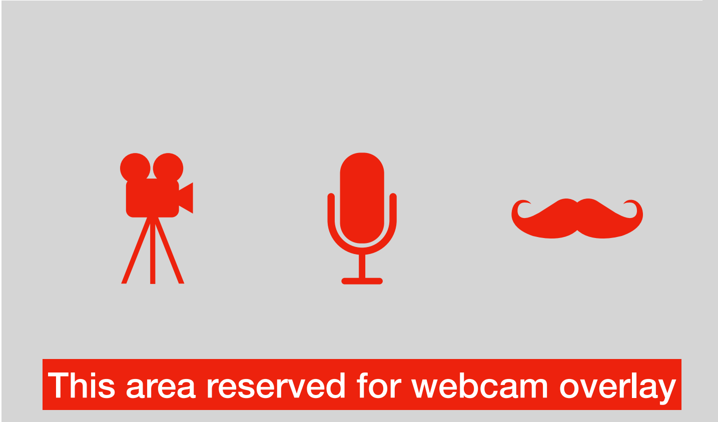



Duncan+1991, Baliunas+1998

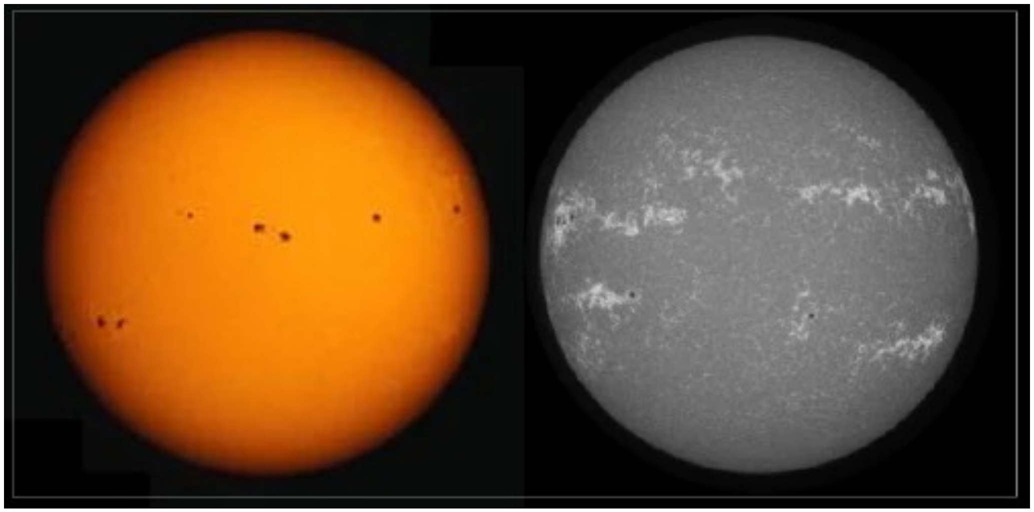



- Activity cycles… a rich history!



# Ca II HK



Visible light (broadband)

Ca II K filter

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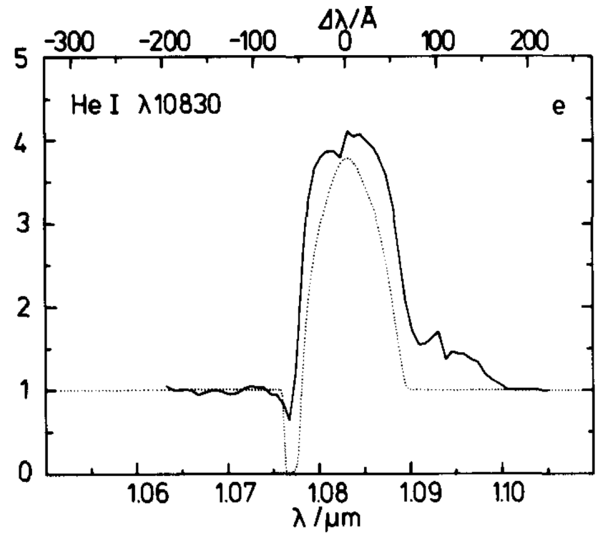
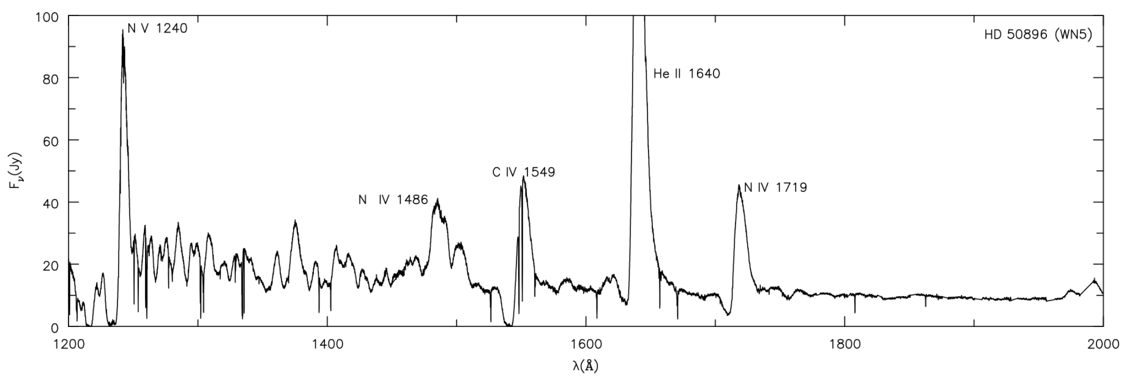
# Emission lines in Wolf Rayet stars?

- Line profiles are REALLY interesting
- Very broad, very Gaussian, but not totally symmetric…

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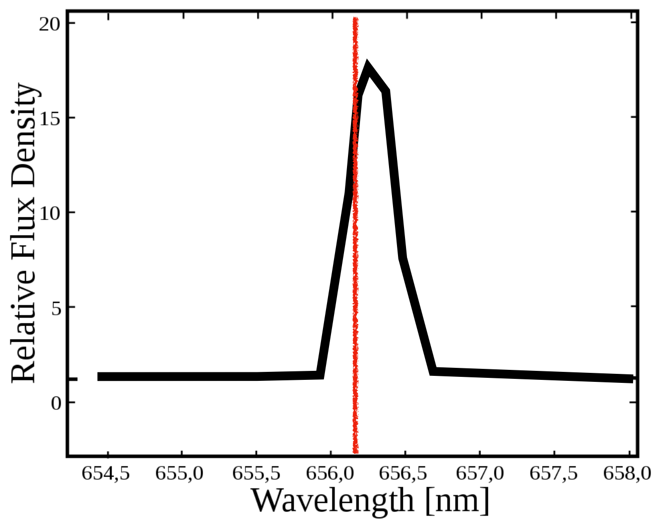
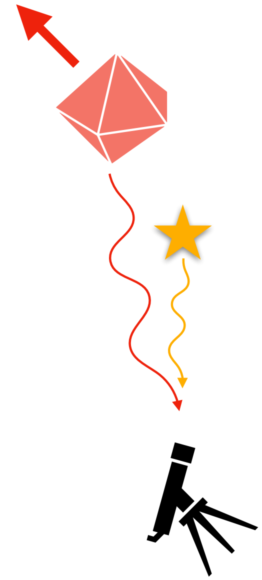
http://kookaburra.phyast.pitt.edu/hillier/publications/Wolf_Rayet_paper.pdf

# Emission lines from outflows

Red-shifted line: *motion away*



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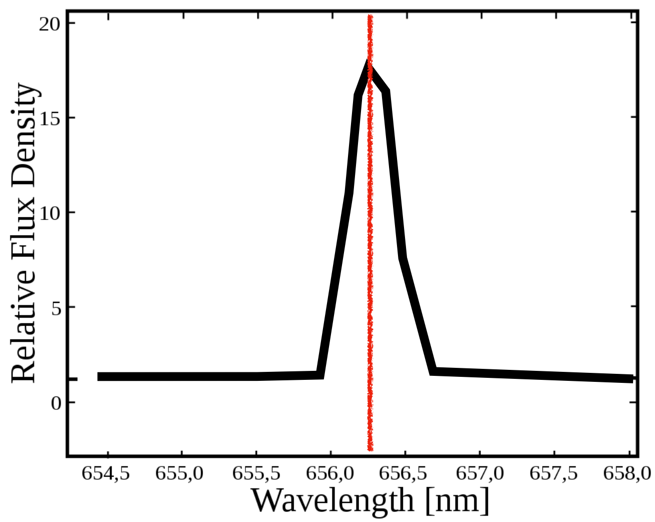
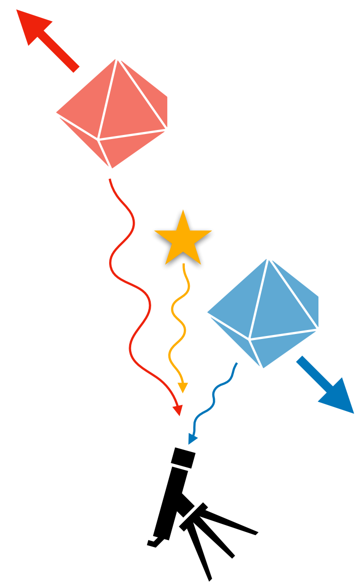
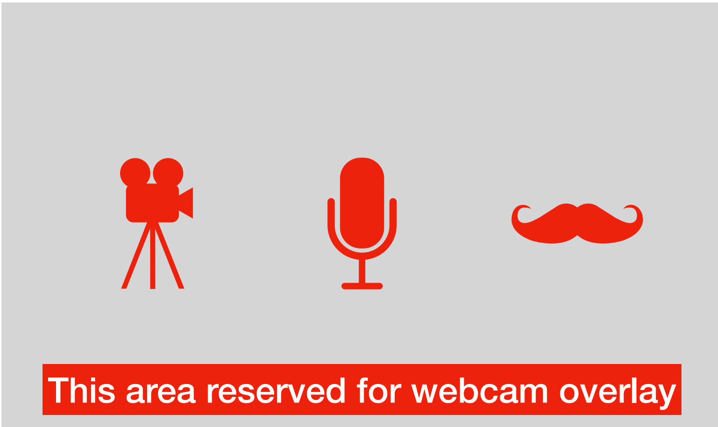
# Emission lines from outflows

Broadened line: *motion all directions*

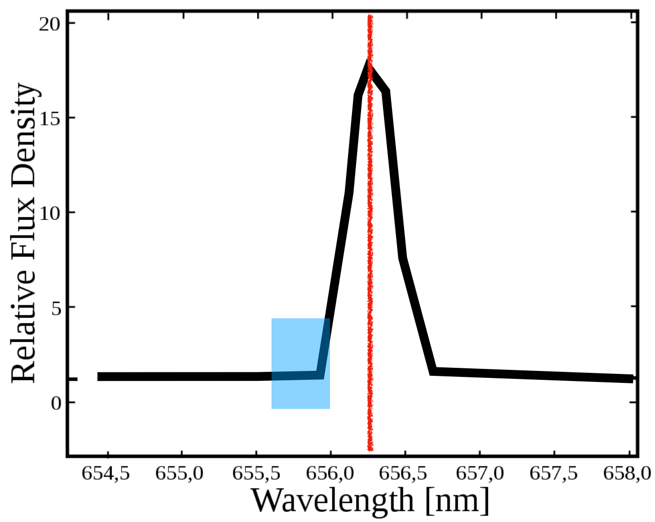


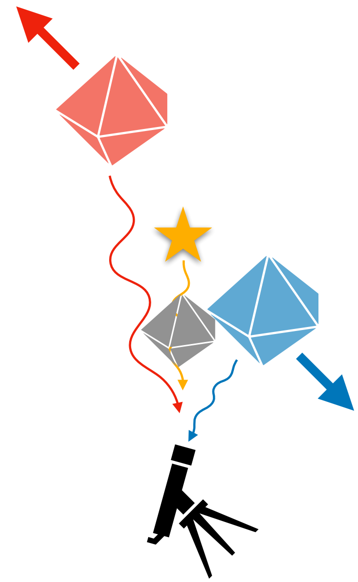



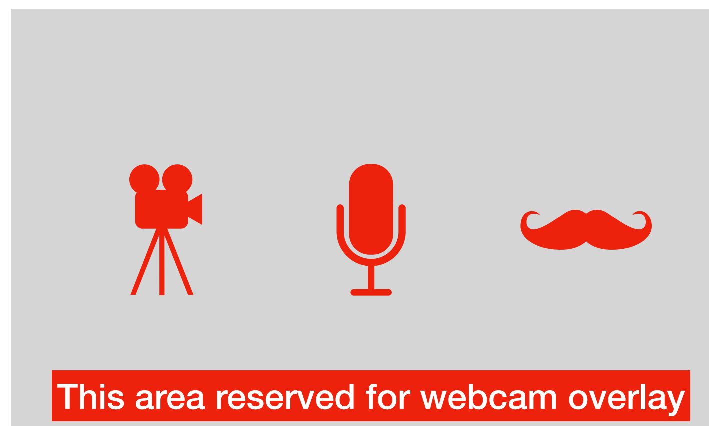


# Emission lines from outflows

What happens when some of the outflow gets in the *way* of the star?

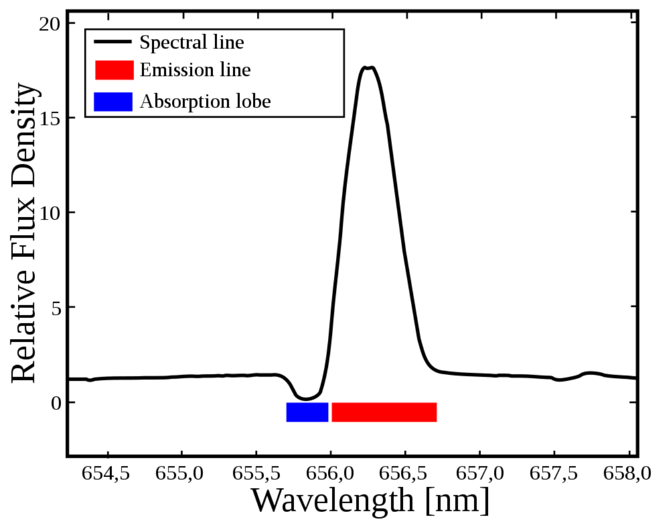


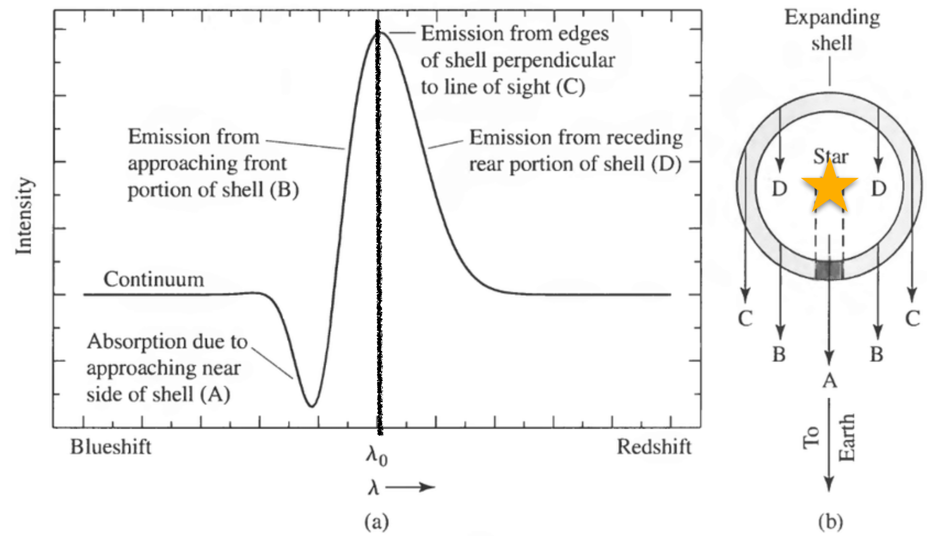





# Emission lines from outflows

**P Cygni line profile**:
expanding shell of material

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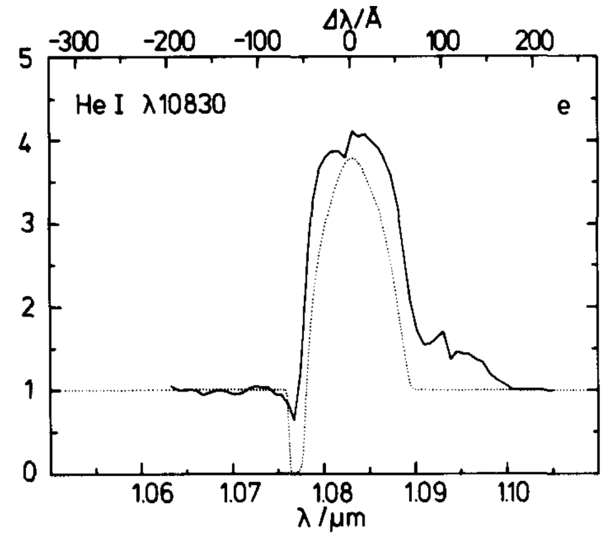
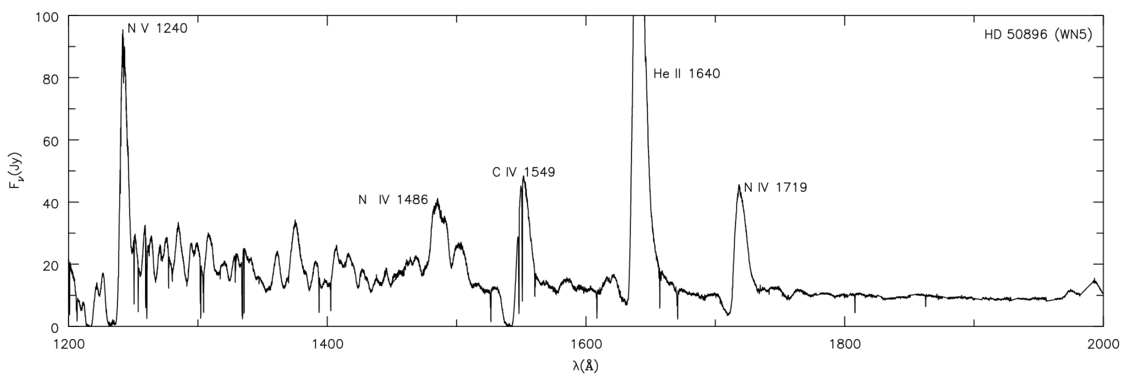
# Emission lines in Wolf Rayet stars?

- Line profiles are REALLY interesting
- Very broad, very Gaussian, but not totally symmetric…

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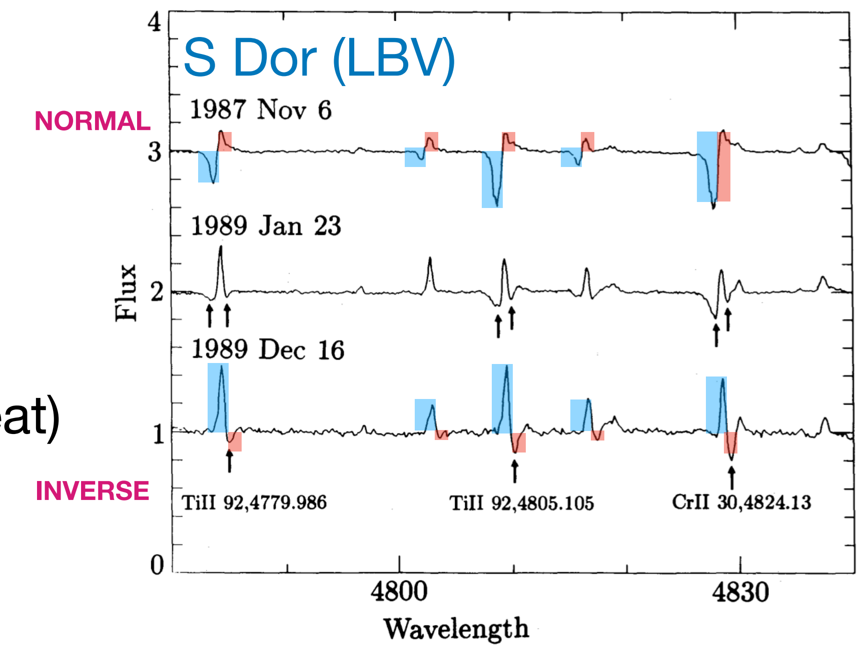
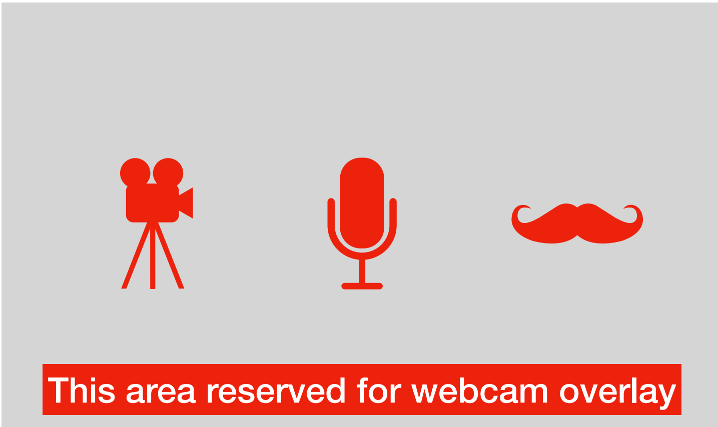
http://kookaburra.phyast.pitt.edu/hillier/publications/Wolf_Rayet_paper.pdf

# *Inverse* P Cygni Profiles

- If a P Cygni profile is a classical indicator of outflows… an *inverse* P Cygni = *infall*
- We DO see this… here's a really strange (neat) example of a star that shows **both**
- An indicator of *accretion!*

Wolf & Stahl (1990)

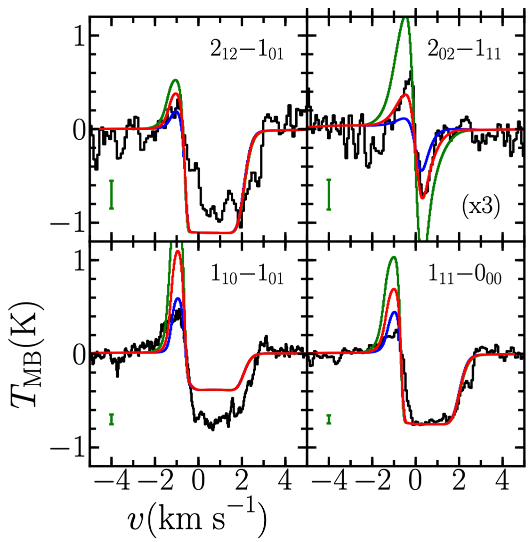


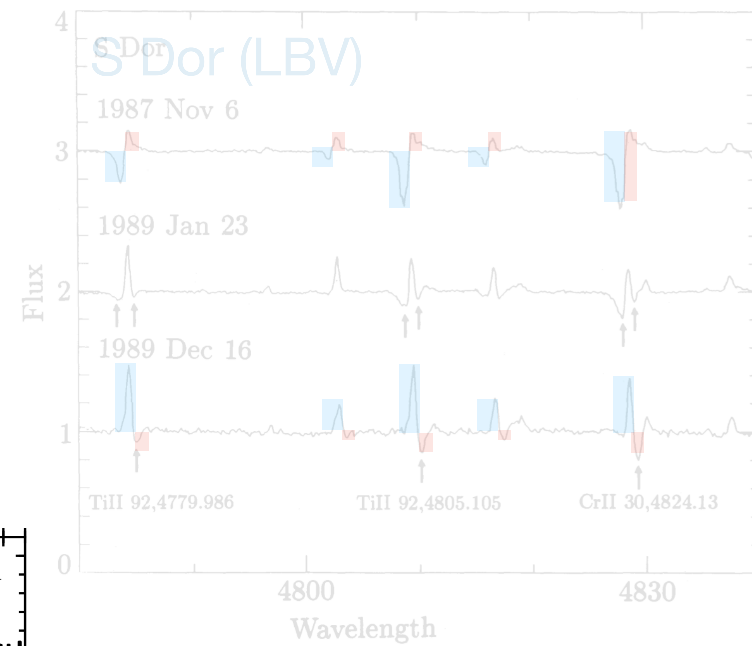
# *Inverse* P Cygni Profiles

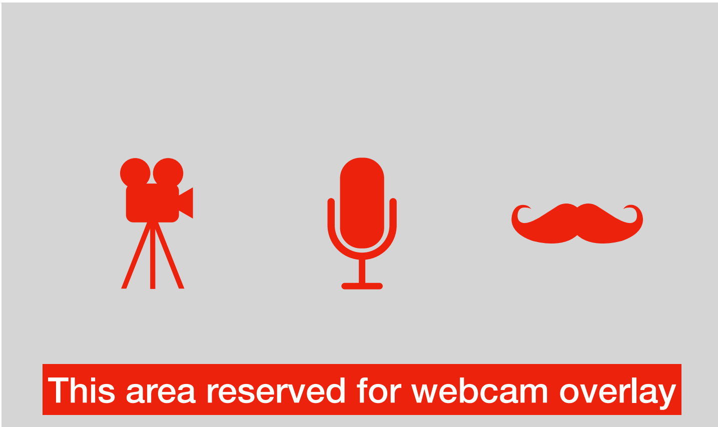
- If a P Cygni profile is a classical indicator of outflows… an *inverse* P Cygni = *infall*
- We DO see this… here's a really strange (neat) example of a star that shows **both**
- An indicator of *accretion!*
    - Example of $H_2O$ lines around protostars
    - "*Waterfalls around Protostars*", amazing paper title….

Mottram+2013




Wolf & Stahl (1990)



# Next time…

- Extracting stellar parameters from spectral lines

- Also point to a really good, short (<20 min) primer on line broadening by Aaron Parsons (Berkeley): https://www.youtube.com/watch?v=wzhnF66ZomE

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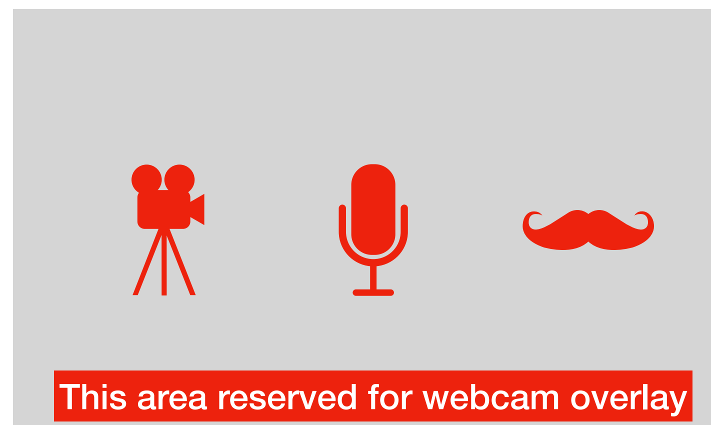
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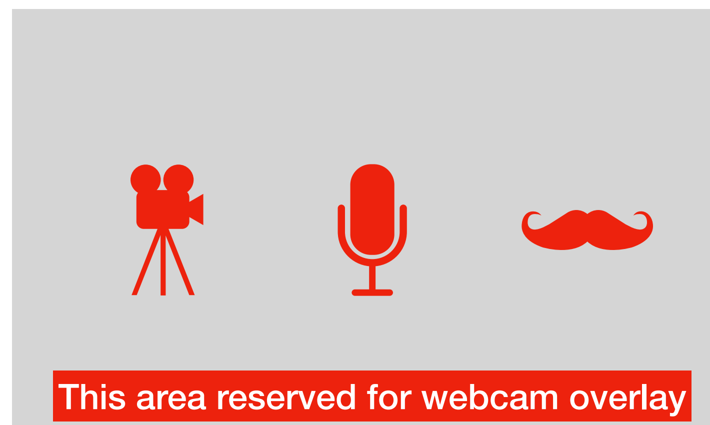
# ASTR 421

## Stellar Observations and Theory

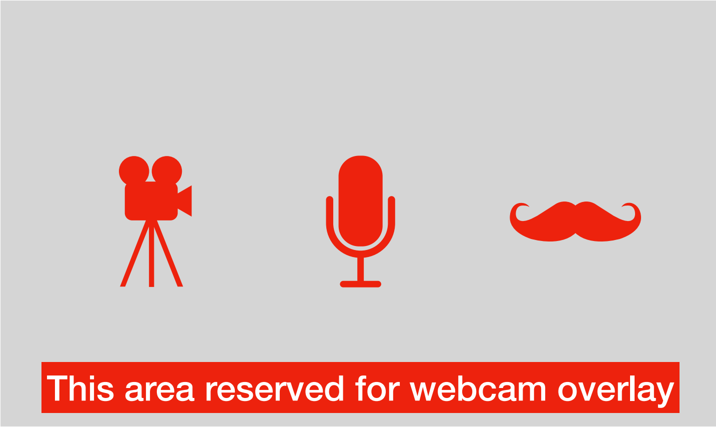
# Lecture 10
# Line Profiles: III

Prof. James Davenport (UW)



# Today

- Actual measurements of lines (FWHM, EW)
- How we get “stellar parameters” out of spectra



# Things that lines can teach us

## Line analysis

- Stellar atmospheres are parameterized by:
  - Effective temperature
  - Gravity
  - Metallicity
  - Macro/microturbulence
- The depth & shape of absorption lines depend on all of these:
  - Equivalent width ratios of the same species depend upon temperature & density
  - Pressure broadening depends upon density and temperature
  - Doppler broadening depends on temperature and turbulence
  - Line ratios between species depend upon metallicity & temperature
- We would like to go from spectral properties to stellar properties



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# Inverse problem

- But, the connection is complicated: requires 3D magneto-hydrodynamic simulations with radiation transfer!
- How do we go from stellar spectra to stellar properties?
- Challenges:
    - Difficult to include all lines
    - Many free parameters to adjust
    - 3D models are expensive
- Semi-empirical approach:
    - Parameterize the 1-D temperature profile
    - Fit for each absorption line separately
    - Using LTE & assumed abundances: solve for line profiles & limb-darkening (if available).
    - Infer the temperature, surface gravity, metallicity & turbulence.



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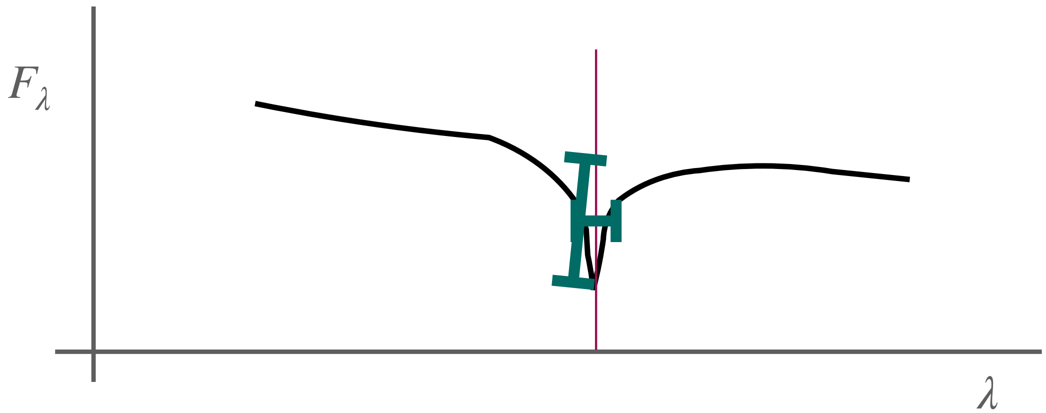
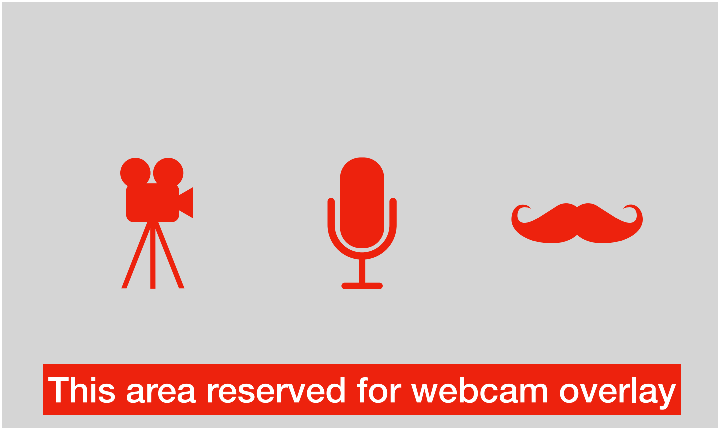
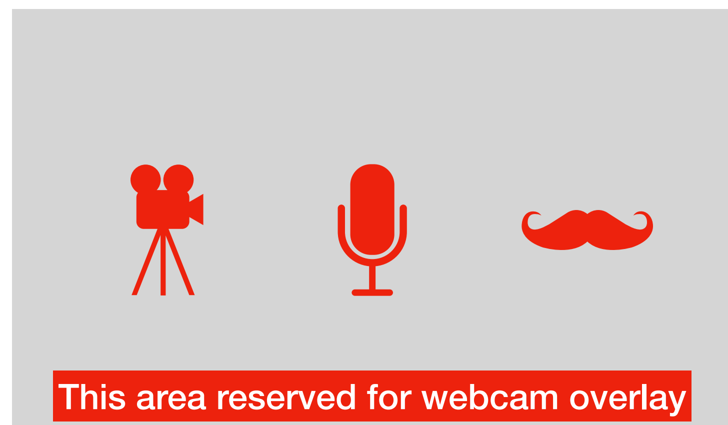
# Where do lines form?

- First, some terminology:
  - Spectrum $\equiv (\tau = 2/3)$
  - Continuum (blackbody)
  - Wings (both sides)
  - Core (center)
  - $\lambda_{lab}$ (note: vac or air wavelengths)
  - **FWHM**

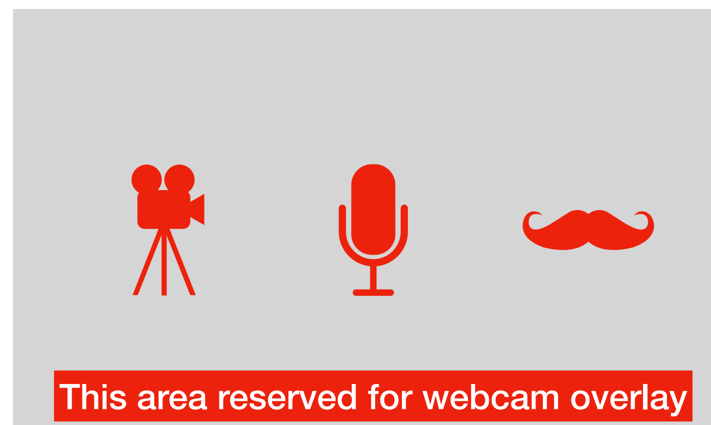


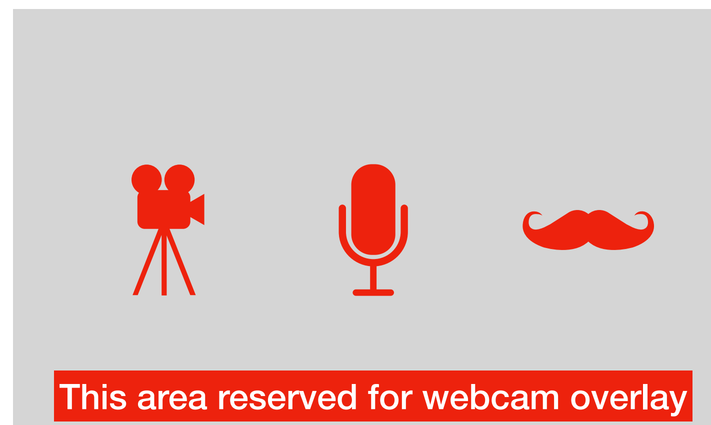
# Equiv width



# Curve of growth



# Estimating abundances?



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