Spectral Line Broadening

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Natural Broadening

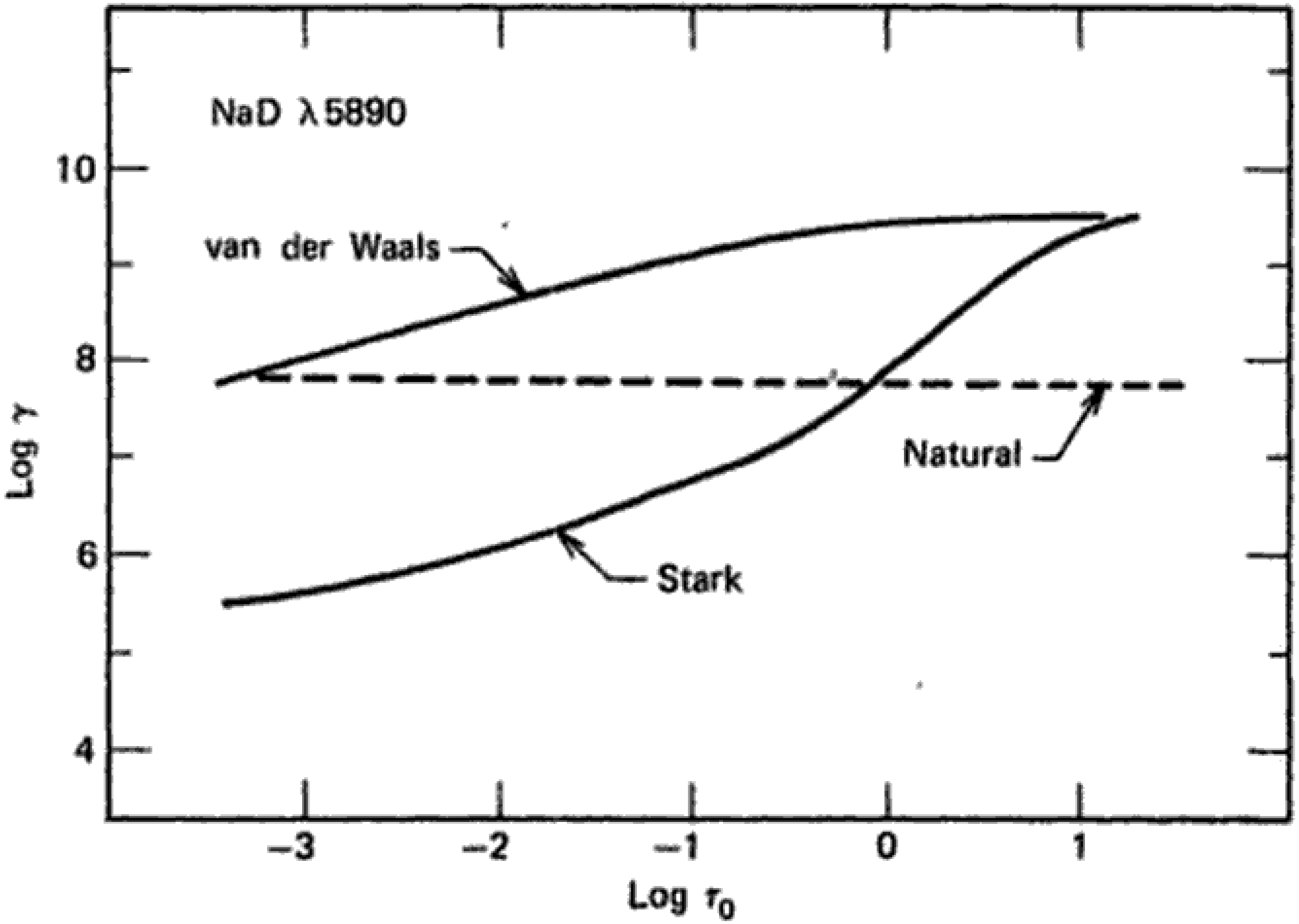
- Uncertainty of energy levels
- Usually much smaller than other broadening mechanisms.
- Resonance lines
  - Transition from ground state to first energy level
    - Often the strongest lines
      - Least energy needed

Pressure Broadening

- Collisional interactions between absorber and other particles
- Perturbs energy level: $\Delta E \propto^{-n}$
  - Upper level perturbed the most

n	Name	Type	Perturber	Lines affected
2	Linear Stark	H + charged particle	Proton, electron	Hydrogen
3	Resonance	Atom A + atom A	self	Hydrogen
4	Quadratic Stark	Ion + charged particle	electrons	Most lines, esp. hot stars
6	Van der Waals	Atom A + atom B	Usually hydrogen	Most lines, esp. cool stars

Damping Constants



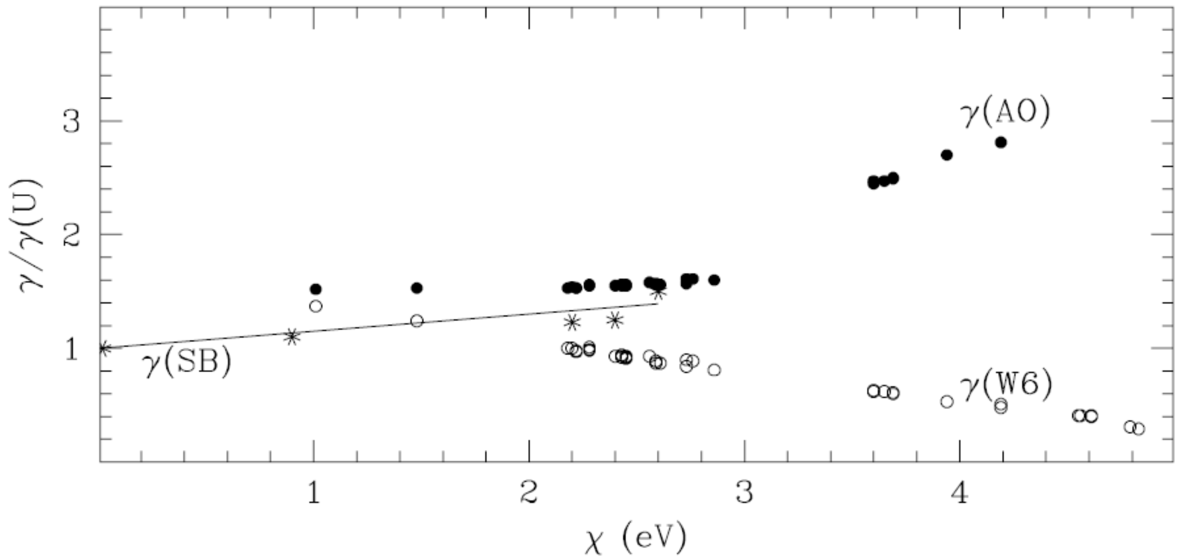
Sodium line for Solar model. From Gray 1992oasp.book.....G

Damping Constants

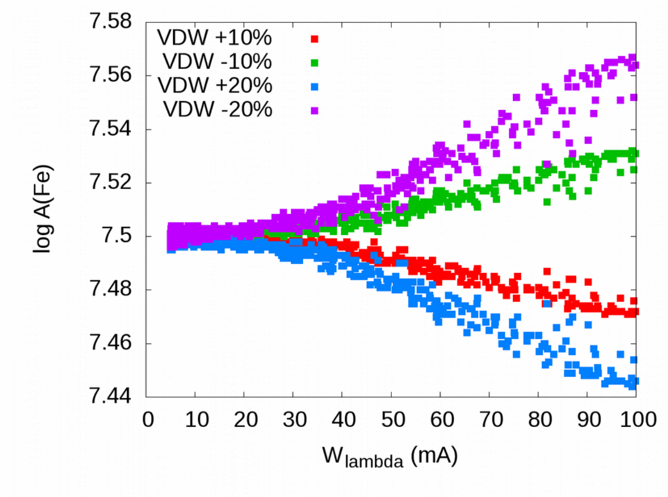
- Lorentz (damping) profile
- Values given in line lists (e.g. VALD)
- What are their accuracies?
  - Some transition probabilities (gf values) have an accuracy (e.g. NIST)
  - Paul Barklem's review 2016A&ARv..24....9B *Accurate abundance analysis of late-type stars: advances in atomic physics*

Collisional Broadening

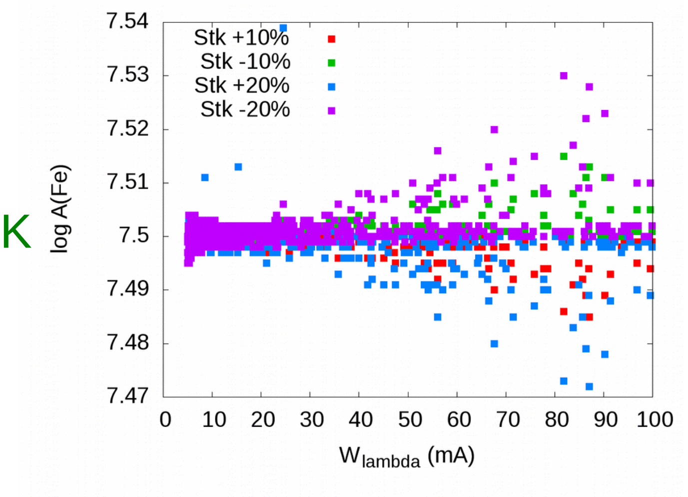
- Ryan 1998 (A&A, 331, 1051)
  - Even weak lines can be affected by damping
  - Damping errors depend on excitation potential
    - errors in microturbulence and effective temperature



Effect of damping



T_{eff} 6000 K
Log g 4.5

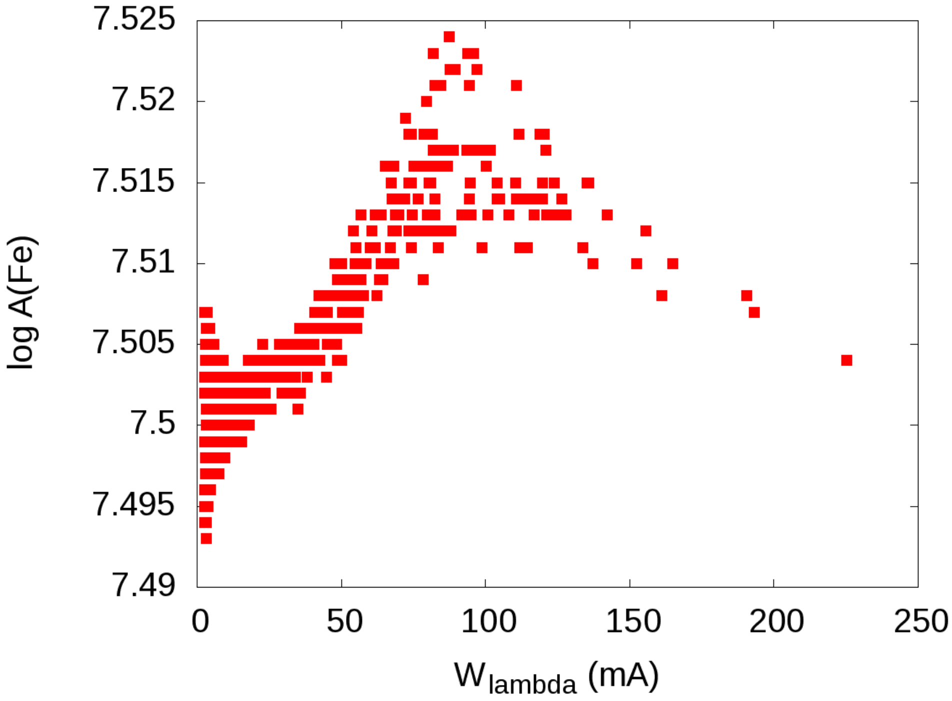


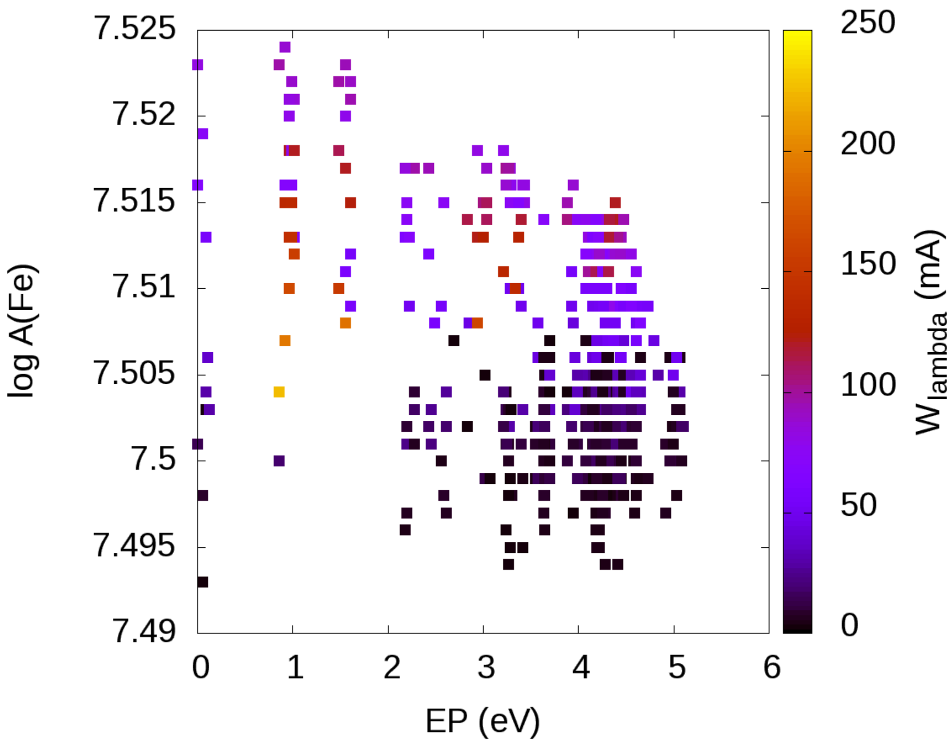
- Errors in damping constants
  - van der Waals (left) and Stark (right)
- VDW could lead to errors in microturbulence

Astrophysical gf values

- Pros:
  - For Sun well known parameters
  - Differential results
    - Improved precision
- Cons:
  - Usually assumes shift only due to gf values
    - What about damping, microturbulence, etc.?
- Widely-used and can give good results
  - But, values do depend on model and assumed parameters.

Astrophysical gf Systematics





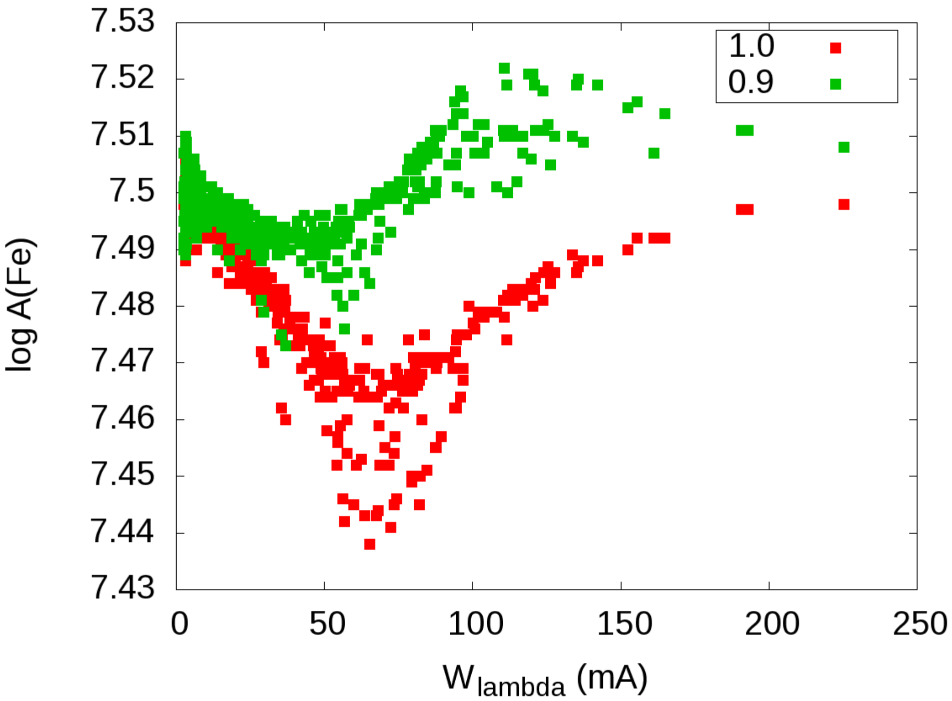
- Astrophysical gf values created at 6000 K but with +20% error in van der Waals damping.
  - Plots show difference in at 6500 K.

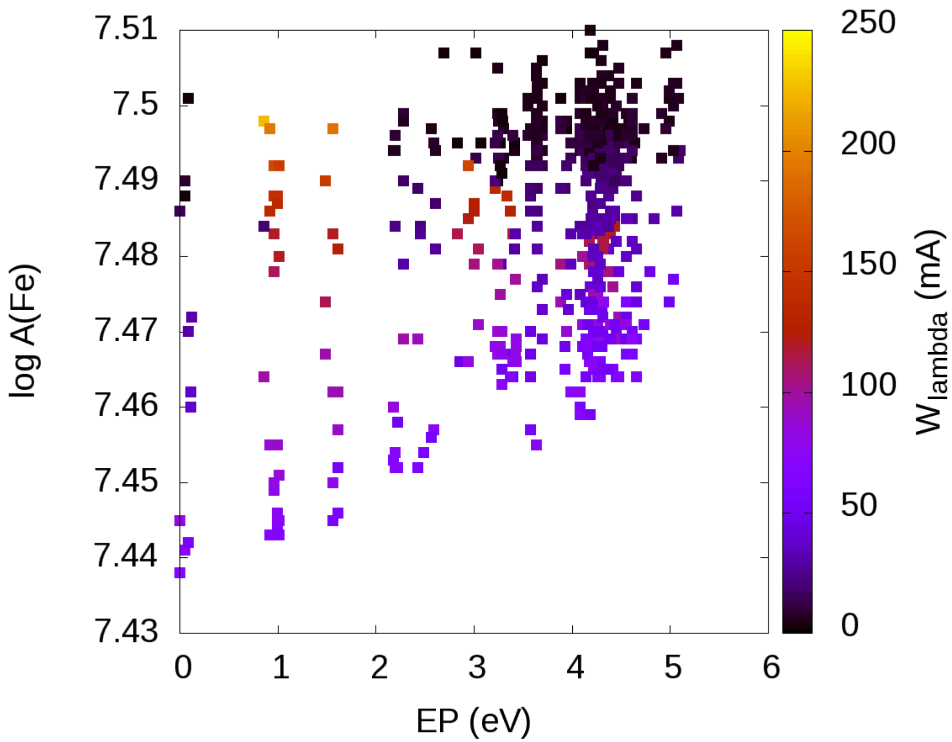
Solar Microturbulence Value

- Edvardsson et al. 1993 (A&A, 275, 101) 1.15 km/s
- Bruntt et al. 2010 0.95 km/s
- Valenti & Fischer 2005 0.85 km/s
- Santos et al. 2004, (A&A, 415, 1153) 1.00 km/s
- Magain (1984) 0.85 km/s (centre of solar disk)
  - From Blackwell et al. 1984, (A&A,132, 236) using Holweger & Mueller 1974, (SoPh, 39, 19) Solar model

Which to use in Astrophysical gf determination?

Astrophysical gf Systematics



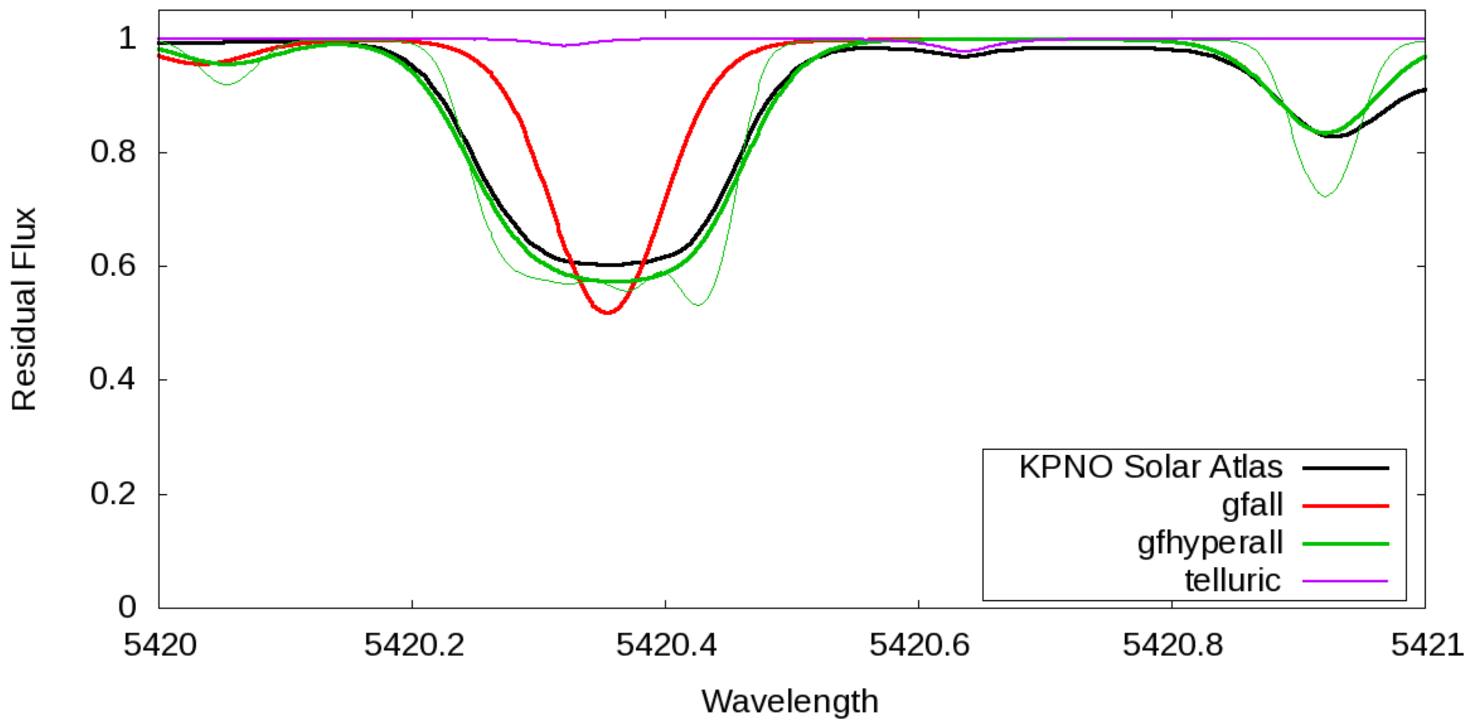


- Astrophysical gf values created at 6000 K but with assumed microturbulence too low by 0.1 km/s.
  - 0.9 km/s instead of "*true*" 1.0 km/s
- Plots show difference at 6500 K

Zeeman and Hyperfine Splitting

- Zeeman
  - Splitting of energy levels due to magnetic field
- Hyperfine
  - Intrinsic due to nuclear structure
- Isotopes
  - Most line lists assume solar isotopic mix.

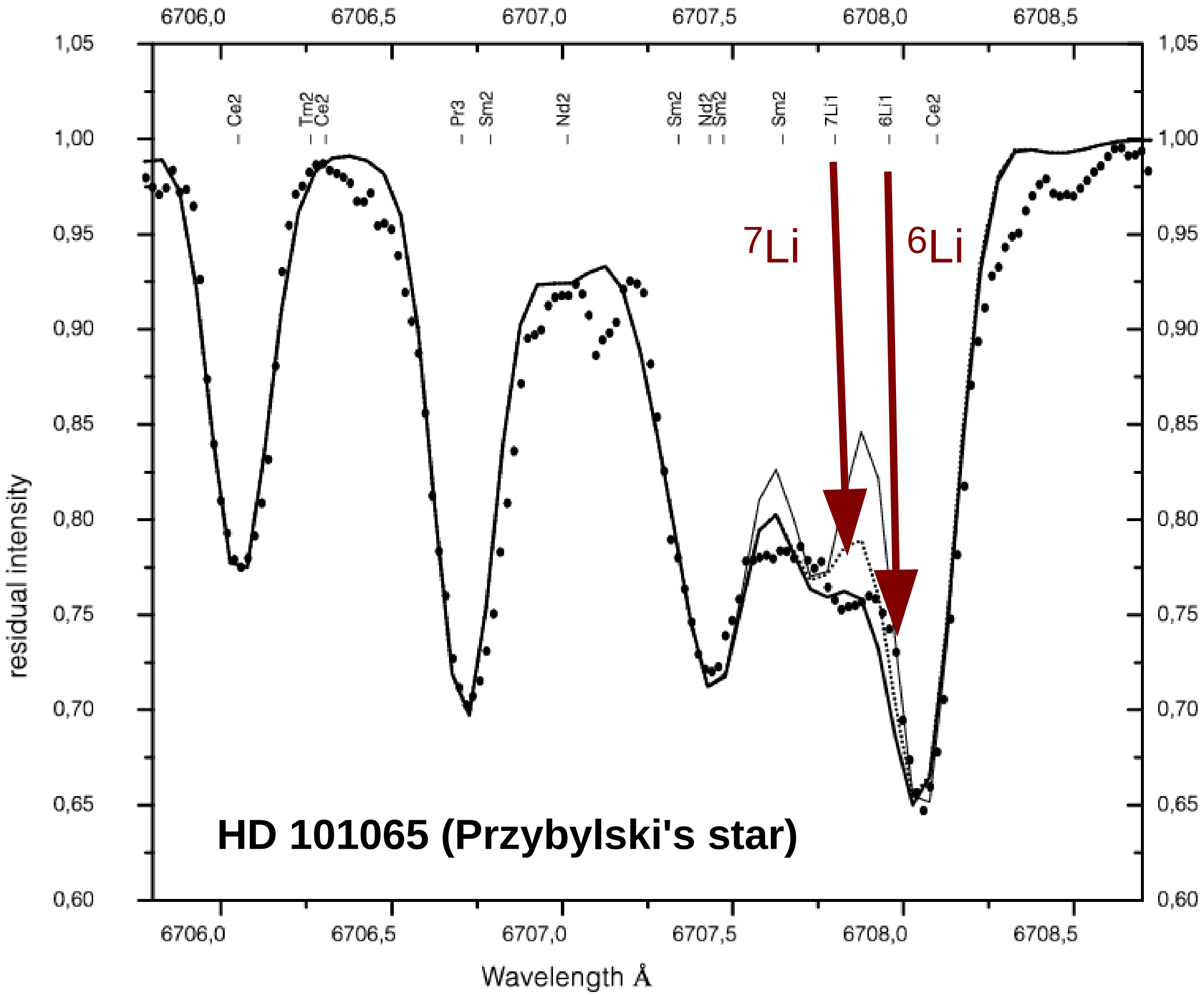
Hyperfine Structure



Solar Mn I line at 5420Å

- The splitting of energy levels in odd atomic elements
  - Multiple components to spectral lines
    - See Wahlgren, 2005, MSAIS, 8, 108

Non-solar Lithium isotopic ratio



2003A&A...409..707S

Convection and turbulence

- Effects the atmosphere of A stars and cooler.
- Visible as Solar Granulation
  - Surface convection cells
- Indirectly inferred via
  - Microturbulence
  - Macroturbulence
  - Line bisector curvatures
- Free parameters in 1-d models
  - Can vary with depth in atmosphere

Convection Models

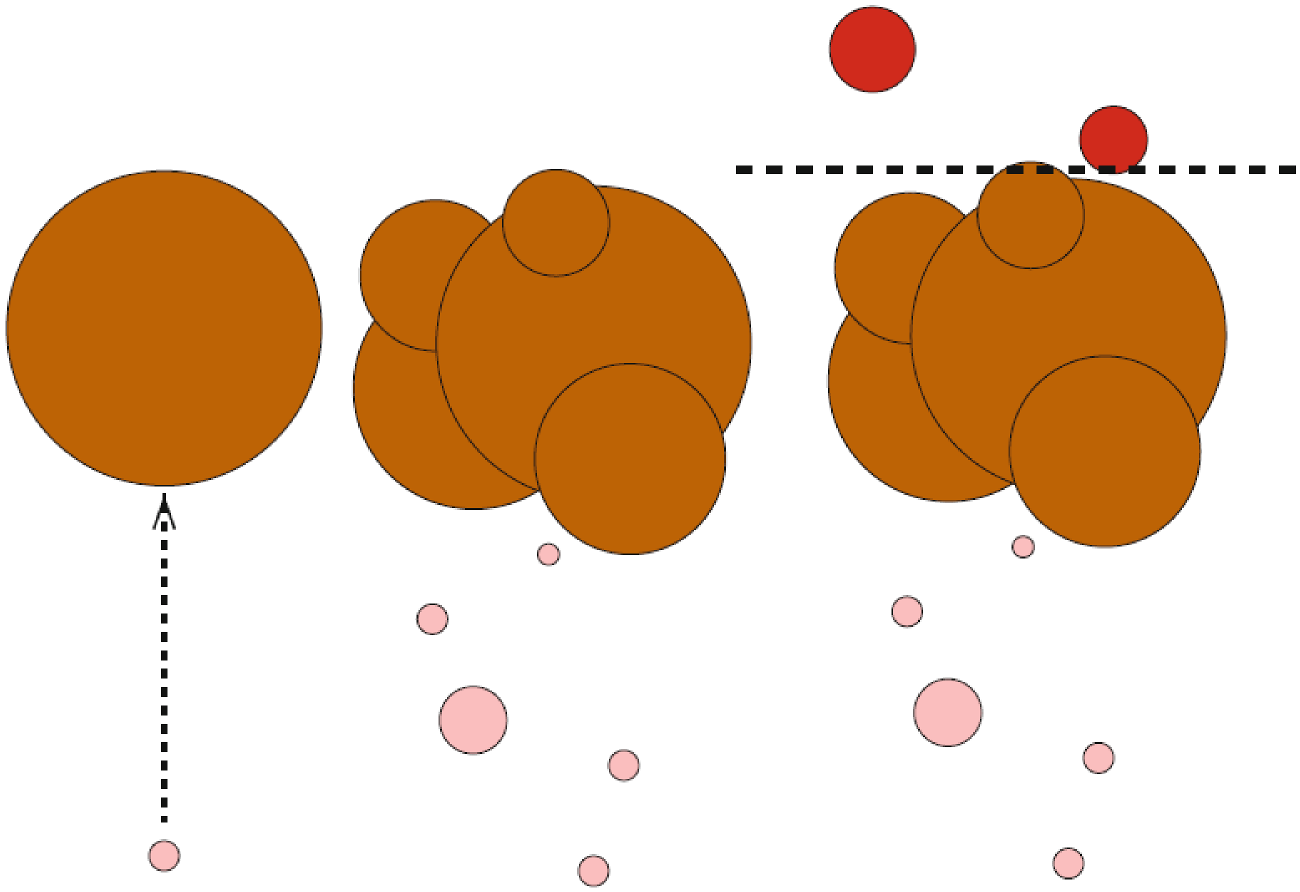
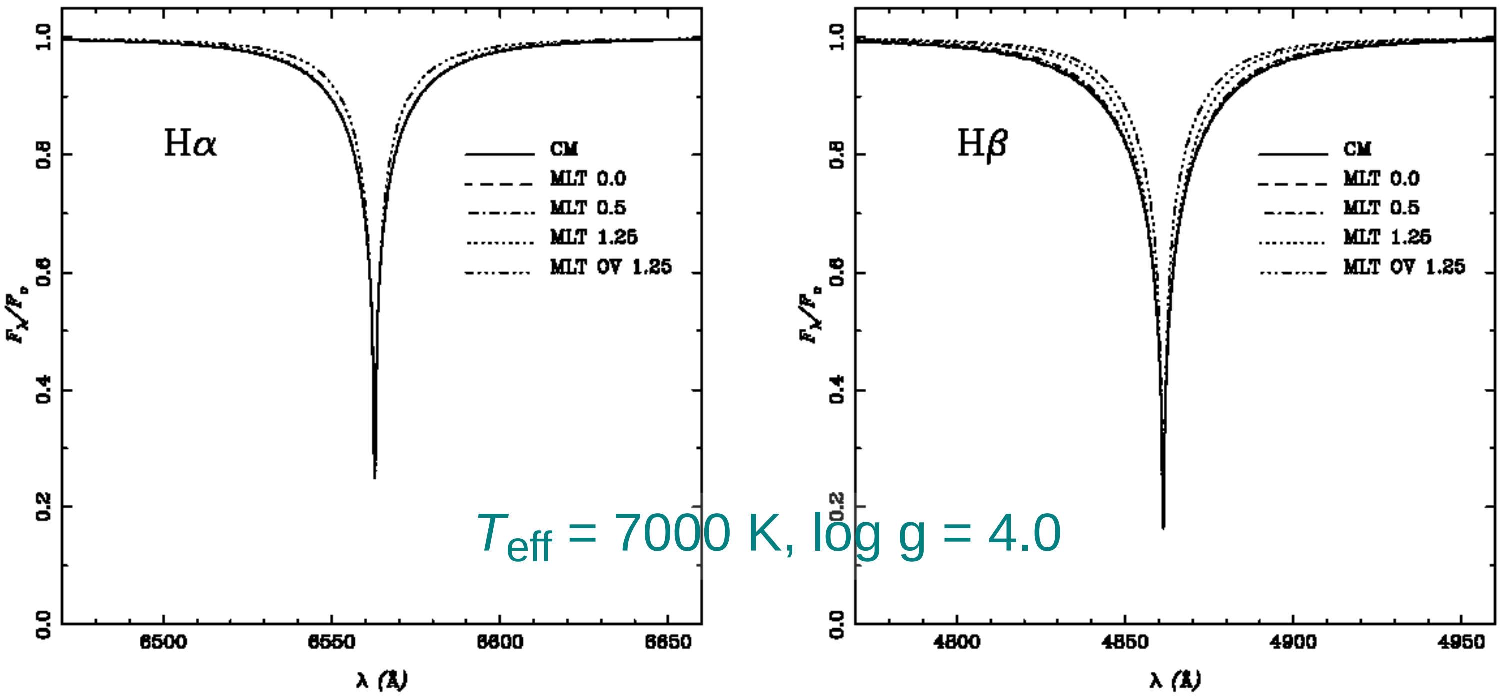


Fig. 1 Schematic bubble representations of convection treatments. In mixing-length theory (**a**), a single bubble rises within the atmosphere, while in turbulent convection bubbles of varying sizes rise (**b**). In (**c**) we have overshooting above the convection zone

2014dapb.book..131S

Balmer profile variations



T_{eff} = 7000 K, log g = 4.0

- Formed at different depths within atmosphere
  - probe differing parts of atmospheric structure
- Changing the efficiency of convection, by increasing mixing length, has significant effect on computed profile

Balmer profile sensitivities

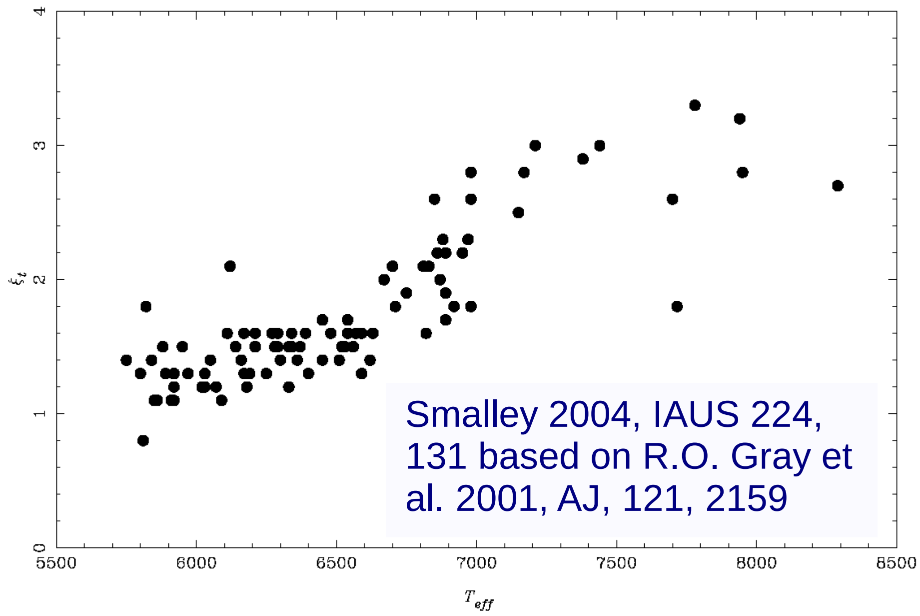
- $H\alpha$ insensitive to mixing-length
- $H\beta$ sensitive to mixing-length
- Both lines affected by overshooting
  - sensitive to temperature and metallicity
  - surface gravity sensitivity for hotter stars

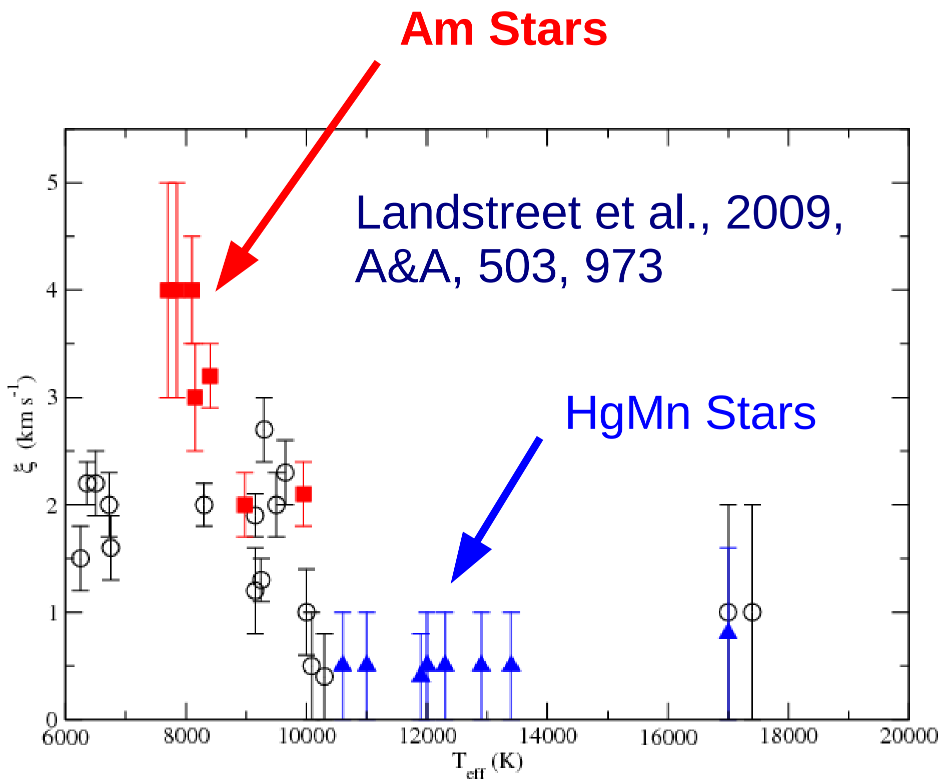
Van't Veer & Megessier, 1996, A&A 309, 879

Microturbulence

- A ***free*** parameter introduced to ensure that abundances from weak and strong lines agree
- Extra source of broadening
  - added to thermal broadening
- Small scale motions within the atmosphere

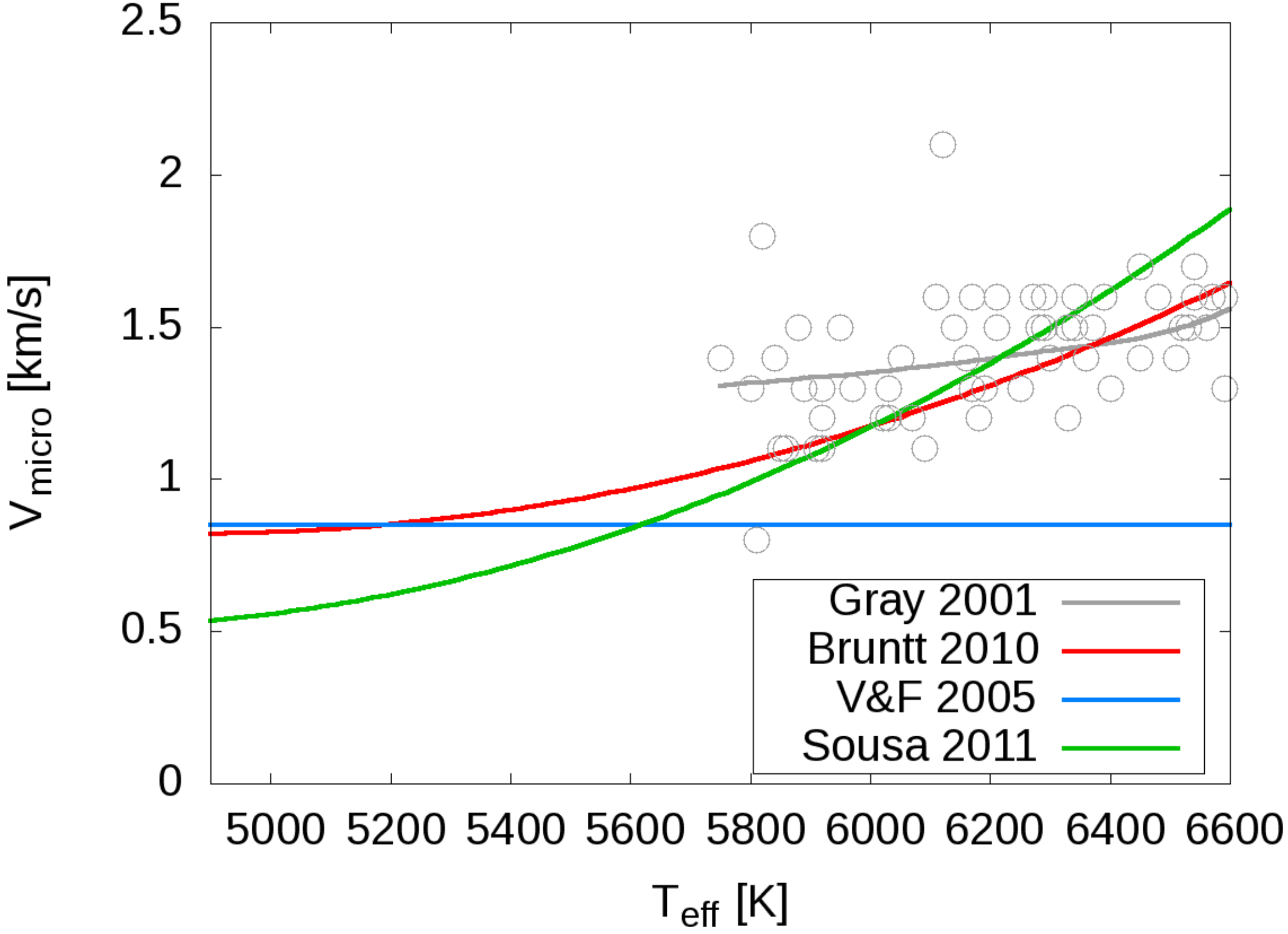
Microturbulence Variations





- Microturbulence varies with T_{eff}
  - increases with increasing temperature
    - peaking around mid-A type

Microturbulence Calibrations

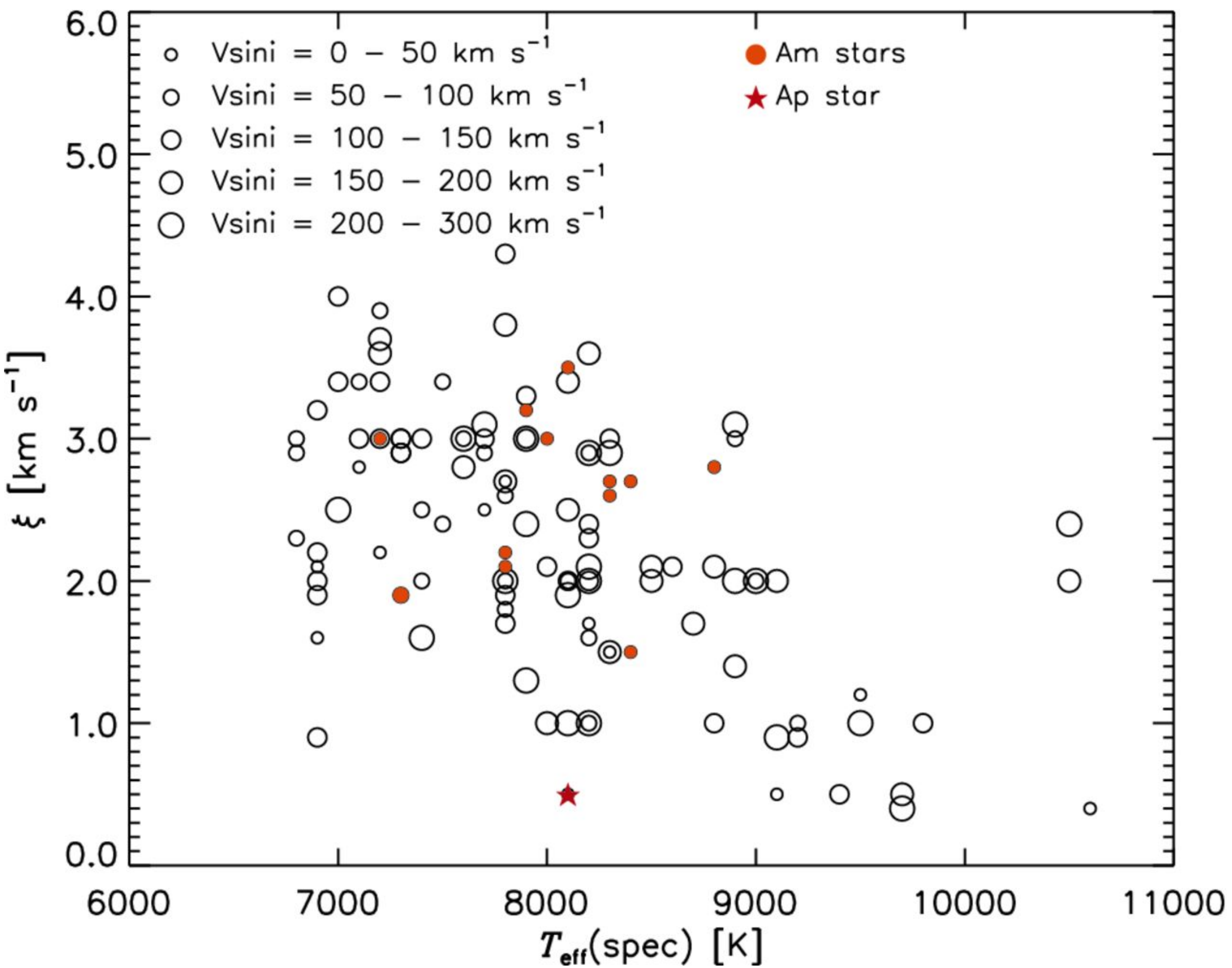


Valenti & Fischer 2005 found: “strongly correlated values of v_{mic} and [M/H], suggesting that v_{mic} and [M/H] are partially degenerate.” Adopted fixed value.

Gray 2001 fit by Smalley 2004 IAUS 224, 131
Sousa 2011 is fit given in 2013ApJ...768...79G

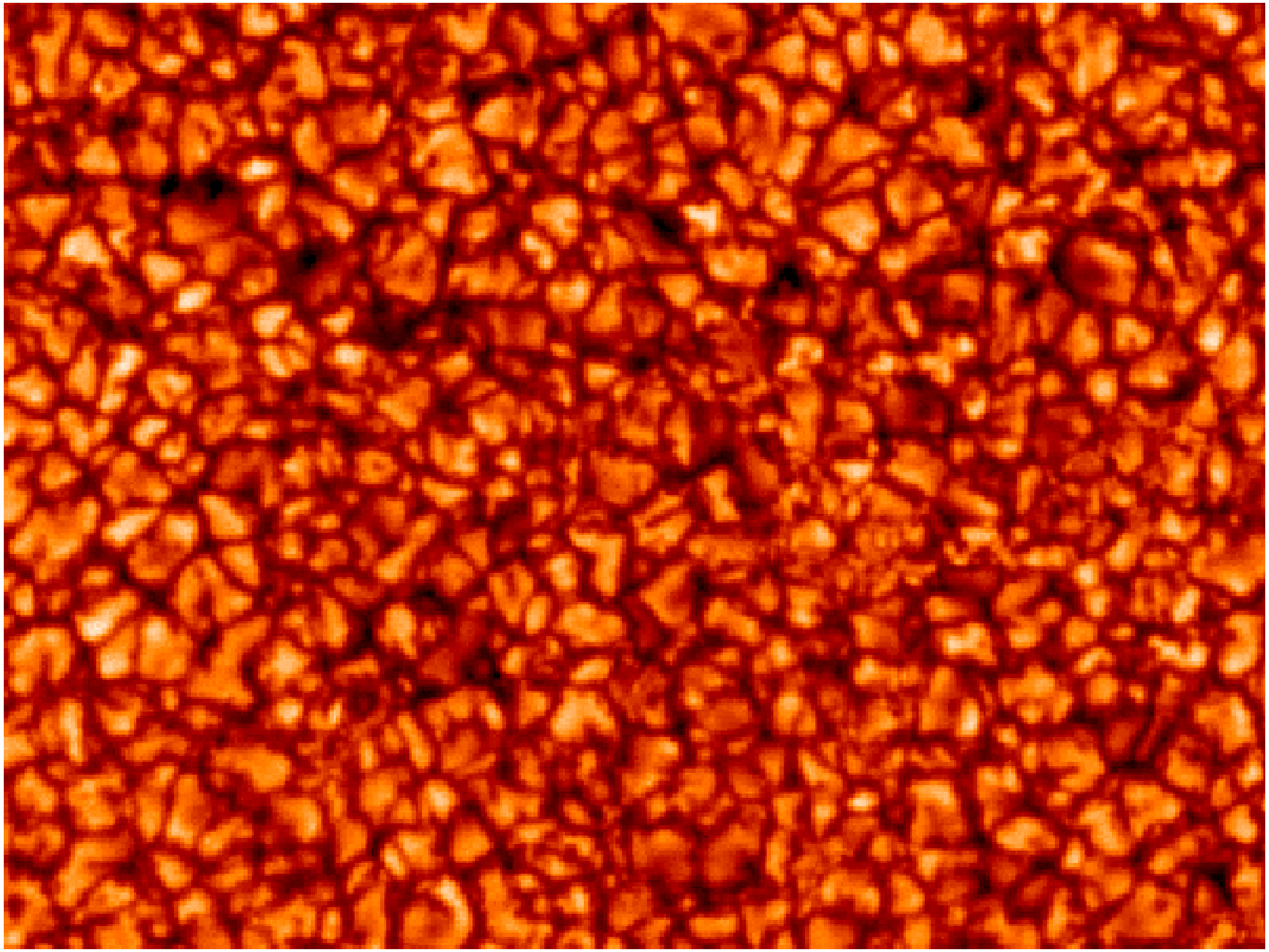
Valenti & Fischer, 2005, ApJS,159, 141
Bruntt et al., 2010, MNRAS, 405, 1907

Microturbulence in A and B stars



2015MNRAS.450.2764N

Solar Granulation

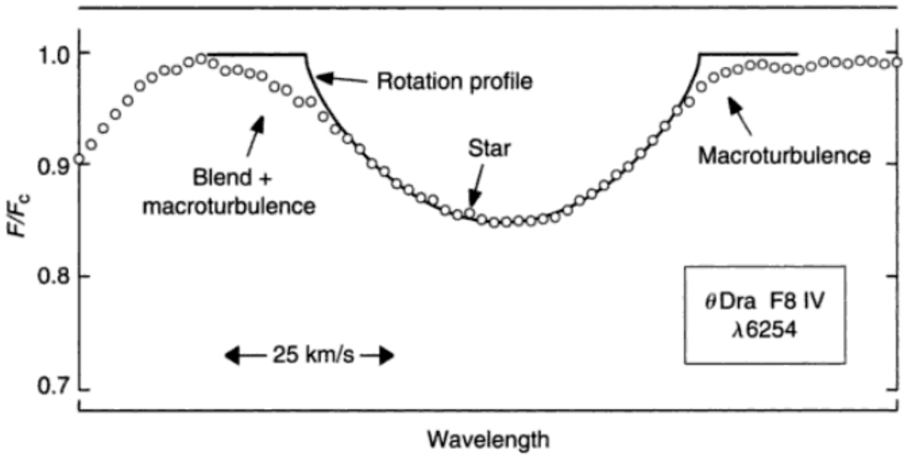


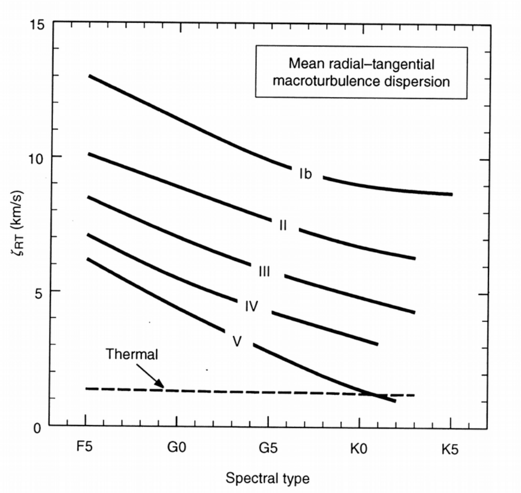
http://zeus.nascom.nasa.gov/~dmueller/gran_intro.htm

Macroturbulence

- Extended shallow wings
- Strong in giants and supergiants
- Seen in A-type stars
- Even B supergiants
  - Przybilla et al., 2006, A&A, 445, 1099

Large-scale velocities within atmosphere





D.F. Gray (2008) Book

Gray's Radial-Tangential Model

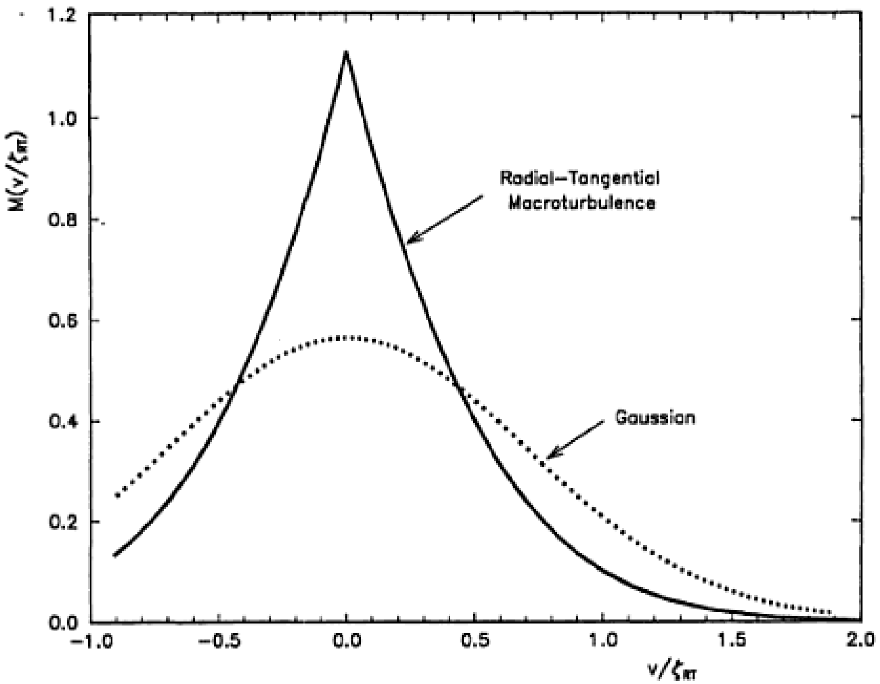


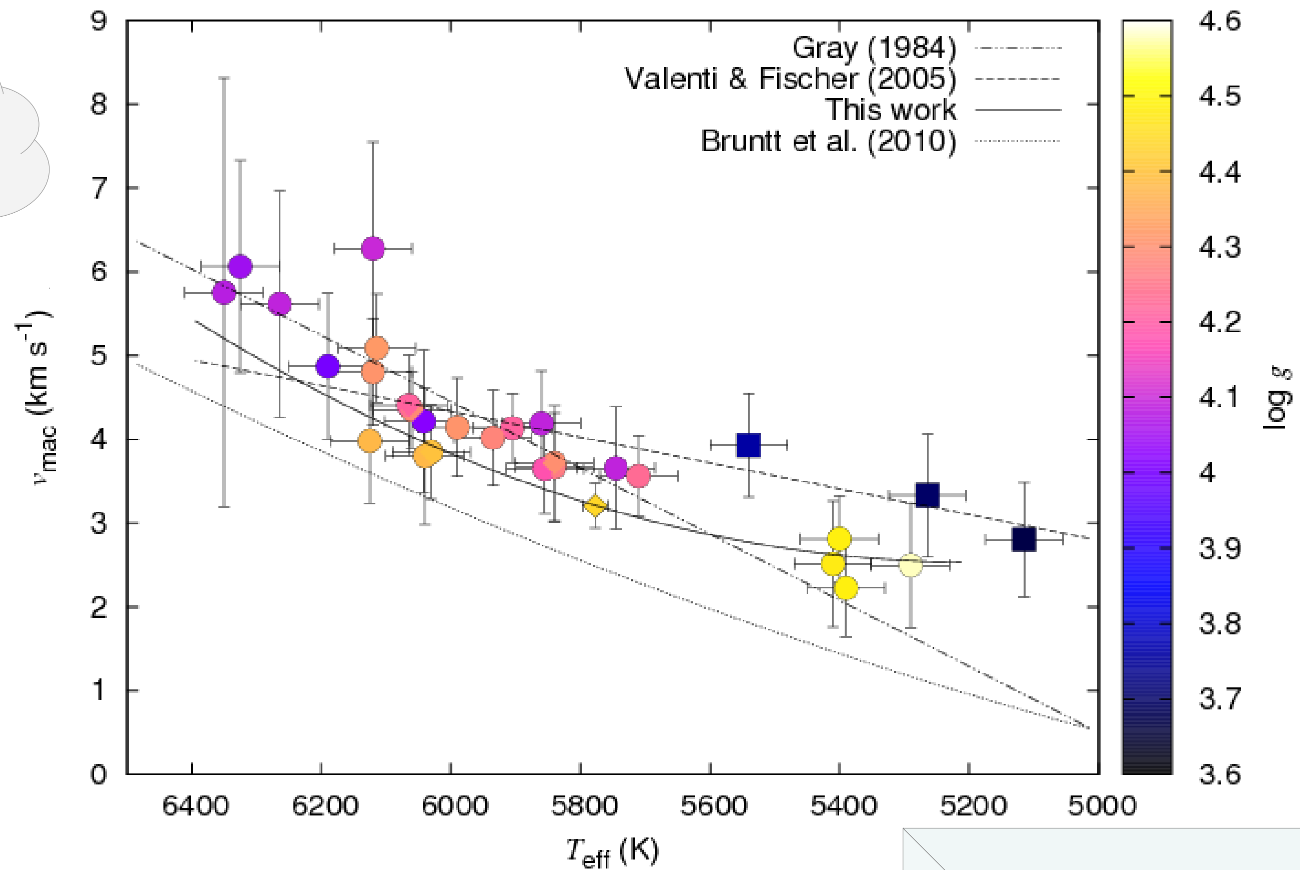
Fig 17.5 D.F. Gray (2008) Book

- Dopper broadening in both radial and tangential directions
  - ½ surface radial
  - ½ surface tangential
- Assume same velocity for both (ζ_{RT})

A ***free*** parameter

Macroturbulence in solar-type Stars

Calibration for A/F stars?



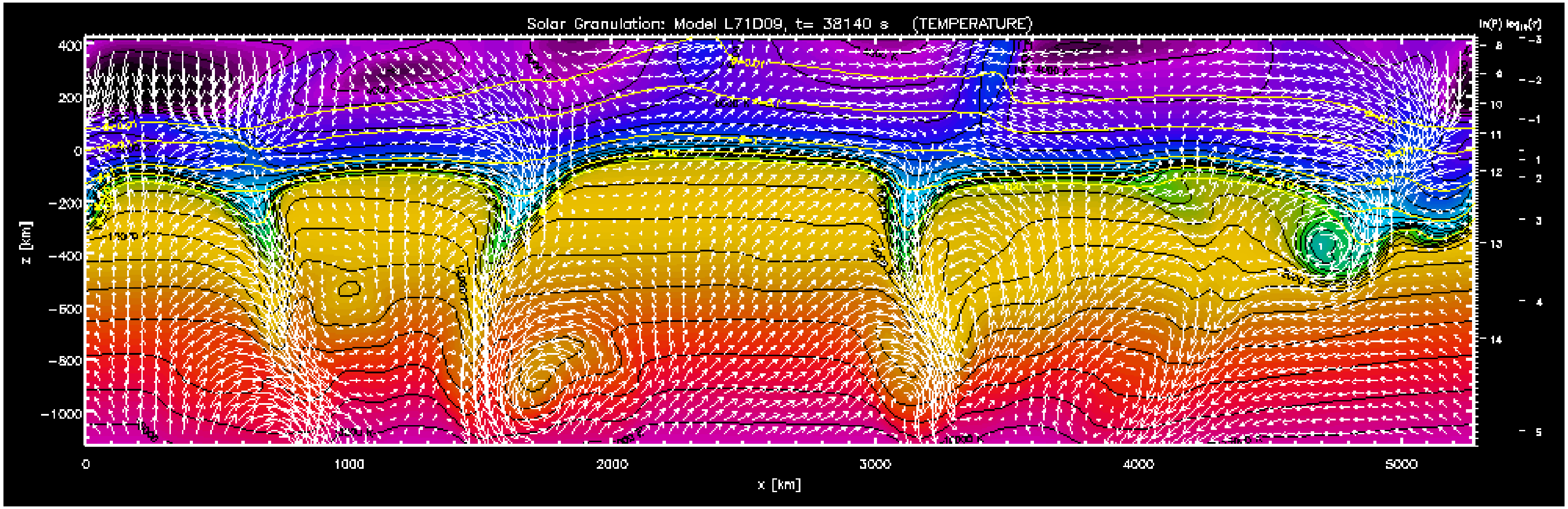
2014MNRAS.444.3592D

Calibration using Kepler asteroseismic *v* sin *i* values

No need for microturbulence and macroturbulence

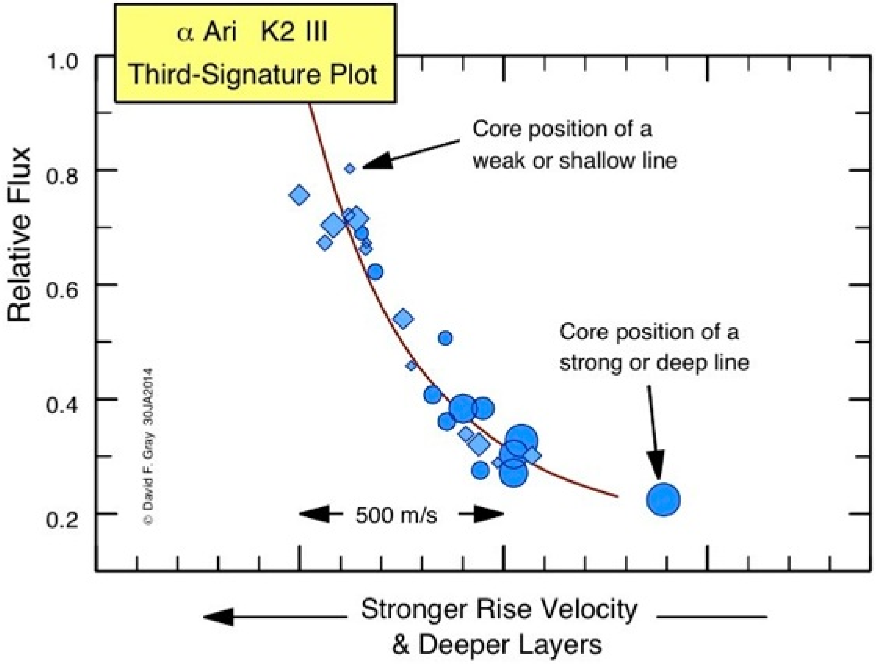
- Numerical simulations avoid the need for such free parameters (e.g. Asplund et al., 2000, A&A 359, 729)
  - not turbulent motions, but velocity gradients

No longer free parameters and should be constrained when using 1-d models



http://www.aip.de/groups/sternphysik/stp/2d_convect.html

Spectral Line Shifts



http://www.astro.uwo.ca/~dfgray/Granulation.html

- Position of line cores shifted by velocity fields
  - Vary with depth
  - Time variable
    - “noise” in radial velocity measurements

A Convection Recipe

No convection		Weak convection (sub-surface)	Strong convection (surface)
$l/H = 0$	$l/H = 0$	$l/H \simeq 0.5$	$l/H \simeq 1.25$
$\xi_{\rm t} = 0$	$\xi_{\rm t} \sim 2\,{\rm km\,s^{-1}}$	$\xi_{\rm t} \sim 2\text{-}4\ {\rm km\,s^{-1}}$	$\xi_{\rm t} \sim 1\text{-}2\ {\rm km\,s^{-1}}$

A0V 10 000 K | A5V 8500 K | F0V 7000 K

Smalley, 2004, IAUS 224, 131

Stellar Rotation

- Doppler shifts due to stellar rotation
- Characteristic broadening shape.
- Normally assume solid-body rotation of a spherical star
- Observe projected rotation velocity (*v* sin *i*)

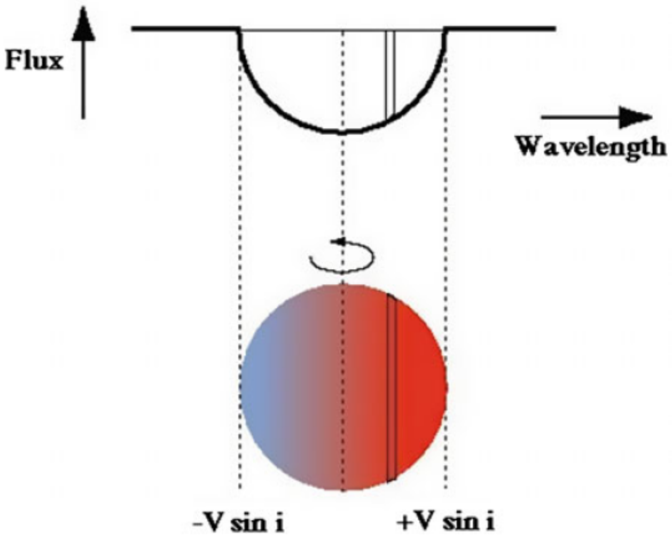


Fig. 1 Schematic view of the Doppler broadening of a spectral line due to rotation

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Determining *v* sin *i*

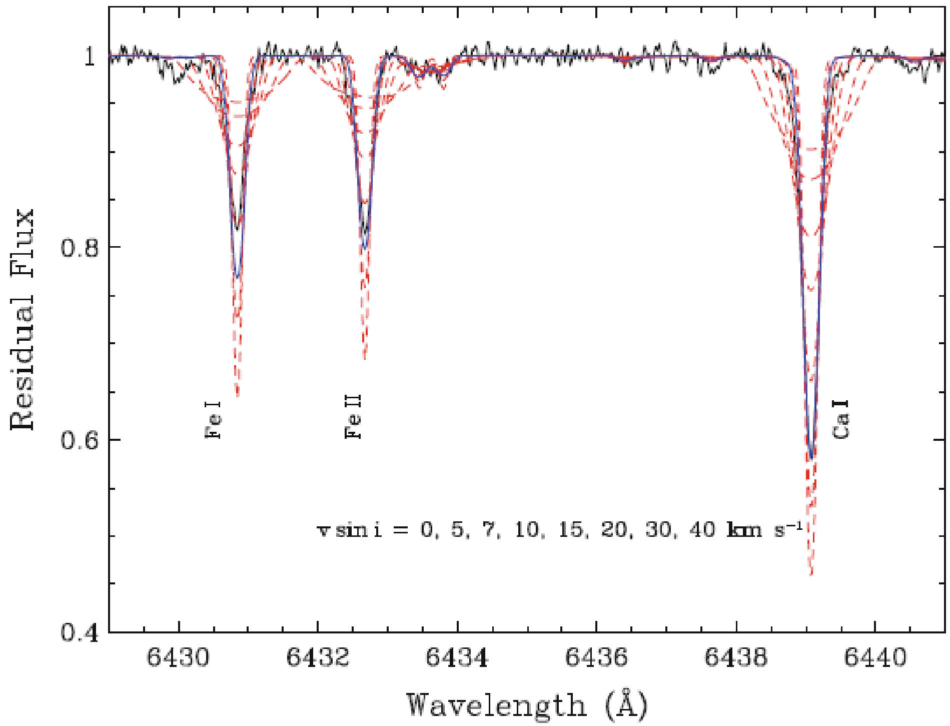

Fig. 4 Part of an observed spectrum with several synthetic spectra overimposed. Each synthetic spectrum was computed for different value of rotational velocity. The best fit is achieved for $v \sin i = 7\,\mathrm{km\,s^{-1}}$

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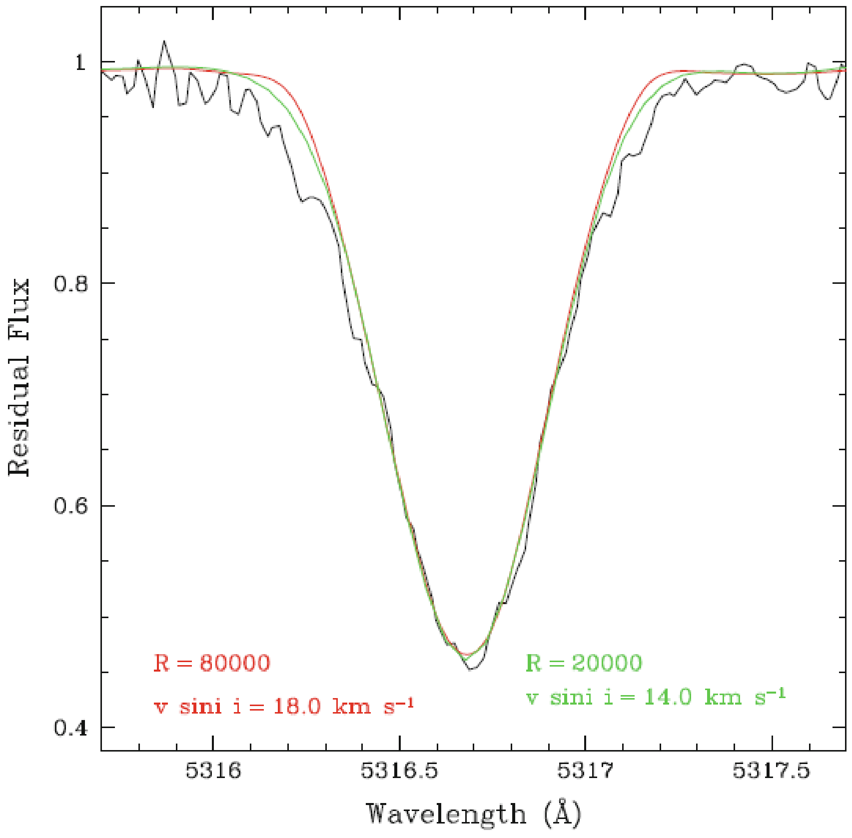
Effect of Resolution



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- Spectrograph resolution can be important.
- Ensure that the correct resolution is used when determining v sin I.

Summary

- Some broadening mechanisms are fixed for all stars and come in the linelists used:
  - Damping Constants
    - Natural (Radiative)
    - Pressure (Stark, VDW)
- Other mechanisms depend on the star.
  - Thermal (Doppler) Broadening
  - Microturbulence
  - Macroturbulence
  - Rotation
- Some are (or can be) free parameters
  - even when they ought not to be!