ASTR 421

Stellar Observations and Theory

Lecture 09
Line Profiles: II

Prof. James Davenport (UW)

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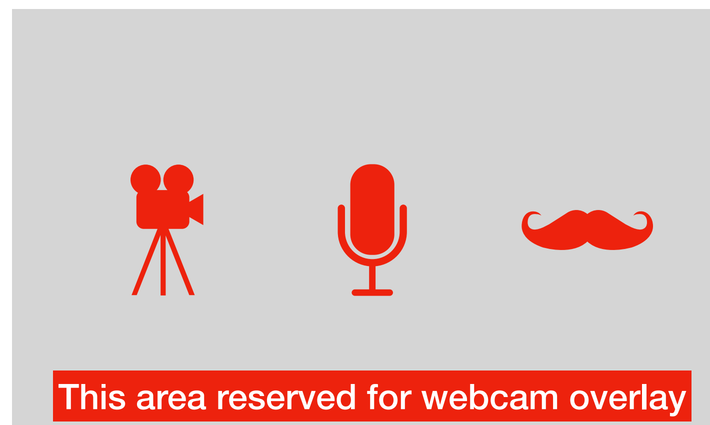
Today

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



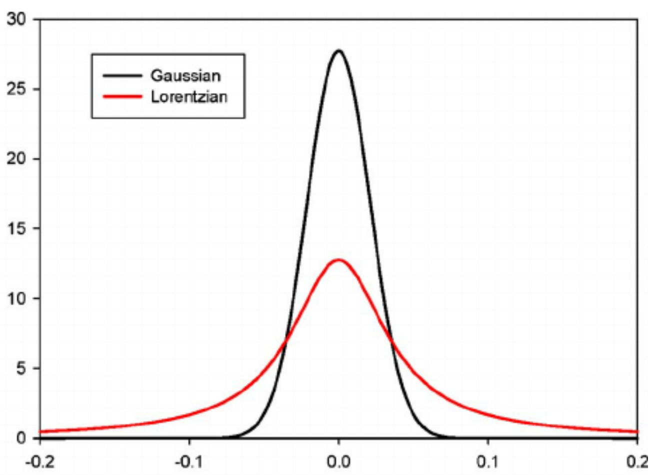
Overview of Line Broadening

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

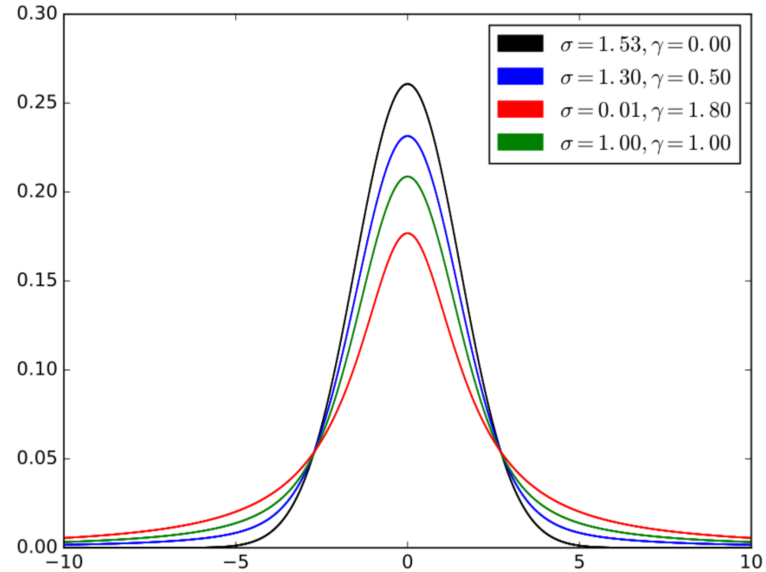
Lorentzian profile

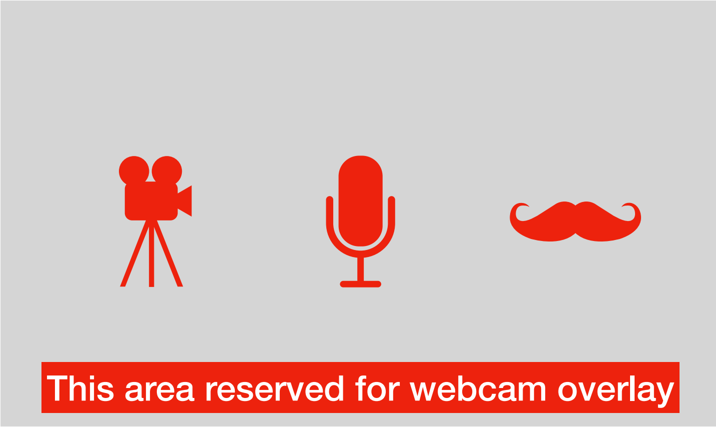


The Voigt Profile

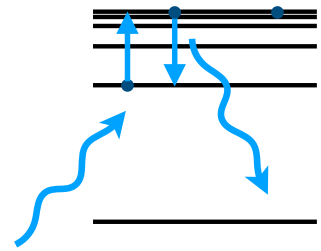
- A *convolution* of Gaussian & Lorentzian profiles
- This the classic line profile equation we use in most cases
  - Core: mostly Gaussian shape
  - Wings: mostly Lorentz shape
- **Useful for constraining physics behind both thermal & pressure broadening in a line!**

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

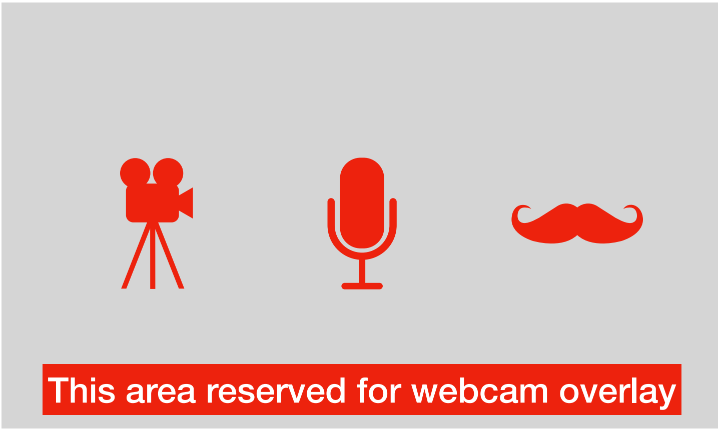




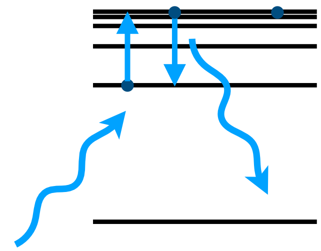
Natural broadening



- 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:
  $FWHM = \frac{\lambda^2}{\pi c \Delta t}$ (eqn 9.61)
- Example for $H\alpha$: FWHM $\sim 2 \times 10^{-5}$nm (!)
  - **TYPICALLY VERY SMALL**

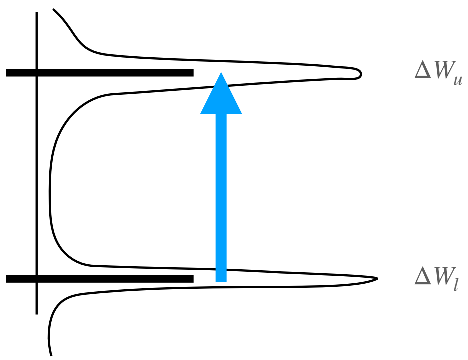


Natural broadening

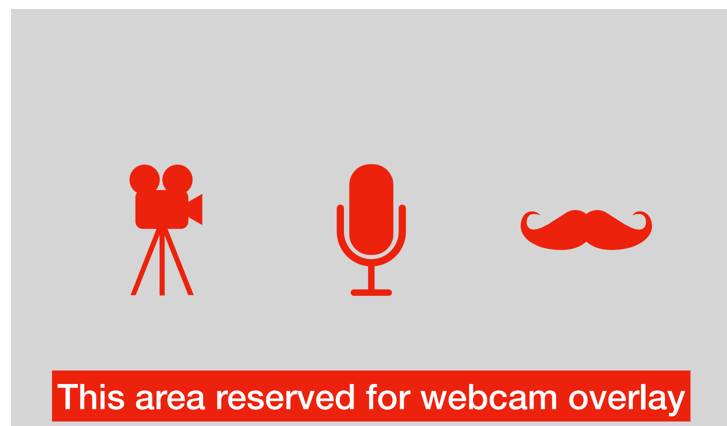


- Arises due to Heisenberg uncertainty principle
  $\Delta E \, \Delta t \approx \hbar$

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

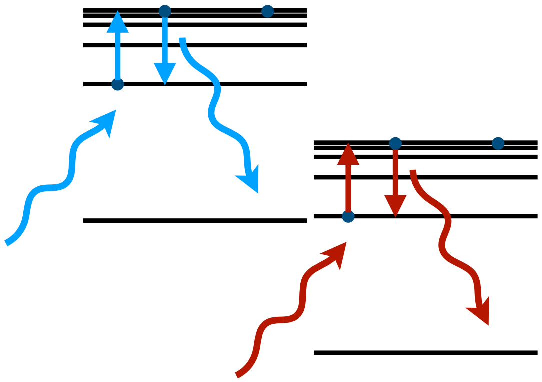


Gray, Fig 11.1



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**



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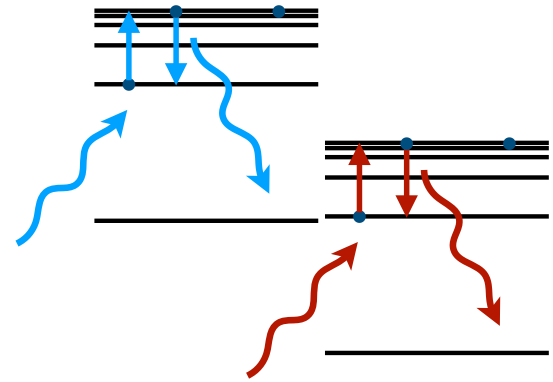
Thermal (Doppler) broadening

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

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

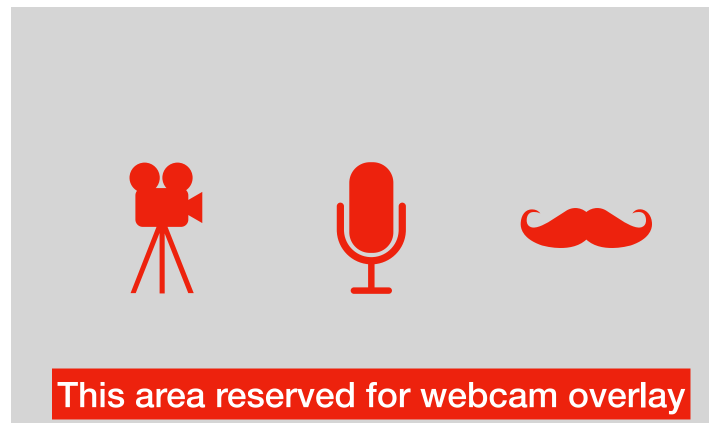


- A handy reminder for Doppler shift: $\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$

  (in non-relativistic limit)

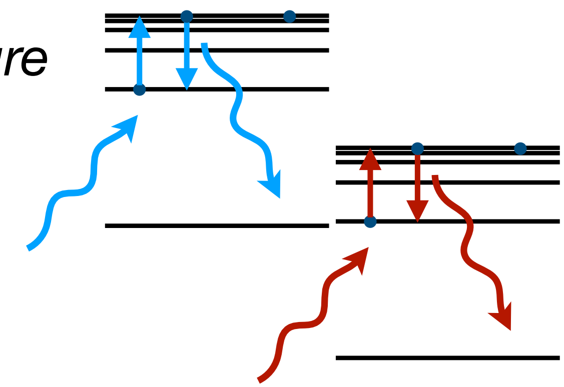
- This yields good approximation of:

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

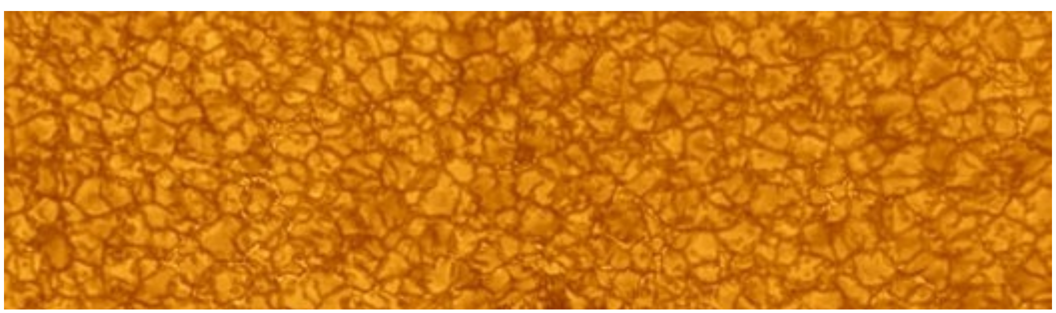


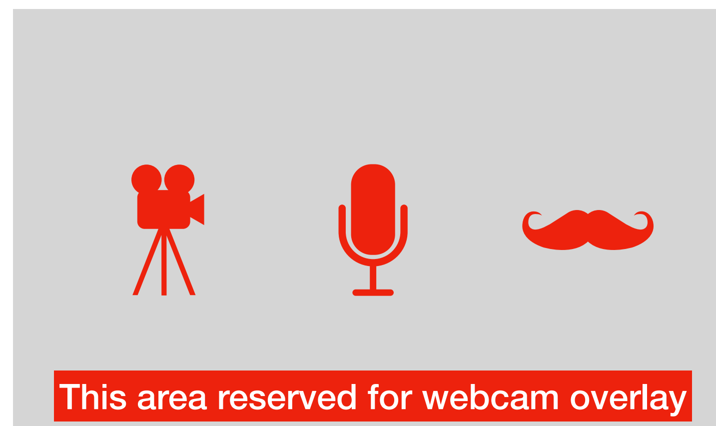
Thermal (Doppler) broadening

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



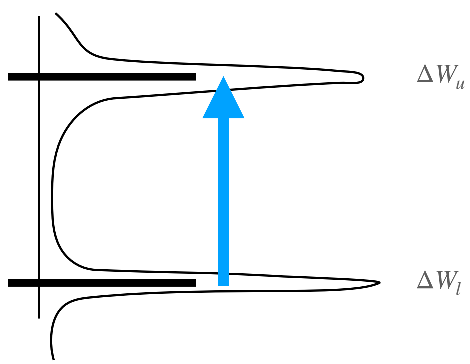
- For $H\alpha$ on (above?) the Sun, we expect just the *temperature* to cause $\Delta\lambda \approx 0.04$nm
  - MUCH LARGER than Natural Broadening…
- Other velocity motions can cause Doppler broadening i.e. not explicitly *thermal* behavior
- e.g. microturbulence, especially due to convective motions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

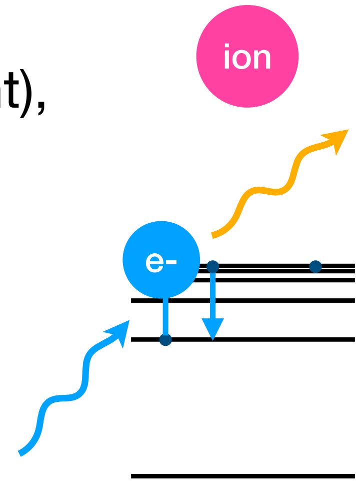


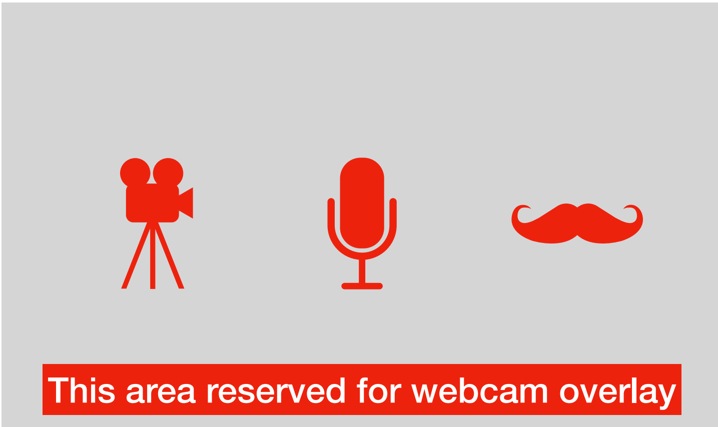


Pressure broadening

- 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



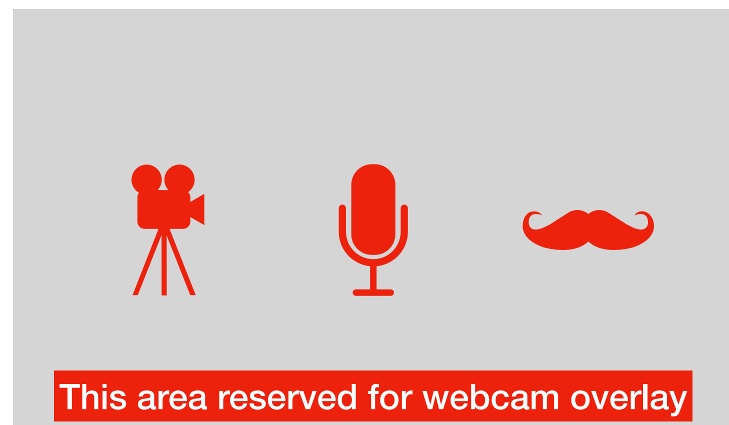




Pressure broadening

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

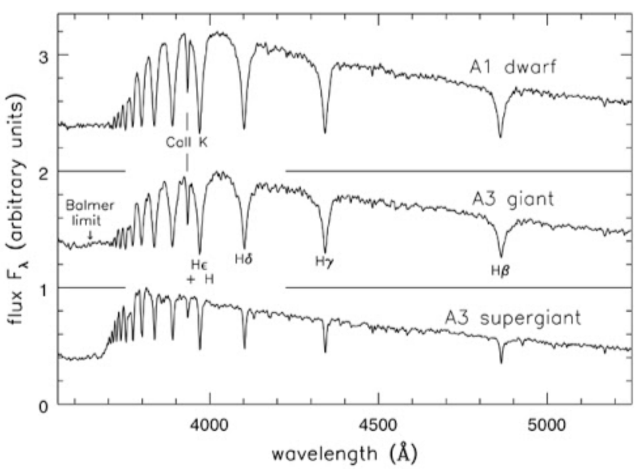
$$\Delta\lambda \approx \frac{\lambda^2\, n\sigma}{\pi c}\sqrt{\frac{2kT}{m}}$$

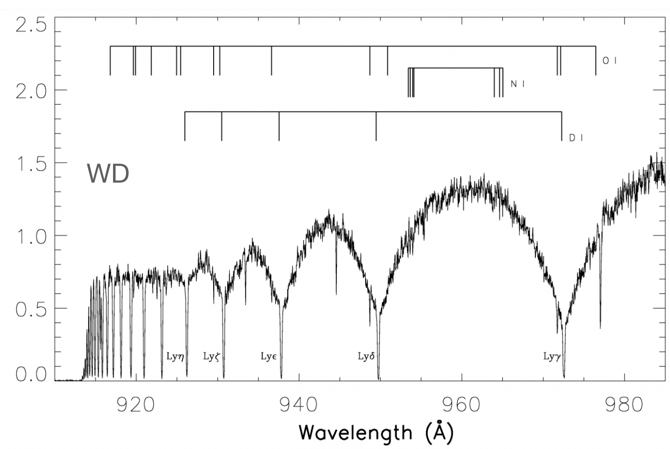


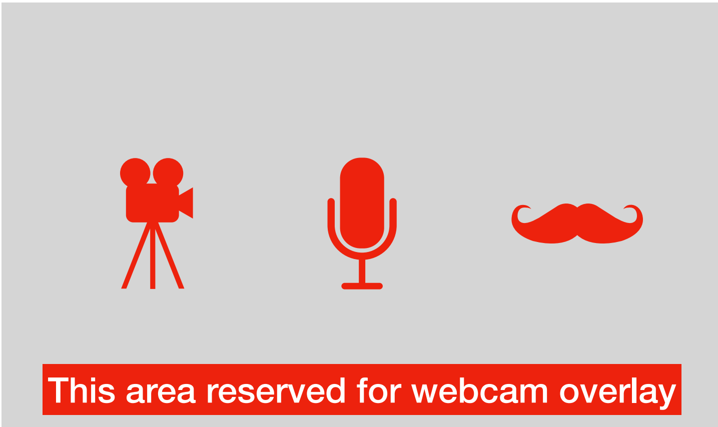
Pressure broadening

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

- 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!







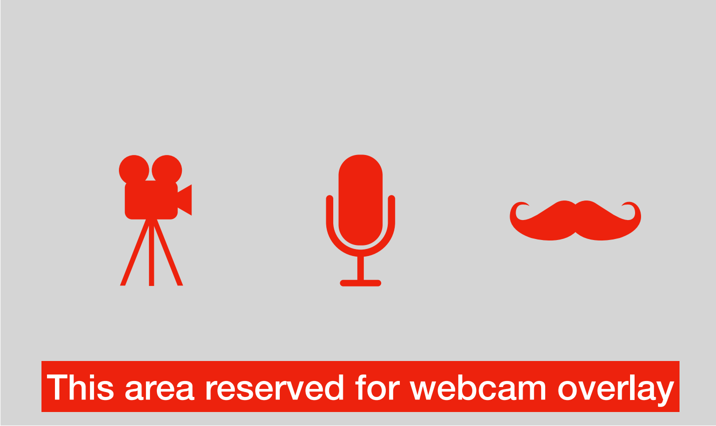
Pressure broadening

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

STARK EFFECT

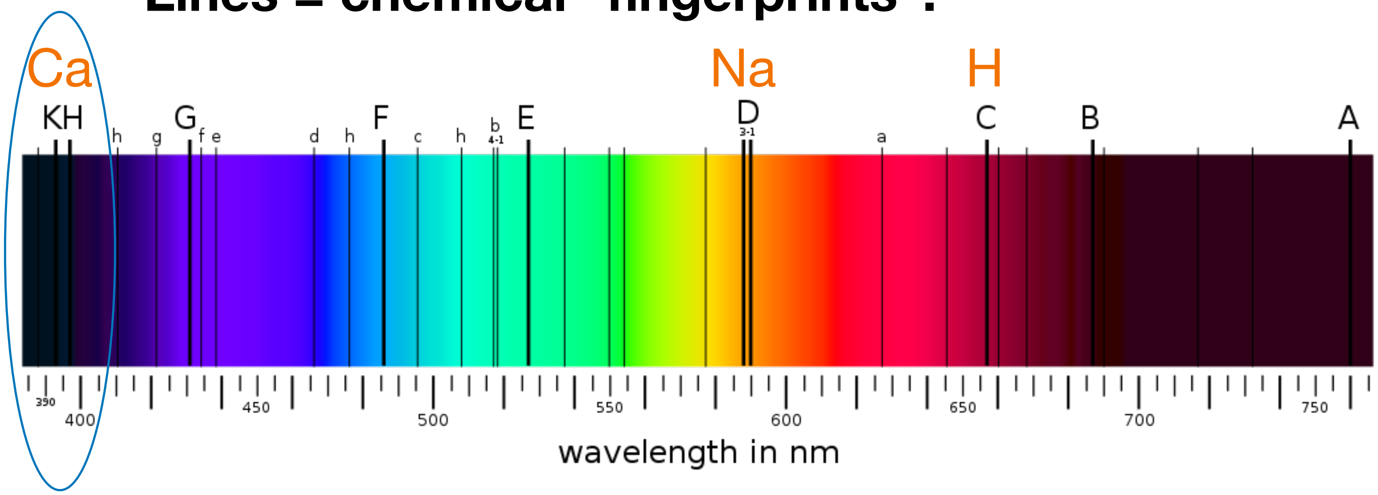
- Various physics creating these collisions:
  - **Linear Stark Effect** (mostly for H lines, impacting Protons & e-)
  - **Quadratic Stark** (most lines in hot stars, impacting ions & e-)
  - **van der Waals** (most lines in cool stars, impacting neutral H)

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

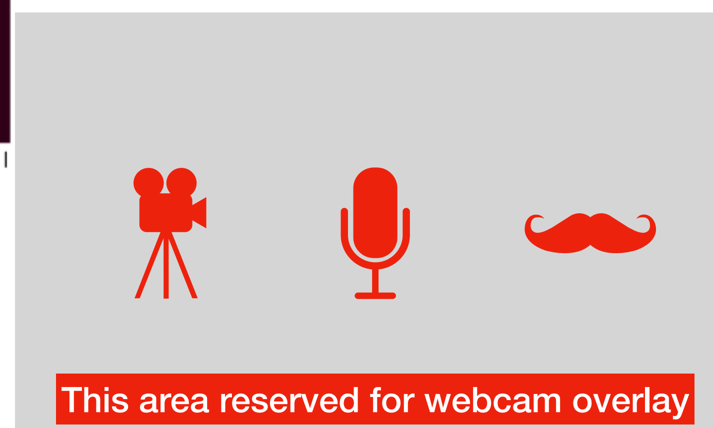


Fraunhofer lines

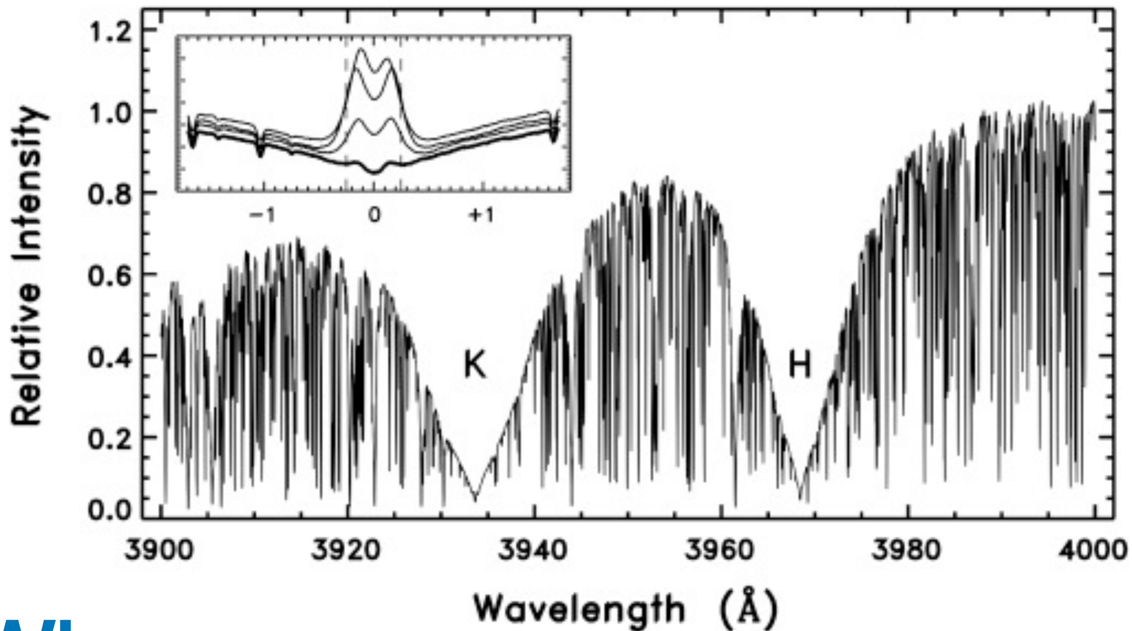
- Cataloged in solar spectrum by Fraunhofer in 1814
- Seen in many other stars
- Kirchhoff & Bunsen noticed these == emission line from burning! (1859)
  Lines = chemical “fingerprints”!



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



Ca II (or Ca+) “HK”



Whoa…

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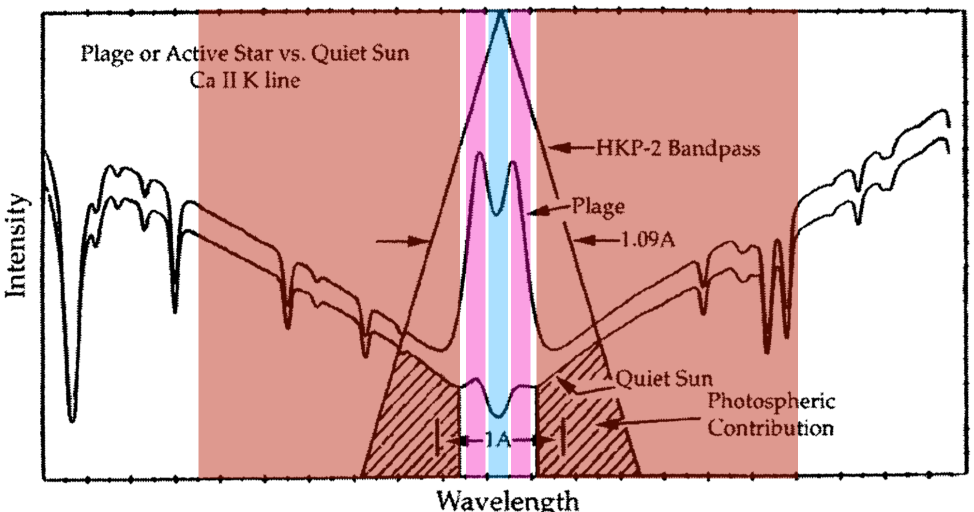
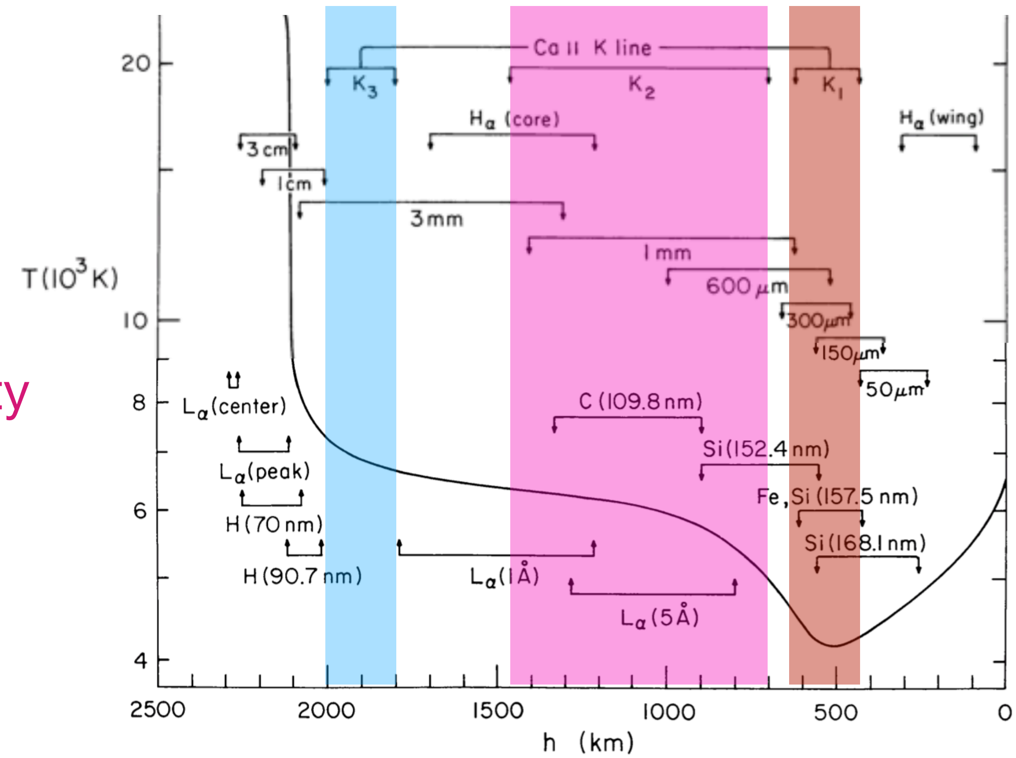
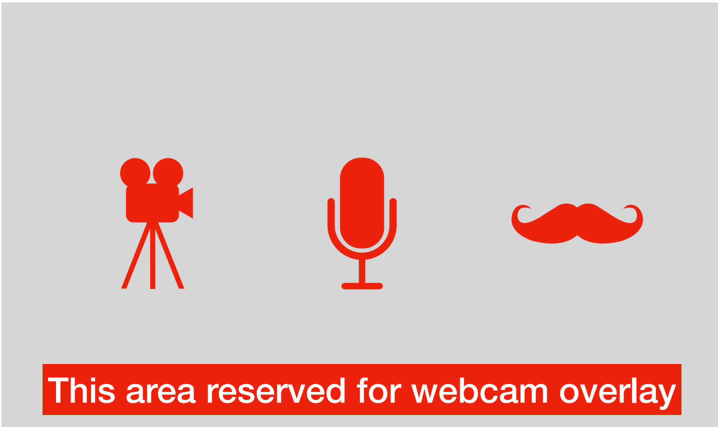
Ca II (or Ca+) "HK"

Important tracer of chromospheric **B** activity



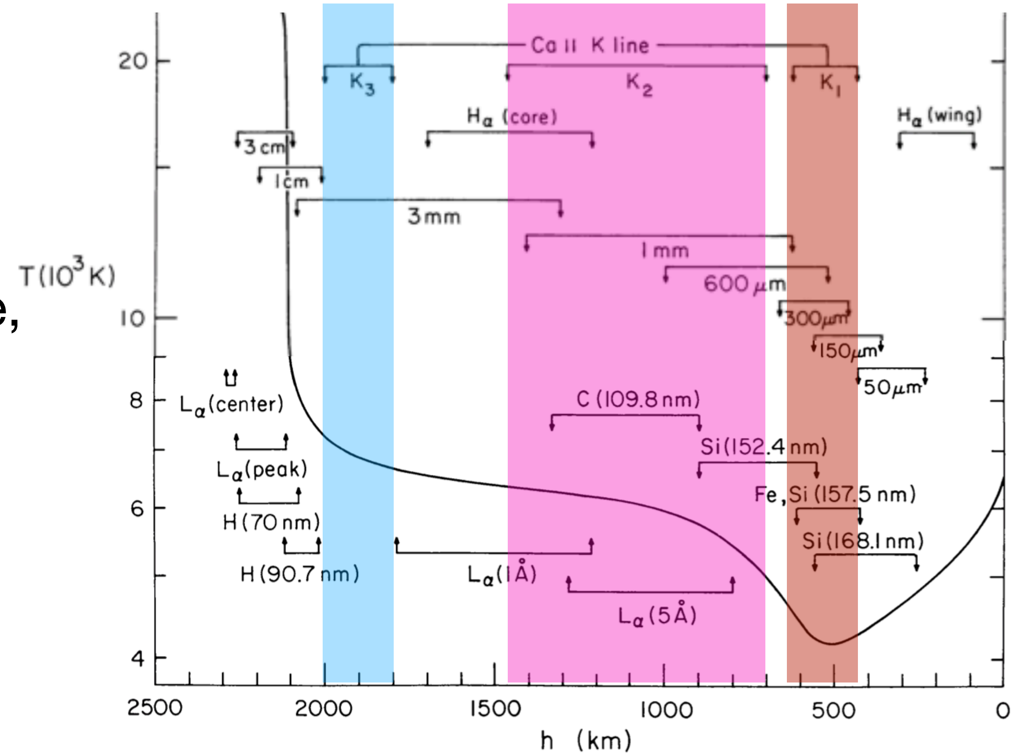
Duncan+1991, Baliunas+1998

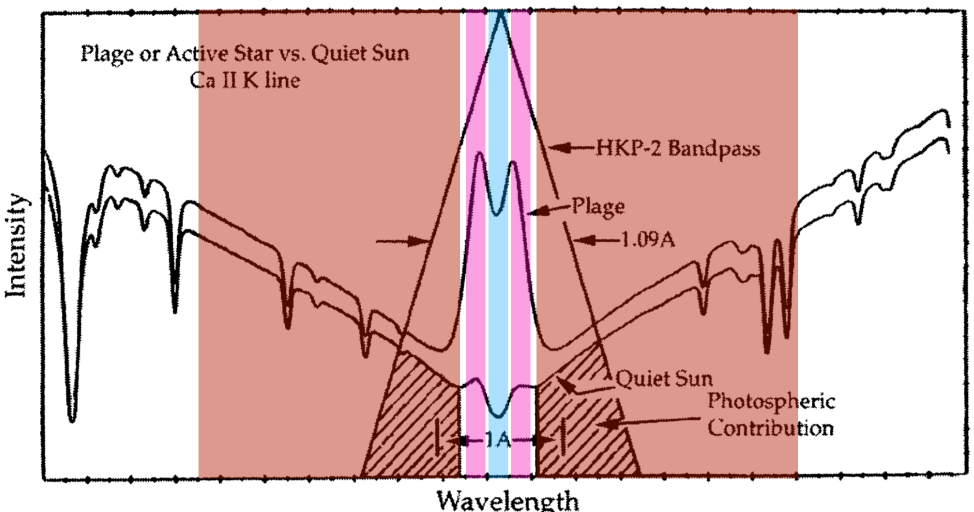




Ca II (or Ca+) “HK”

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





Duncan+1991, Baliunas+1998

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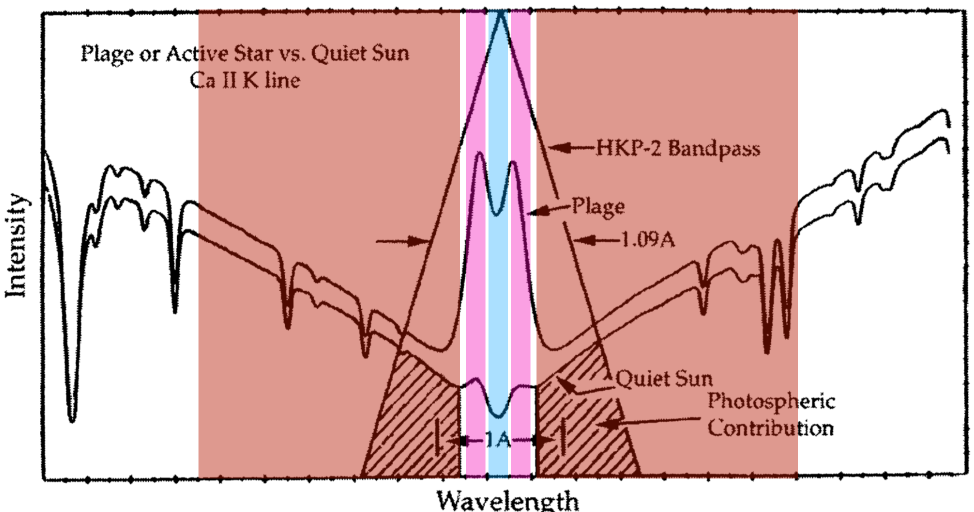
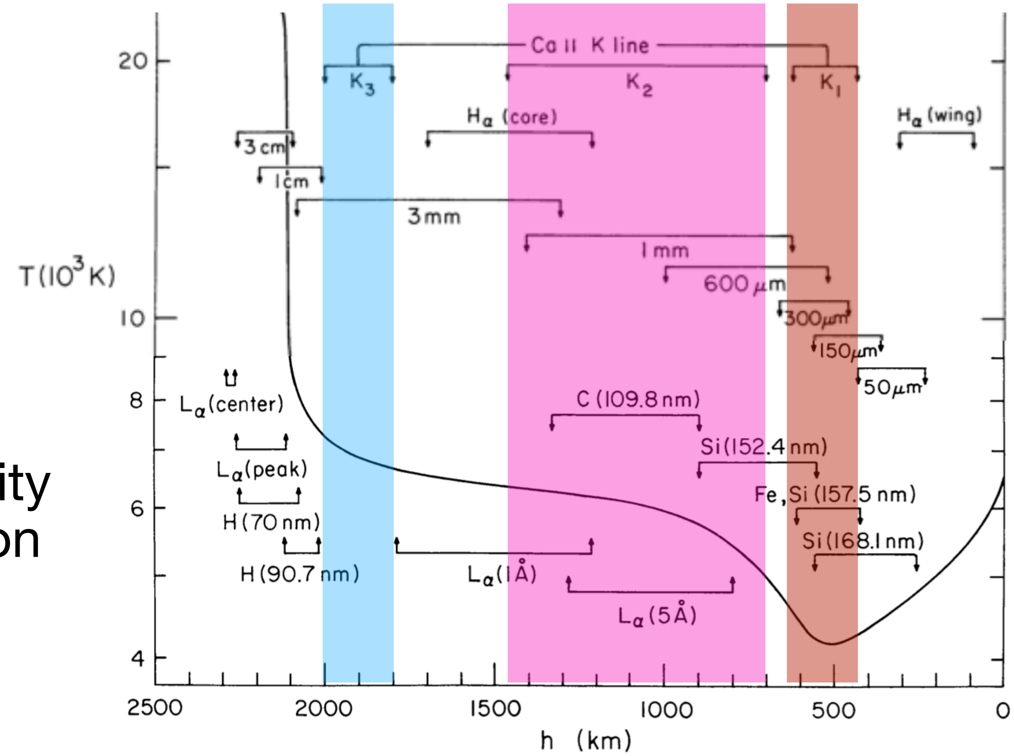
Ca II (or Ca+) "HK"

- 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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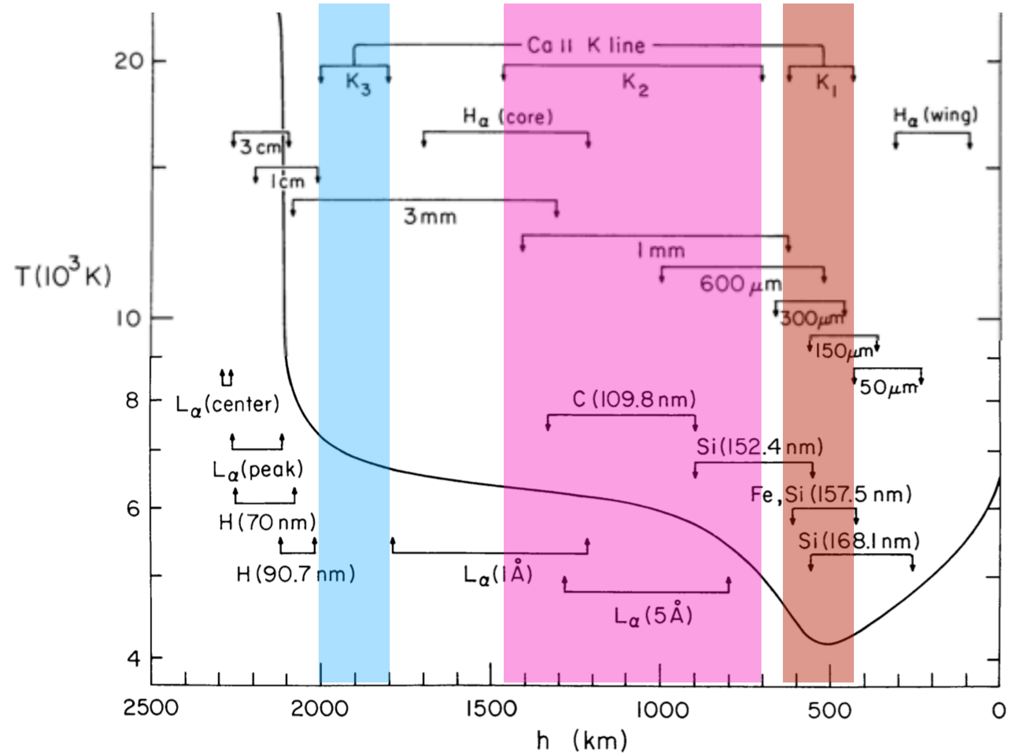
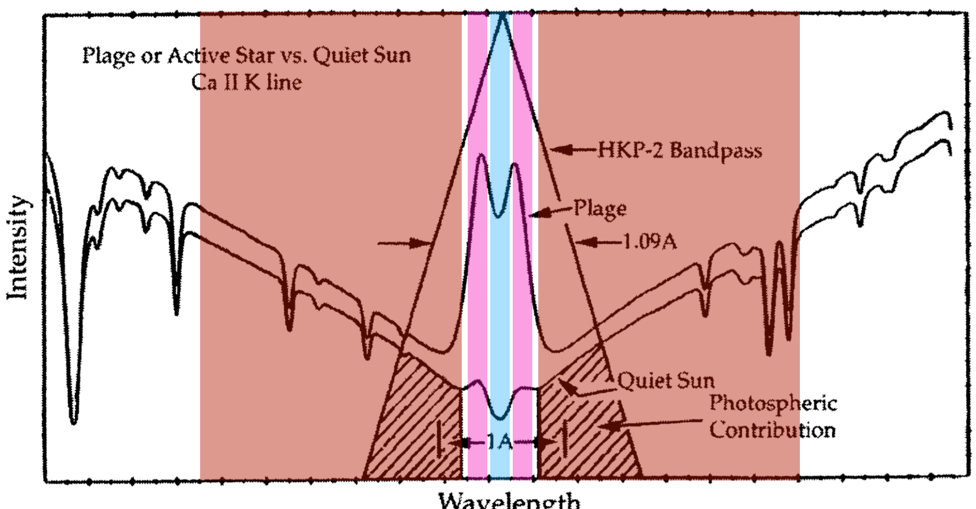
Ca II (or Ca+) "HK"

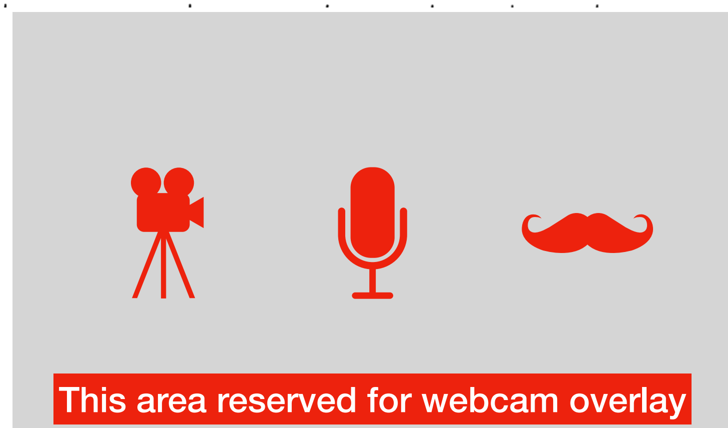
- Interestingly, the dip can be offset from line center, due to motions of gas (Doppler shift) in the upper chromosphere

Bjørgen+2018



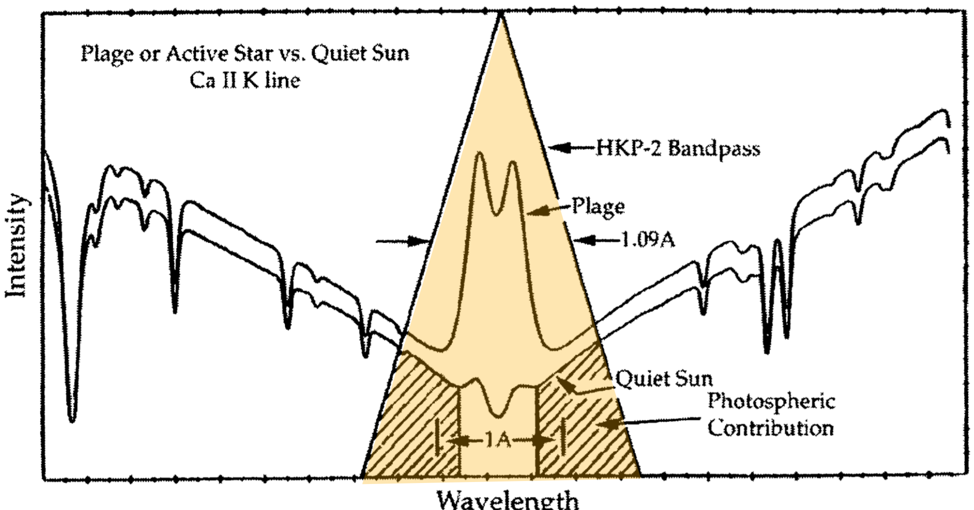


Duncan+1991, Baliunas+1998

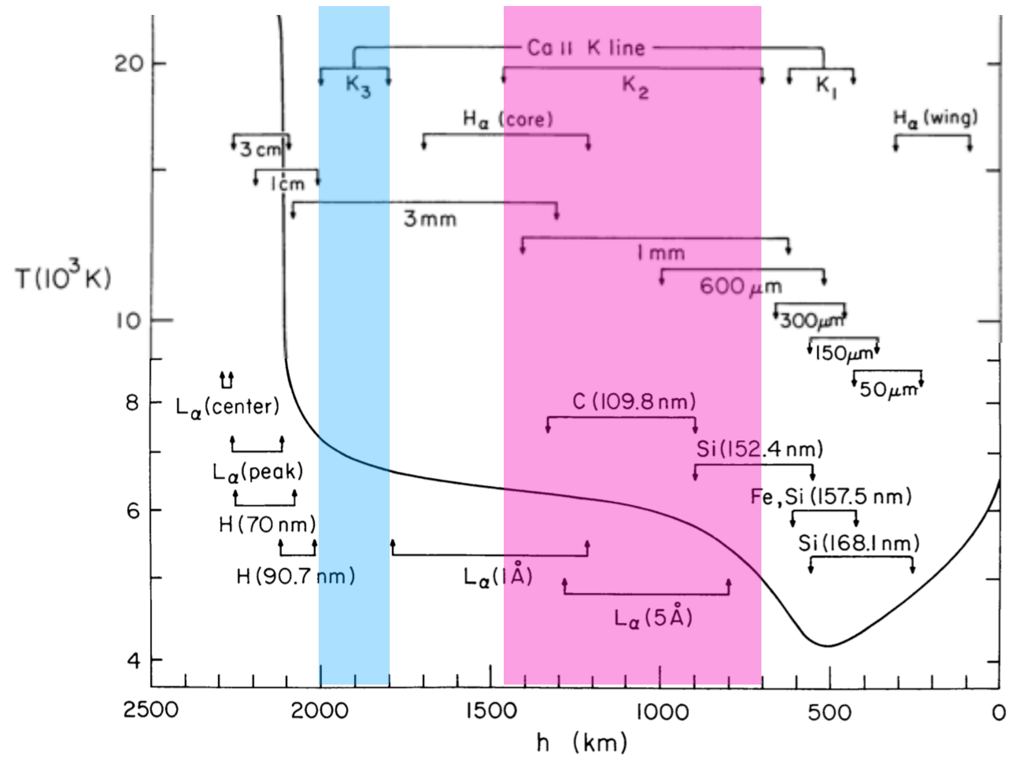


Ca II (or Ca+) “HK”

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



Duncan+1991, Baliunas+1998



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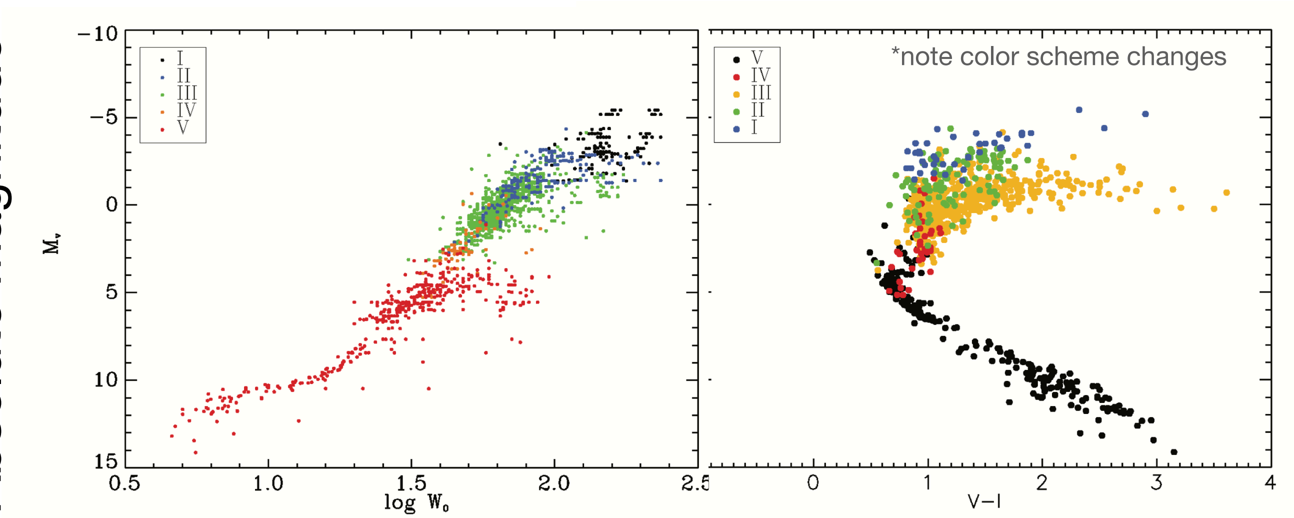
Wilson-Bappu Effect

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

Absolute Magnitude



log(Width)

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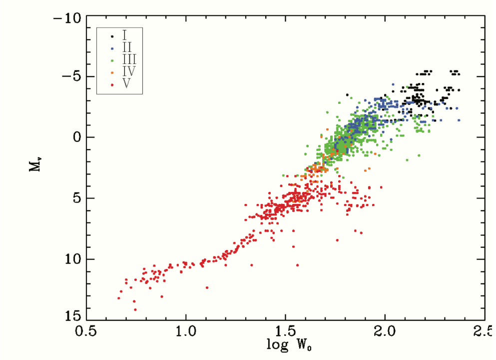
Gomez & Wallerstein (2011)

Wilson-Bappu Effect

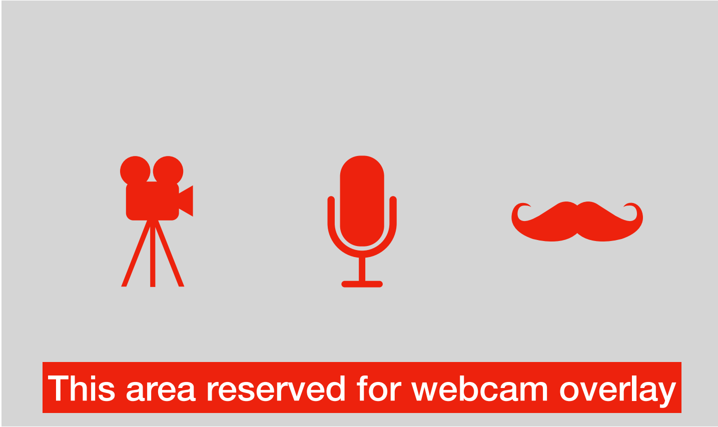
- Empirical connection between width of Ca II line core and a star's *luminosity*

- Since Ca II lines can be very broad,
  can be easier way to estimate luminosity
  (and thus distance) to a star…



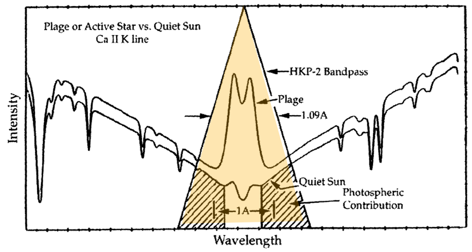
- Ca II line definition varies from author to author
  works best for dwarfs with chromospheres

- Sensitive to both gravity effects AND
  chromospheric activity…

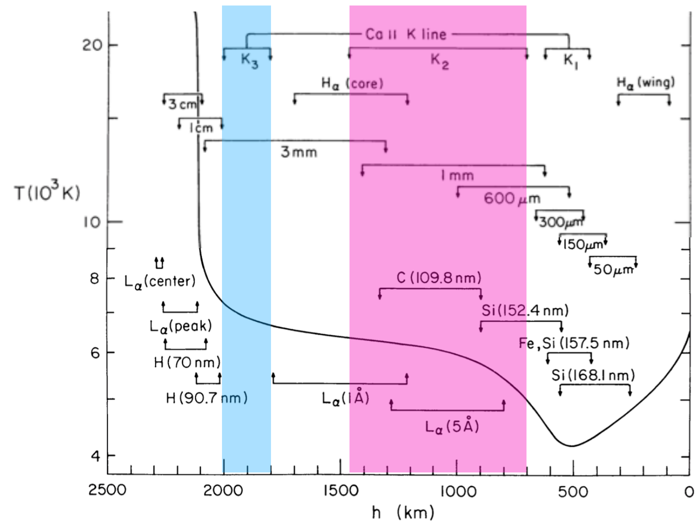


Gomez & Wallerstein (2011)

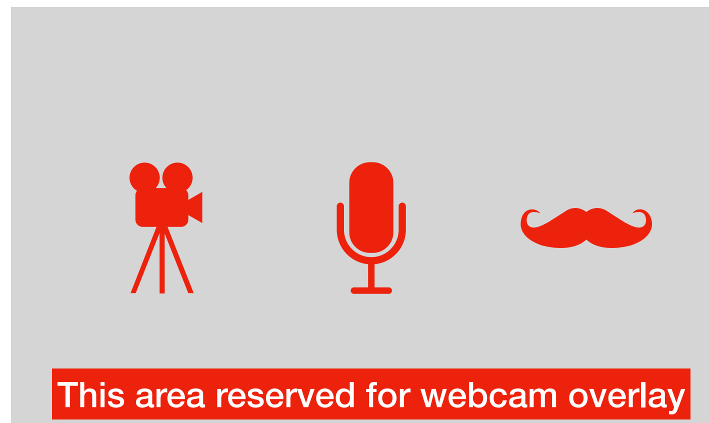
Ca II HK



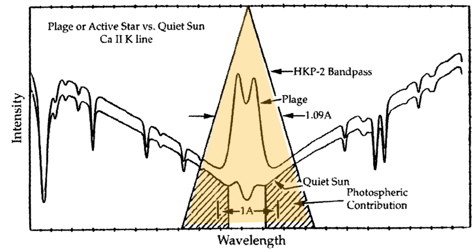
Duncan+1991, Baliunas+1998



- 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



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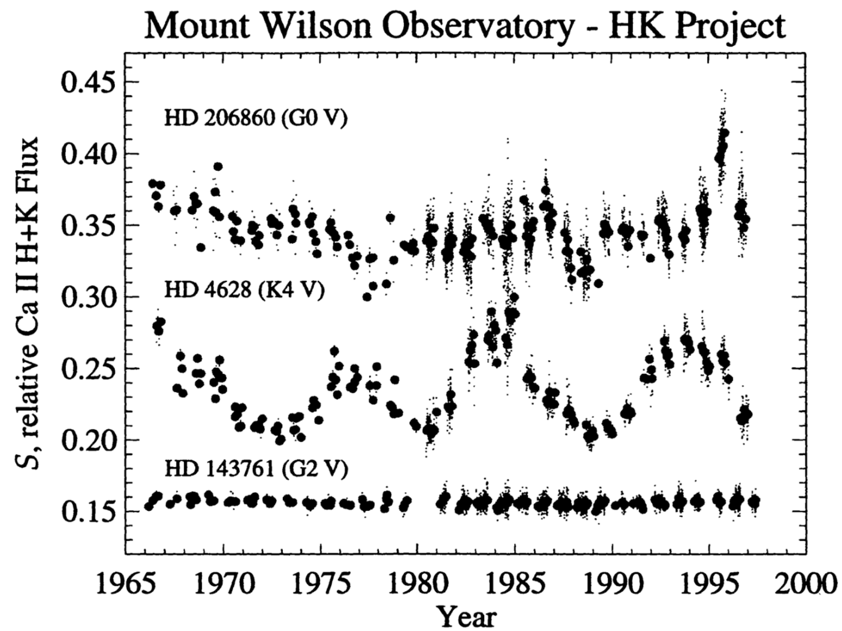
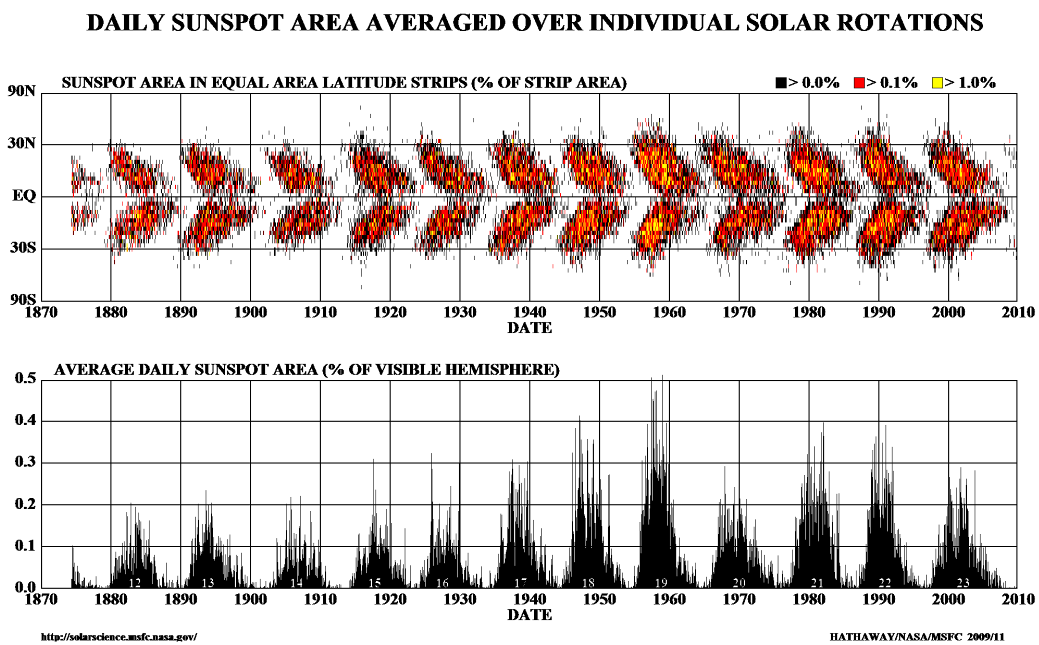
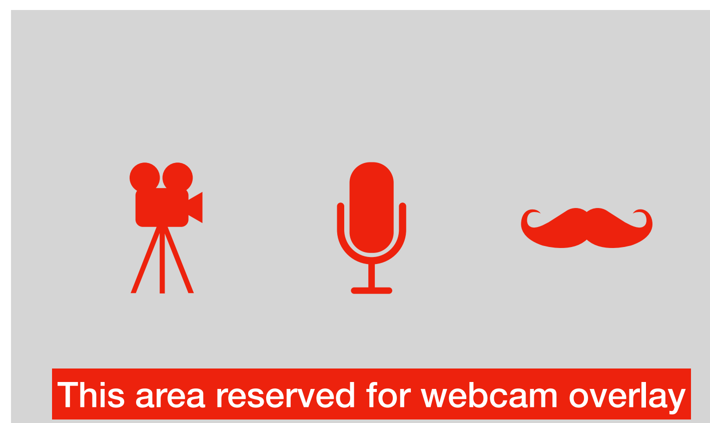
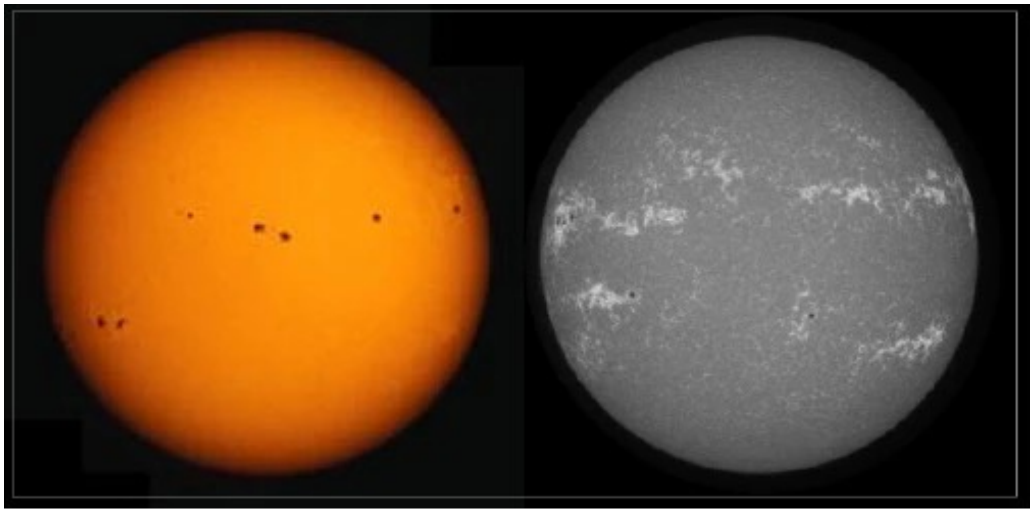


- Activity cycles… a rich history!





Ca II HK

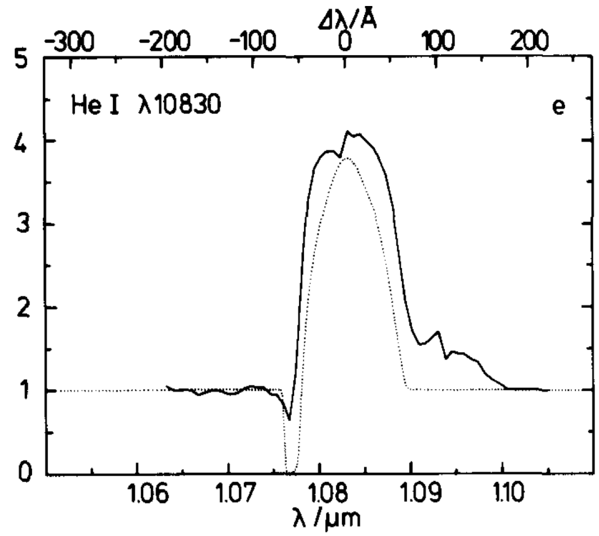


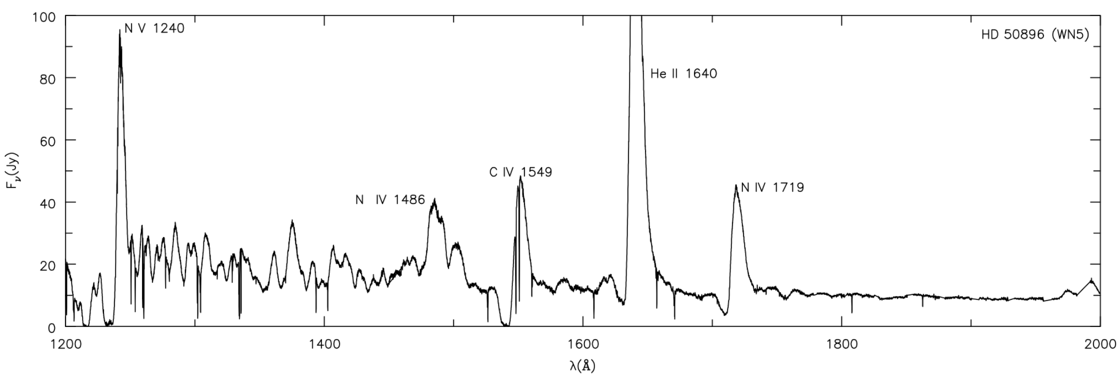
Visible light (broadband)

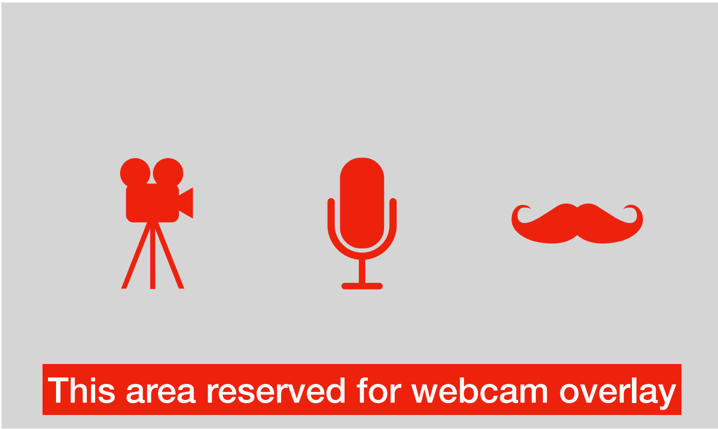
Ca II K filter

Emission lines in Wolf Rayet stars?

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



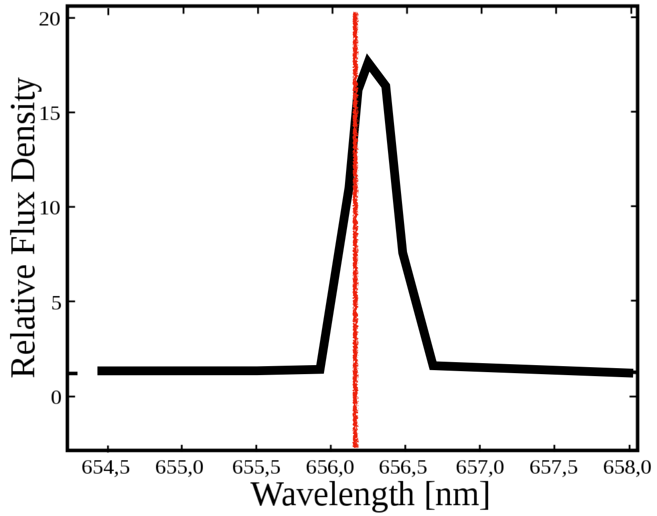


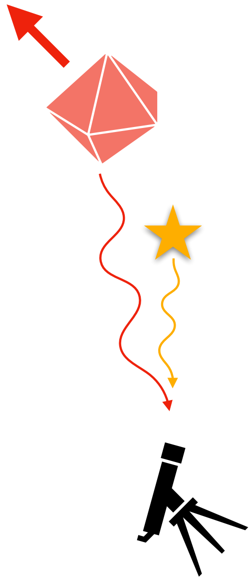


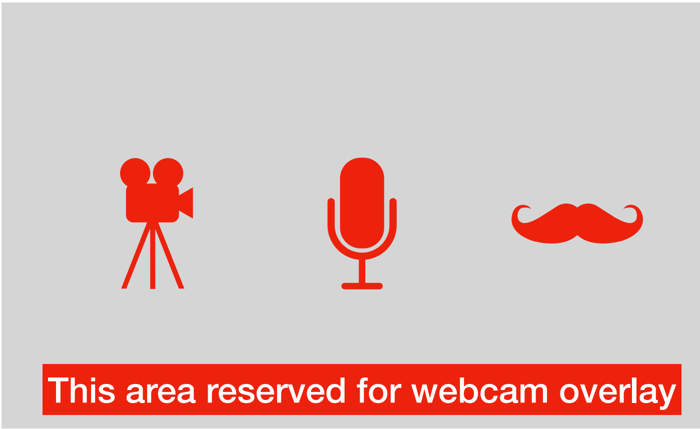
http://kookaburra.phyast.pitt.edu/hillier/publications/Wolf_Rayet_paper.pdf

Emission lines from outflows

Red-shifted line: *motion away*

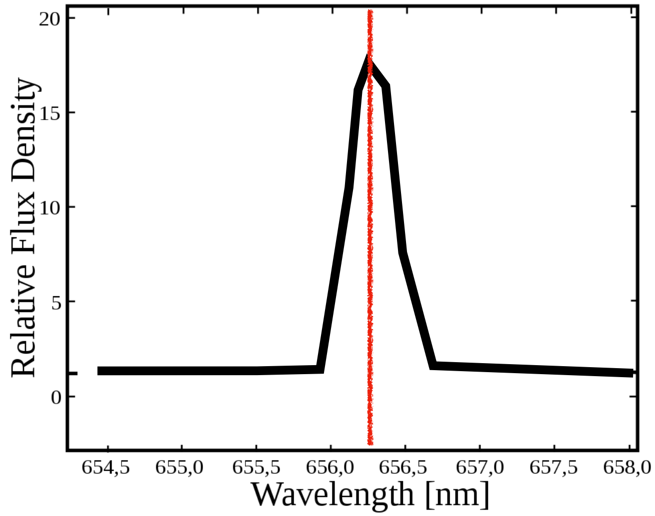


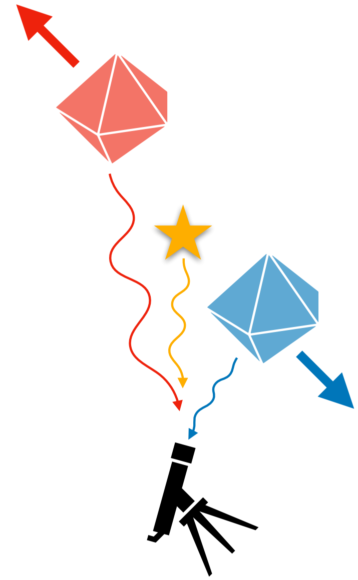


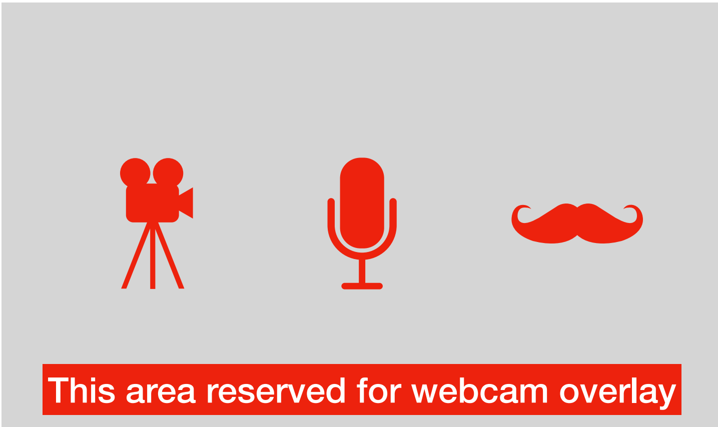


Emission lines from outflows

Broadened line: *motion all directions*

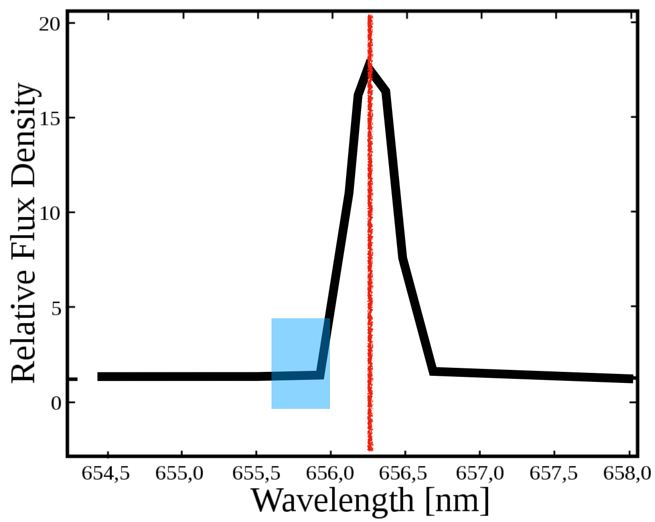


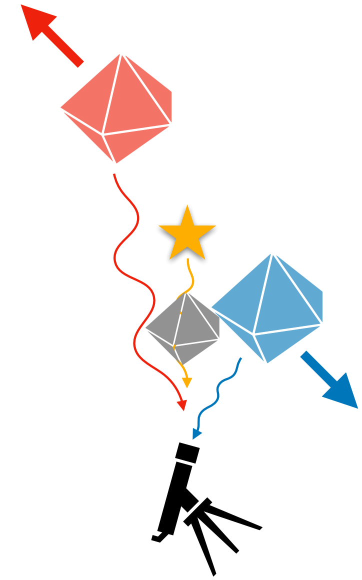


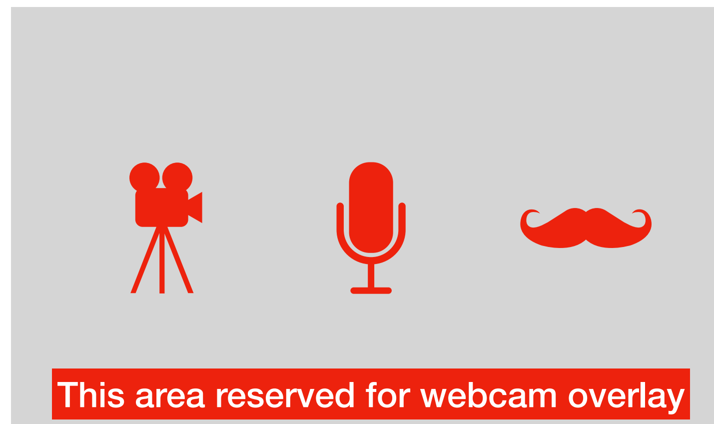


Emission lines from outflows

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

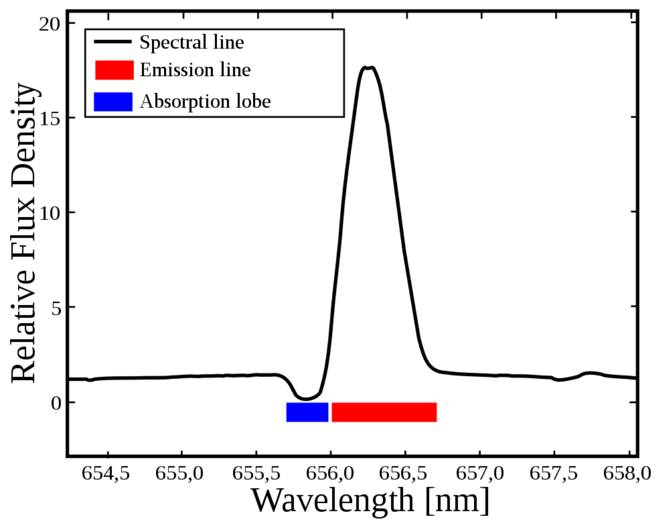


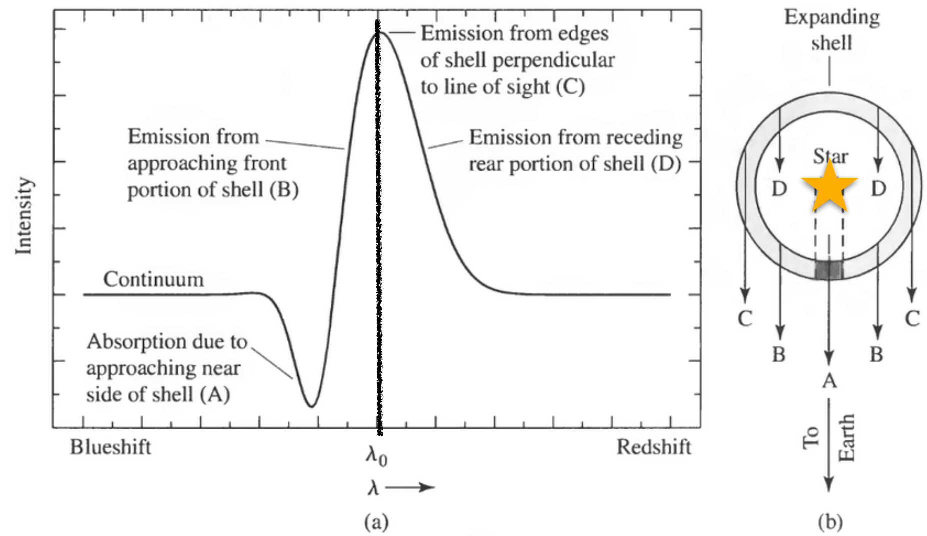




Emission lines from outflows

P Cygni line profile:
expanding shell of material





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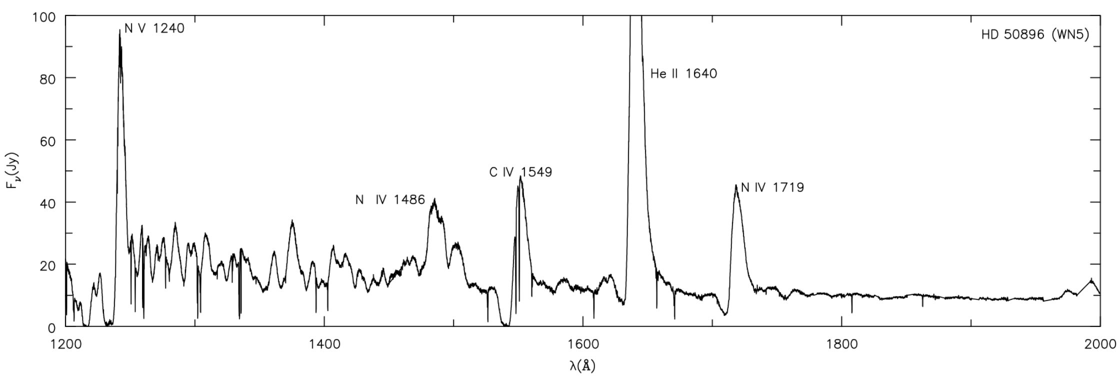
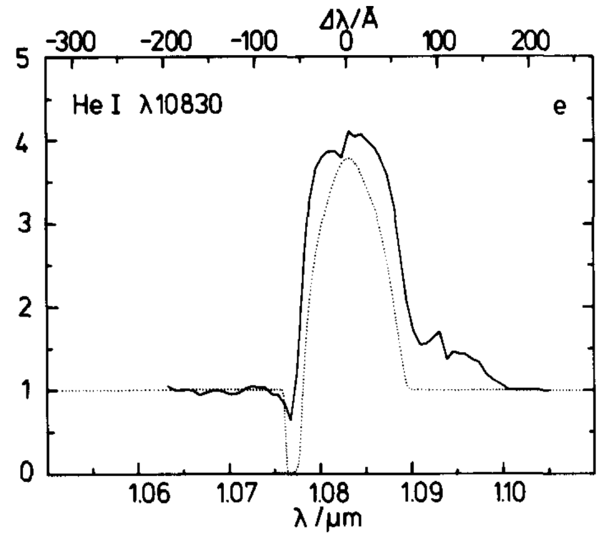
Emission lines in Wolf Rayet stars?

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





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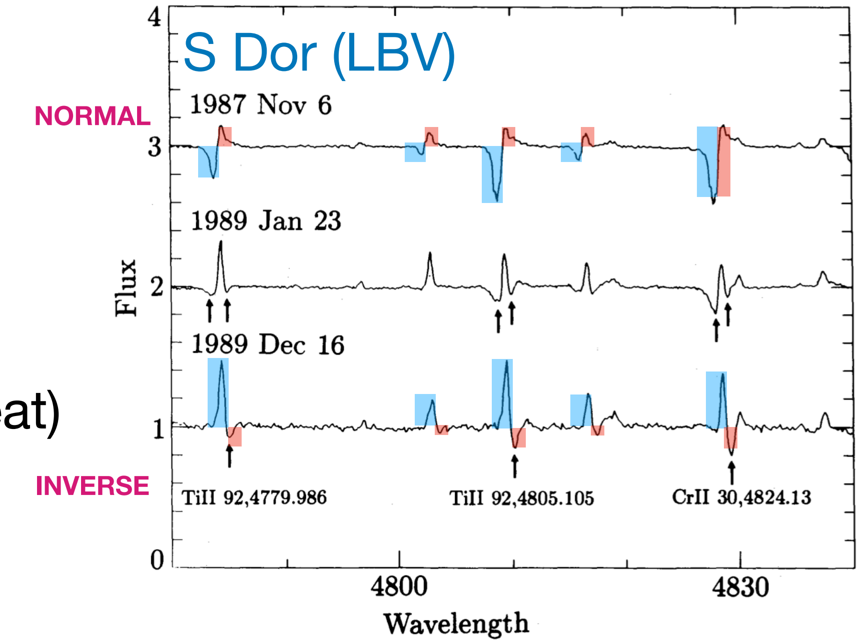
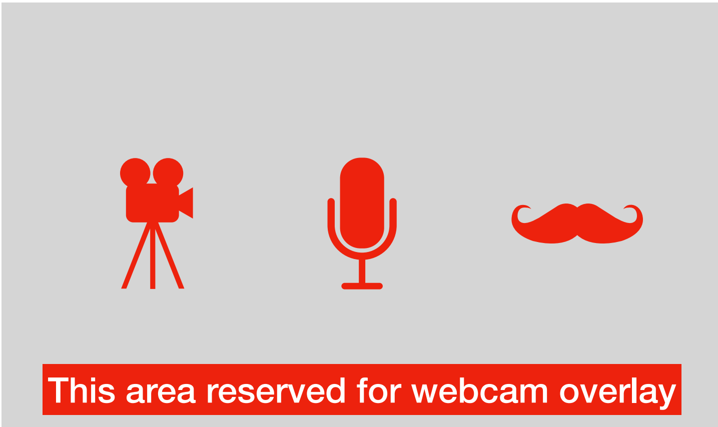
http://kookaburra.phyast.pitt.edu/hillier/publications/Wolf_Rayet_paper.pdf

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

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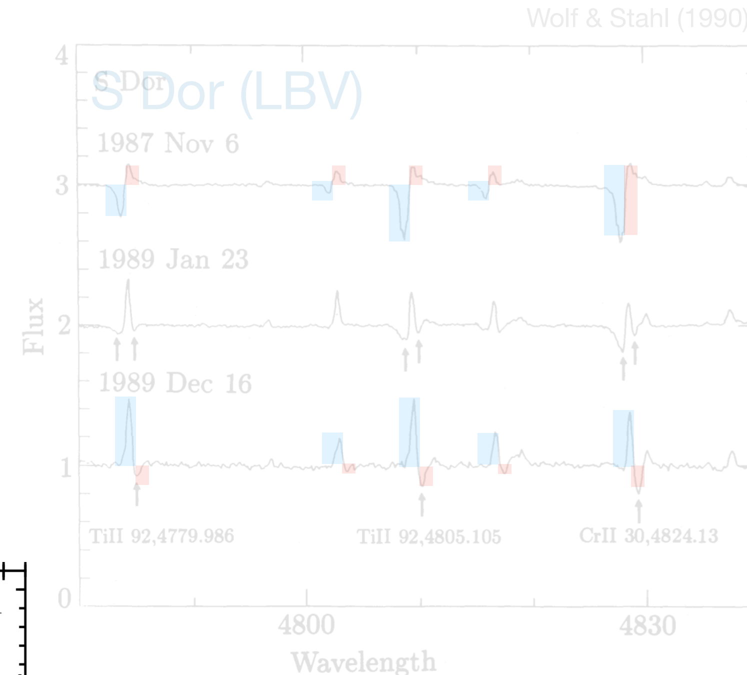
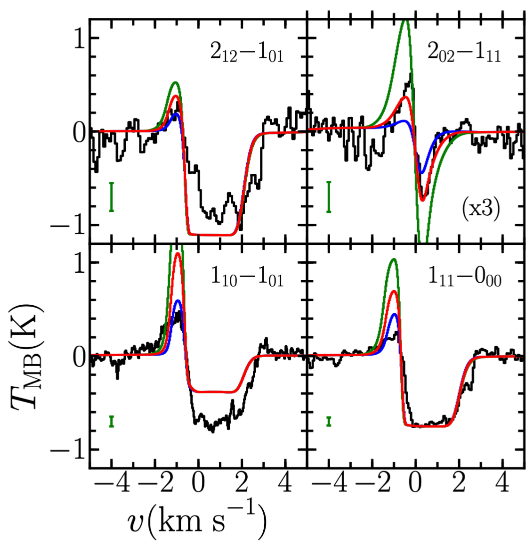
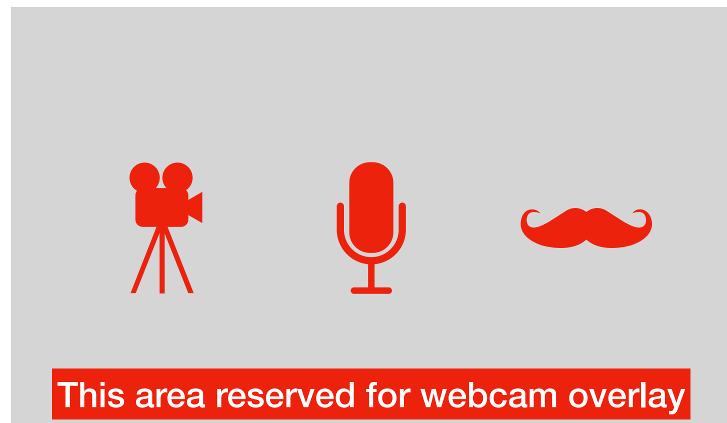


- An indicator of *accretion!*
  - Example of H_2O lines around protostars
  - "*Waterfalls around Protostars*", <u>amazing</u> paper title….

Mottram+2013





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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