Towards the Model Photosphere

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HYDROSTATIC EQUILIBRIUM
GAS PRESSURE
ELECTRON PRESSURE

Model atmospheres (example)

$\log \tau_0$	T (K)	$\log P_g$ (dyne/cm²)	$\log P_e$ (dyne/cm²)	$\log \kappa_0/P_e$ (cm²/g per dyne/cm²)	x (km)
Solar model, $S_0 = 1.0$, $\log g = 4.438$ cm/s²					
−4.0	4310	2.87	−1.16	−1.22	−509
−3.8	4325	3.03	−1.02	−1.23	−476
−3.6	4345	3.17	−0.89	−1.24	−448
−3.4	4370	3.29	−0.78	−1.25	−422
−3.2	4405	3.41	−0.66	−1.26	−397
−3.0	4445	3.52	−0.55	−1.28	−373
−2.8	4488	3.64	−0.44	−1.30	−349
−2.6	4524	3.75	−0.33	−1.32	−325
−2.4	4561	3.86	−0.23	−1.33	−301
−2.2	4608	3.97	−0.12	−1.35	−277
−2.0	4660	4.08	−0.01	−1.37	−252
−1.8	4720	4.19	0.10	−1.40	−228
−1.6	4800	4.30	0.22	−1.43	−203
−1.4	4878	4.41	0.34	−1.46	−177
−1.2	4995	4.52	0.47	−1.50	−151
−1.0	5132	4.63	0.61	−1.55	−124
−0.8	5294	4.74	0.76	−1.60	−97
−0.6	5490	4.85	0.93	−1.66	−70
−0.4	5733	4.95	1.15	−1.73	−43
−0.2	6043	5.03	1.43	−1.81	−19
0.0	6429	5.10	1.78	−1.91	0
0.2	6904	5.15	2.18	−2.01	15
0.4	7467	5.18	2.59	−2.11	27
0.6	7962	5.21	2.92	−2.18	37
0.8	8358	5.23	3.16	−2.23	46
1.0	8630	5.26	3.32	−2.25	56
1.2	8811	5.29	3.42	−2.27	68
$S_0 = 0.7$, $\log g = 4.6$, normal abundances					
−4.0	3017	3.22	−2.12	−0.46	−246
−3.0	3111	3.89	−1.51	−0.53	−179

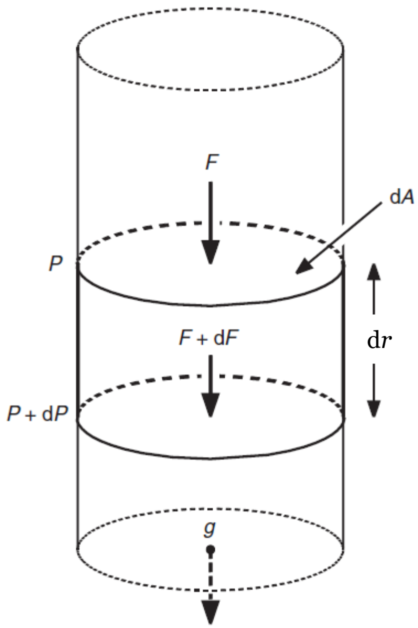
Usual assumptions to start with:

1. Plane parallel geometry, making all physical variables a function of only one space coordinate.
2. Hydrostatic equilibrium, meaning that the photosphere is not undergoing large scale-accelerations comparable to the surface gravity; there is no dynamically significant mass loss.
3. Structures such as granulation or star spots are negligible, or at least can be adequately represented by mean values of the physical parameters.
4. Magnetic fields are excluded.

Ideal gas

We require a knowledge of the **electron pressure** in order to use the Saha equation, which is related to the **gas pressure**. How do we calculate this in stellar atmospheres?

We start with **hydrostatic equilibrium**.



Forces acting upon the volume element of density $\rho(r)$ are gravity:

$$dF_g = -\frac{Gm(r)dm}{r^2} = -\frac{Gm(r)\rho(r)}{r^2}dAdr$$

plus buoyancy (pressure difference × area):

$$dF_P = -dPdA$$

Since the mass of the atmosphere is negligible compared to the stellar mass and the radius of the photosphere is negligible vs the stellar radius R,

$$dF_g = -\frac{Gm(r)\rho(r)}{R^2}dAdr = -g\rho(r)dAdr$$

since

$$g = \frac{Gm(R)}{R^2}$$

Hydrostatic equilibrium

Hydrostatic equilibrium is the balance between gravitational and pressure forces ($dF_g + dF_p = 0$). Then

$$\frac{dP}{dr} = -g\rho(r)$$

We can eliminate $\rho(r)$ with the ideal gas equation, $P_g = \frac{\rho k T}{\mu m_p} = \frac{\Re \rho T}{\mu}$

$$\frac{dP_g}{dr} = -g\frac{\mu(r)}{\Re\, T(r)} P_g(r)$$

where $\Re = \frac{k}{m_p} = 8.3\times10^7$ erg/mol/K is the gas constant

μ - mean molecular weight

Pressure Scale Height

We obtain

$$\frac{1}{P_g}\frac{dP_g}{dr} = \frac{d\ln P_g}{dr} = -\frac{g\mu(r)}{\Re T(r)}$$

For an idealized isothermal ($T(r)$=constant) atmosphere with $\mu(r)$=const, we can integrate this expression

$$P_g(r) = P_g(r_0)e^{-(r-r_0)g\mu/\Re T} = P_g(r_0)e^{-(r-r_0)/H}$$

where we have introduced the scale height *H*,

$$H = \frac{kT}{g\mu m_p} = \frac{\Re T}{g\mu}$$

i.e. gas pressure changes by a factor of **e** over a scale height.

For a (ficticious) atmosphere of constant density, corresponding to the gas pressure at the base of the real atmosphere, we can put the total mass of the real atmosphere into a layer of height *H*.

Examples

Betelgeuse	μ=1 (H)	T=3600K	Log g=0	$H=4R_{\odot}$
Sun	μ=1 (H)	T=6000K	Log g=4.4	H=200 km
Earth	μ=28 (N_2)	T=300K	Log g=3	H=9 km
White Dwarf	μ=0.5 ($H^+ + N_e$)	$T=1.5x10^4$ K	Log g=8	H=0.25 km
Neutron Star	μ=0.5 ($H^+ + N_e$)	$T=10^6 – 10^7$ K	Log g=15	H=2 mm

Gas Pressure $P_g(\rho)$

When using the Saha equation, we need T and P_g in a particular layer of the atmosphere, which can be described by geometric depth t or optical depth τ. Temperature dependence on average optical depth is known

$$T^4(\bar{\tau}) \approx \frac{3}{4}(\bar{\tau} + \frac{2}{3})T_{eff}^4$$

The average optical depth $d\bar{\tau} = -\kappa_R \rho \, dr$ may be expressed via the Rosseland mean opacity per unit mass (cm^2/g), κ_R.

Thus, we generally express the gas pressure as a function of optical depth. From hydrostatic equilibrium we obtain

$$\frac{dP_g}{dr} = -g\rho(r) \quad \longrightarrow \quad \frac{dP_g}{d\bar{\tau}} = \frac{g}{\kappa_R}$$

The gas pressure can now be obtained by integrating this differential equation, although in general κ_R, is a complicated function of temperature and pressure.

Integration of hydrostatic equation

- In the simplest case, assuming a constant mean opacity (which is not a very sensible approximation, but ok for electron scattering), with $\tau=0$ and $P_g=0$ at the surface:

$$P_g = \frac{g}{\kappa_R}\bar{\tau}$$

Knowing $T(\tau)$ for a given T_{eff}, we can assume a value for κ_R, insert this into the above equation and compute a value for the gas pressure.

- More realistically, for this differential equation can be obtained the following formal solution (look at the Gray textbook):

$$\frac{dP_g}{d\bar{\tau}} = \frac{g}{\kappa_R}$$

$$P_g = g^{2/3}\left(\frac{3}{2}\int_{-\infty}^{\log\tau_0}\frac{t_0 P_g^{1/2}}{\kappa_0 \log e}\,d\log t_0\right)^{2/3}$$

where κ_0 *is* the opacity at some reference wavelength (e.g. 5000Å).

Guess $P_g(\tau_0)$ for all τ_0 initially and then numerically evaluate the integral on the right for each τ_0 to obtain a better estimate of $P_g(\tau_0)$ on the left-hand side. Iterate this procedure.

Gravity dependence of P_g

$$P_g = g^{2/3}\left(\frac{3}{2}\int_{-\infty}^{\log \tau_0} \frac{t_0 P_g^{1/2}}{\kappa_0 \log e}\,\mathrm{d}\log t_0\right)^{2/3}$$

The pressure dependence inside the integral is weak and so

$$P_g \approx C(T) g^{2/3}$$

i.e. the gas pressure for a given optical depth increases with $g^{2/3}$.

Increasing the surface gravity the photosphere compresses, increasing all pressures.

For different stars we see down to $\tau=2/3$, whose pressure varies approximately as $g^{2/3}$.

The larger the pressure, the greater the Rosseland mean opacity, so we see geometrically higher layers in stars with higher gravity.

Giants have deep atmospheres, dwarfs thin ones.

Electron pressure

So far, we have dealt with the gas pressure, but it is the **electron** pressure that is needed in the Saha equation.

We can generally say,

$$P_g = NkT$$

where N is the sum of all particles/cm^3 , and

$$P_e = n_e kT$$

with n_e=number of electrons/cm^3. Of course,

$$n_e = n^+ + 2n^{2+} + 3n^{3+} \text{ etc.}$$

In the simplest case of pure hydrogen,

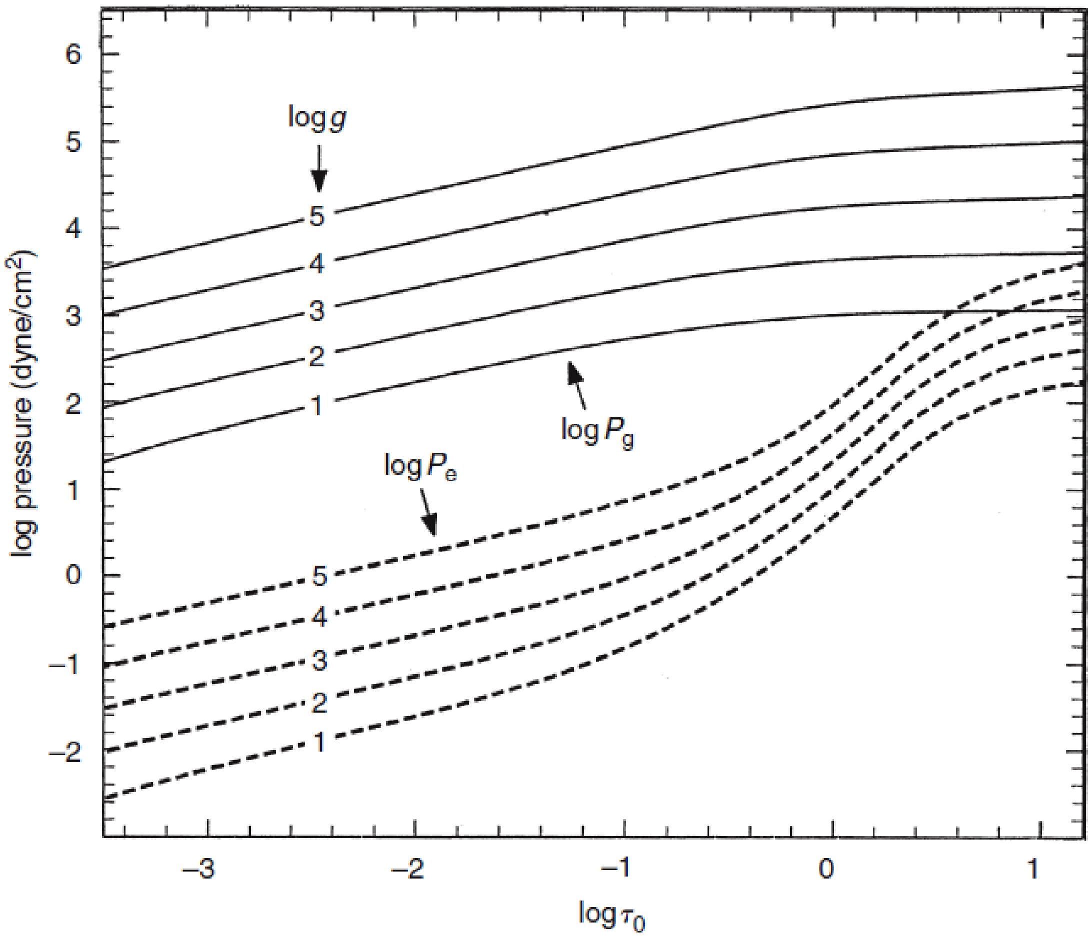
$$N = N(H) + N(H^+) + n_e = N(H) + 2N(H^+) = P_g / kT$$

since from charge conservation $n_e = N(H^+)$.

For ionized hydrogen, we find $P_e = 0.5 P_g$, For doubly ionized helium, $P_e = 2/3\ P_g$.

Given $N(H^+) n_e / N(H) = f(T)$ from Saha equation, we may solve for $N(H^+) = n_e$ and $N(H)$, if T and P_g are known.

Numerical examples



Numerical results show, that the gas pressure exponent is not 2/3, but ranges from 0.57 to 0.64 from shallow to deep layers.

The electron pressure dependence on gravity has two regimes, for cooler and hotter models.
For solar-type stars, approximately, $P_e^2 \propto P_g$, so an exponent of 1/3 predicted, while for hotter stars 2/3.

Numerical calculations show 0.48 to 0.33 from shallow to deep layers in the cooler model, and 0.53 to 0. 82 in the hotter model (Gray Fig. 9.13).

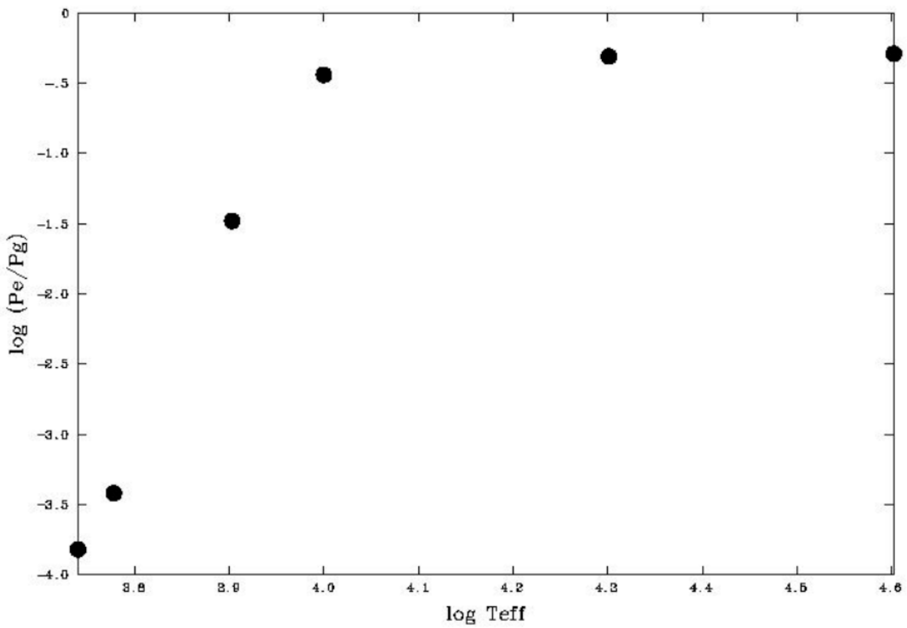
Role of Metals?

For a pure H atmosphere in the case of the Solar photosphere, the gas pressure greatly exceeds the electron pressure. Although metals are few in number, some are very easily ionized e.g. Na/H=2×10^{-6}, Mg/H=3×10^{-5}, Al/H=2.7×10^{-6}, Ca/H=2×10^{-6}, Si/H=3×10^{-5}. These will **contribute** electrons to the atmosphere, increasing P_e and suppress ionization.

	Atom	Stage of ionization													
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
1	H	13.598 44													
2	He	24.587 41	54.417 78												
3	Li	5.391 72	75.640 18	122.454											
4	Be	9.322 63	18.211 16	153.897	217.713										
5	B	8.298 03	25.154 84	37.931	259.366	340.22									
6	C	11.260 30	24.383 32	47.888	64.492	392.08	489.98								
7	N	14.534 14	29.601 3	47.449	77.472	97.89	552.06	667.03							
8	O	13.618 06	35.117 30	54.936	77.413	113.90	138.12	739.29	871.41						
9	F	17.422 82	34.970 82	62.708	87.140	114.24	157.17	185.19	953.91	1 103.1					
10	Ne	21.564 54	40.963 28	63.45	97.12	126.21	157.93	207.28	239.10	1 195.8	1 362.2				
11	Na	5.139 08	47.286 4	71.620	98.91	138.40	172.18	208.50	264.25	299.9	1 465.1	1 648.7			
12	Mg	7.646 24	15.035 28	80.144	109.265	141.27	186.76	225.02	265.96	328.1	367.5	1 761.8	1 963		
13	Al	5.985 77	18.828 56	28.448	119.99	153.83	190.49	241.76	284.66	330.1	398.8	442.0	2 086	2 304	
14	Si	8.151 69	16.345 85	33.493	45.142	166.77	205.27	246.49	303.54	351.1	401.4	476.4	523	2 438	2 673
15	P	10.486 69	19.769 4	30.203	51.444	65.03	220.42	263.57	309.60	372.1	424.4	479.5	561	612	2 817
16	S	10.360 01	23.337 9	34.79	47.222	72.59	88.05	280.95	328.75	379.6	447.5	504.8	564	652	707
17	Cl	12.967 64	23.814	39.61	53.465	67.8	97.03	114.20	348.28	400.1	455.6	529.3	592	657	750
18	Ar	15.759 62	27.629 67	40.74	59.81	75.02	91.01	124.32	143.46	422.5	478.7	539.0	618	686	756
19	K	4.340 66	31.63	45.806	60.91	82.66	99.4	117.56	154.88	175.8	503.8	564.7	629	715	787
20	Ca	6.113 16	11.871 72	50.913	67.27	84.50	108.78	127.2	147.24	188.5	211.3	591.9	657	727	818
21	Sc	6.561 44	12.799 67	24.757	73.489	91.65	111.68	138.0	158.1	180.0	225.2	249.8	688	757	831
22	Ti	6.828 2	13.575 5	27.492	43.267	99.30	119.53	140.8	170.4	192.1	215.9	265.1	292	788	863
23	V	6.746 3	14.66	29.311	46.71	65.28	128.1	150.6	173.4	205.8	230.5	255.1	308	336	896
24	Cr	6.766 64	16.485 7	30.96	49.16	69.46	90.64	161.18	184.7	209.3	244.4	270.7	298	355	384
25	Mn	7.434 02	15.639 99	33.668	51.2	72.4	95.6	119.20	194.5	221.8	248.3	286.0	314	344	404
26	Fe	7.902 4	16.187 8	30.652	54.8	75.0	99.1	124.98	151.06	233.6	262.1	290.2	331	361	392
27	Co	7.881 0	17.083	33.50	51.3	79.5	103	131	160	186.2	276.2	305	336	379	411
28	Ni	7.639 8	18.168 84	35.19	54.9	75.5	108	134	164	193	224.6	321	352	384	430
29	Cu	7.726 38	20.292 40	36.841	55.2	79.9	103	139	167	199	232	266	369	401	435
30	Zn	9.394 05	17.964 40	39.723	59.4	82.6	108	136	175	203	238	274	311	412	454

Gas and electron pressures

To calculate the electron density properly, all low ionization energy species and their corresponding abundances should be included.



For ionized hydrogen, we find $P_e = 0.5 P_g$,
For doubly ionized helium, $P_e = 2/3\ P_g$.

Gas and electron pressures

$T_{\rm eff}$	Log g	Log $P_g(\tau=2/3)$	Log $P_e(\tau=2/3)$
5500	4	4.83	1.01
6000	4	4.76	1.34
8000	4	3.94	2.46
10000	4	3.03	2.59
20000	4	3.40	3.09
40000	4	3.58	3.29

Radiation Pressure, P_r

- Radiation may also have an effect on the pressure. Radiation is an inefficient carrier of momentum (velocities have the highest possible value), but when a photon is absorbed or scattered by matter, it imparts not only its energy to that matter, but also its momentum $h\nu/c$.

- Let's now recall the definition of the K-integral and Eddington approximation (Lectures 7).

Summary

- Hydrostatic equilibrium – P_g changes by a factor of e=2.71 over the scale height.
- $P_g(\rho)$ scales with $g^{1/2}$ in Solar-type stars.
  Dwarfs have high P_g & high mean opacities (thin atmospheres) whilst (super)giants have low P_g and low mean opacities (deep atmospheres).
- Increased P_e in Solar-type stars from readily ionized metals versus pure H case. Ratio of electron to gas pressure is strong function of T.

- **Radiation** may also have an effect on the pressure! We discussed it in previous lectures.

Measuring temperatures and surface gravities

DIRECT MEASUREMENT OF RADII
DETERMINING EFFECTIVE TEMPERATURE AND SURFACE GRAVITY
MODEL-INDEPENDENT METHODS
MODEL-DEPENDENT METHODS
ATMOSPHERIC MODELS
PHOTOMETRIC METHODS
SPECTROSCOPIC METHODS

Fundamental parameters

Stellar parameters:

- Luminosity (L)
- Mass (M)
- Radius (R)

In most cases, cannot be measured directly

Can help in measuring L & M

Atmosphere parameters:

- Effective Temperature (T_{eff})
- Surface gravity ($\log g$)

- Chemical composition (metallicity, element abundances)

~90% of stars in the Galaxy are "normal" (close to the Sun)

Surface Flux, Luminosity and T_{eff}

- Integral over frequency / wavelength at outer boundary (Surface Flux):

$$F_s = \int_0^\infty F_\lambda \, d\lambda$$

- Multiplied by stellar surface area yields the Luminosity, total energy radiated away by the star

$$L = 4\pi R^2 F_s$$

- The total energy arriving above the Earth's atmosphere is its observed flux, $F_\oplus$, corrected for the distance to the star d, neglecting interstellar absorption:

$$L = 4\pi d^2 F_\oplus \quad \rightarrow \quad F_s = F_\oplus (d/R)^2$$

- The Stefan-Boltzmann law, $F = \sigma T_{eff}^4$, or alternatively $L/4\pi R^2 = \sigma T_{eff}^4$ defines the "effective temperature" of a star, i.e. the temperature which a black body would need to radiate the same amount of energy as the star.

Model-independent methods (1)

Direct measurements:

$f_\oplus$ – the flux measured at the Earth ($F_\oplus$ - bolometric flux at the Earth)
F_S – the flux emitted from the stellar surface
d – the distance from us to the star
R – the radius of the star
θ – the angular radius of the star, R/d

Example:
$d = 1.3$ pc, $R = 700000$ km
$\theta = 0.004$ arcsec !!

$$4\pi d^2 F_\oplus = 4\pi R^2 F_S$$

We can relate this equation to the effective temperature

$$F_\oplus = \int_0^\infty f_\oplus(\nu)\, d\nu = \theta^2 \sigma T_{eff}^4$$

If θ is measured and the distance d is known, e.g. from parallax (Gaia, Hipparcos, etc.), then we can obtain R and L.

Inteferometric radii

- We have already introduced interferometry regarding limb darkening (Lecture 18).
- Several ground-based optical and IR interferometers are currently in operation.
- Reliable diameters generally restricted to nearby late-type giants with large angular radii on the sky.
- Radii of a few hundred stars are measured with an accuracy better than 10%.

- **VLTI** (Paranal, Chile): currently the most advanced optical/IR interferometer in operation. Combines large apertures of individual 8-m VLT telescopes with dedicated auxiliary 1.8-m telescopes.
- **Imaging Atmospheric Cherenkov Telescopes** (MAGIC, VERITAS, H.E.S.S., LST-1) are very promising

The New Set at Paranal - The VLT, the VST Dome and the AT1

ESO PR Photo 02d/04 (30 January 2004) © European Southern Observatory

The AT1 Positioned Next to the VLTI Laboratory

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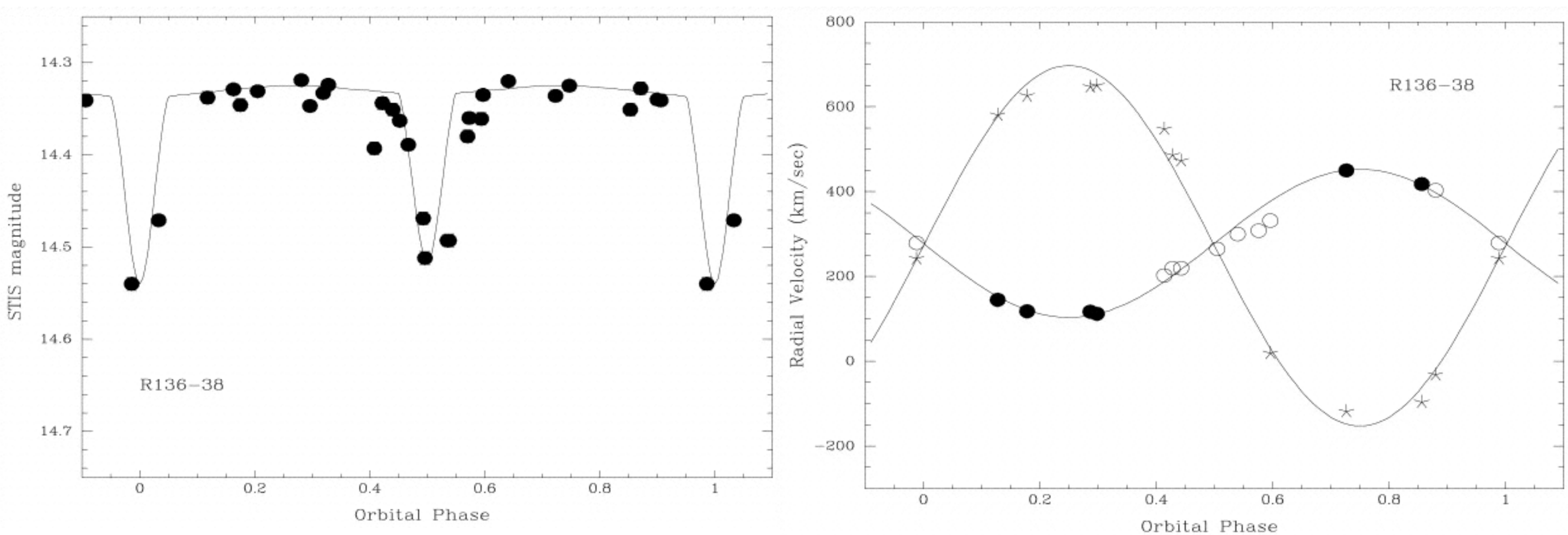
Radii from other direct methods

- **Occultations**
  - Moon used as "knife-edge"
  - Diffraction pattern recorded as flux vs. time
  - Precision ~ 0.5 mas
  - A few hundred radii have been determined
- **Eclipsing binaries**
  - Photometry gives ratio of radii to semi-major axes. Useful simulation at http://www.midnightkite.com/binstar/StarLightPro.exe
  - Velocities from spectra give semi-major axes (i=90°)

Binary Masses

Accurate radii and masses can be obtained from analysis of photometric light curves (*R, I*) & spectroscopic orbit information ($M \sin^3 i$). If eclipsing $i \cong 90°$ → *R, M*.



R136-38 (Massey et al. 2002, ApJ 565, 982) light curve analysis of O3V+O6V in LMC (P=3.4 day): $9.3R_\odot$ (primary) $6.4R_\odot$ (secondary)

Model-independent methods (2)

Direct measurements:

$$4\pi d^2 F_{\oplus} = 4\pi R^2 F_S \qquad g = \frac{GM}{R^2}$$

$$F_{\oplus} = \int_0^{\infty} f_{\oplus}(\nu)\, d\nu = \theta^2 \sigma T_{eff}^4$$

Difficult to reliably measure $F_{\oplus}$ because of interstellar absorption in UV (especially beyond the Lyman continuum)

Model-dependent methods

Using, e.g., model atmospheres and/or theoretical evolution tracks.

- $T_{\rm eff}$ from Bolometric Corrections
  - Lecture 17
- Log g from parallaxes

$$\log g/g_{\odot} = \log M/M_{\odot} + 4 \log T_{\rm eff}/T_{\rm eff,\odot} + 0.4(\mathrm{M}_{\rm bol} - \mathrm{M}_{\rm bol,\odot})$$

- Method of IR fluxes (Blackwell & Shallis 1977)

$$4\pi d^2 F_{\oplus} = 4\pi R^2 F_S \quad \rightarrow \quad \frac{F_{\oplus}}{F_S} = \frac{R^2}{d^2} = \theta^2 = \frac{f_{\oplus}}{f_S}$$

$$T_{eff}^4 = \frac{F_{\oplus}}{\theta^2 \sigma}$$

Also correct for monochromatic fluxes

Alonso et al. : T_{eff}(IRFM) for 1000+ stars

Atmospheric Models

Model atmospheres (T_{eff}, log g, chem. composition)

↓

Specific Intensities (λ)

↓

Emergent Fluxes (λ)

UBVRI… *(U-B),(B-V),(V-R)*,… W_{λ} Line profiles

↓

Observations

Atmospheric Models (1)

- For most stars, Kurucz LTE atmosphere models, accounting for "line blanketing" from metals, generally suffice http://kurucz.harvard.edu/grids.html
- For early-type stars, several non-LTE line blanketed models exist: TLUSTY http://tlusty.oca.eu for plane-parallel O stars, or for O stars with extended atmospheres WMbasic https://www.usm.uni-muenchen.de/people/adi/Programs/Programs.html
- For very late-type stars, opacity from molecules are important e.g. PHOENIX http://phoenix.astro.physik.uni-goettingen.de

Kurucz models

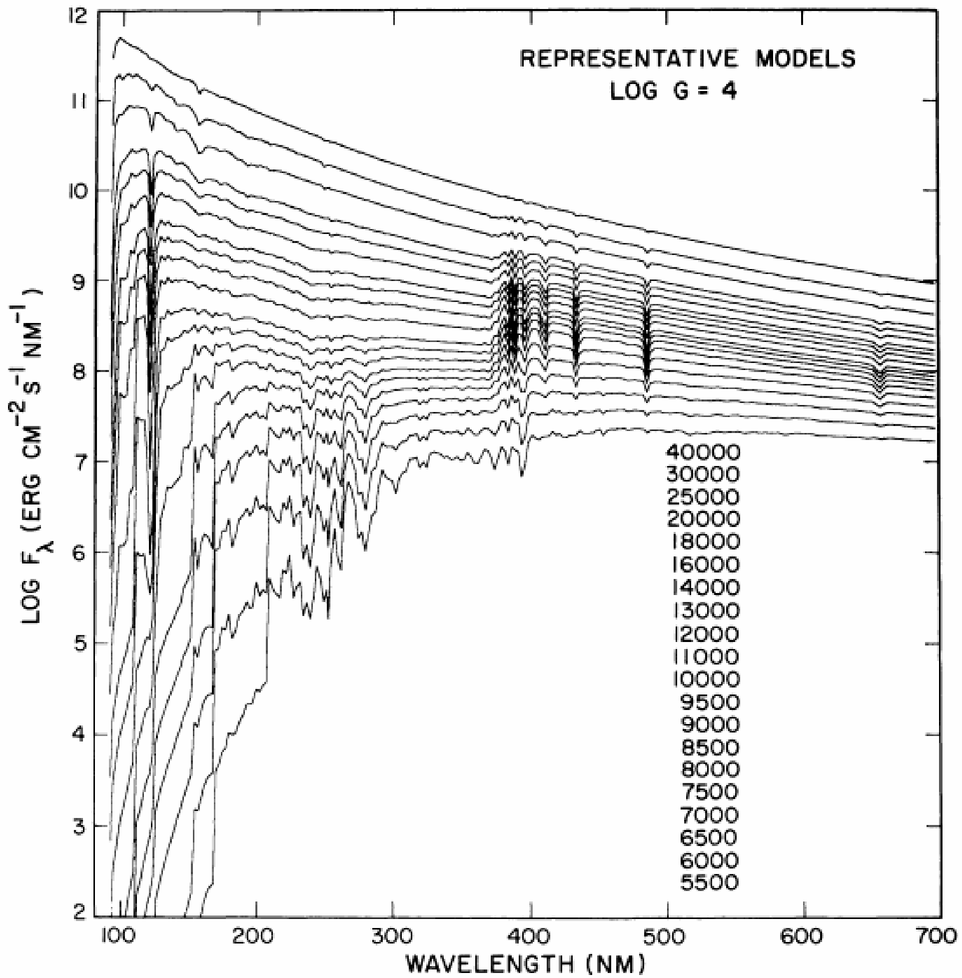


FIG. 16.—The flux F_λ redward of the Lyman limit as a function of T_{eff}

Atmospheric Models (2)

- To determine $T_{\rm eff}$ and $\log g$, one has to use spectral characteristics which are insensitive to chem. composition.
- At least one parameter should have a stronger dependence on $T_{\rm eff}$ than on $\log g$, and another one in the opposite way.
- The more parameters the better.

- If $T_{\rm eff}$ is fixed, then $g = \frac{GM}{R^2} = \frac{4\pi GM\sigma T_{eff}^4}{L}$ → $L \sim \frac{M}{g} T_{eff}^4$

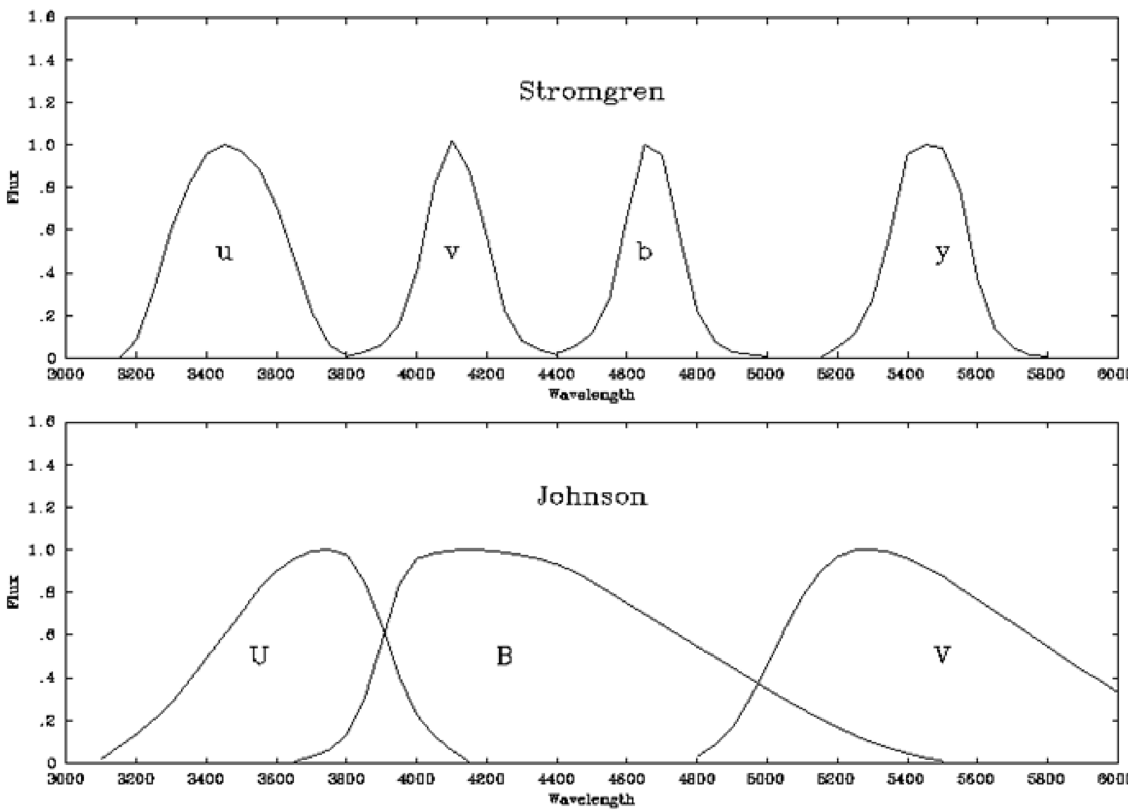
using $L \sim M^n$, we get $g \sim M^{(1-n)}$

g – a luminosity criterium

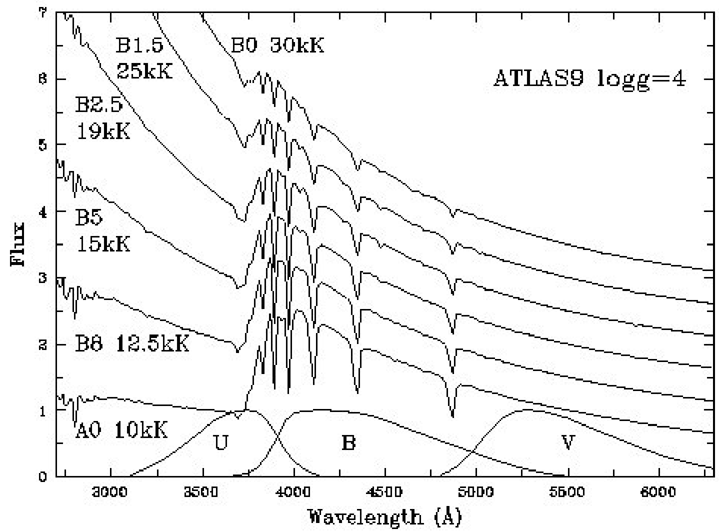
Photometric Methods

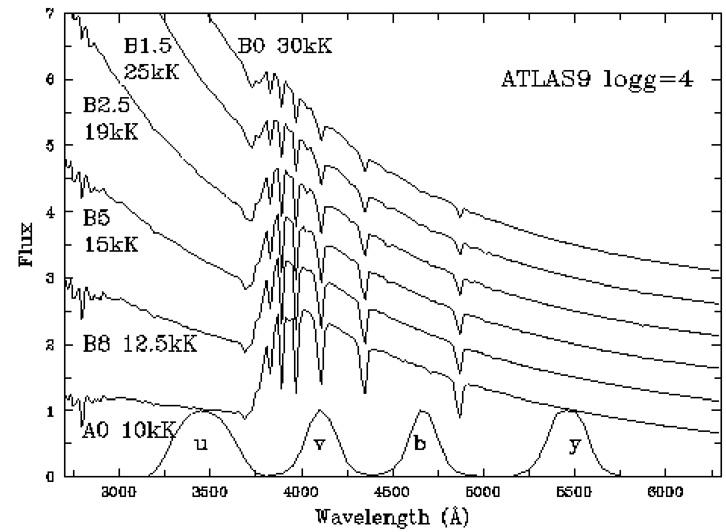
Alternative photometric systems to Johnson *UBV* are available – notably Strömgren (1963) *ubvy*.

These are narrower filters and are rather more useful in extracting T_{eff} and log g than *UBV*.



UBV versus uvby photometry





A comparison of synthetic Kurucz models for the Balmer jump in B dwarfs with the usual Johnson *UBV* filters (left) and Strömgren *ubvy* filters (right). The *U* filter is sensitive to radiation on both sides of the discontinuity, whilst the narrow Stromgren *u* filter samples light below 3647 & *v* filter samples light above, so the *u-v* colour provides T_{eff}.

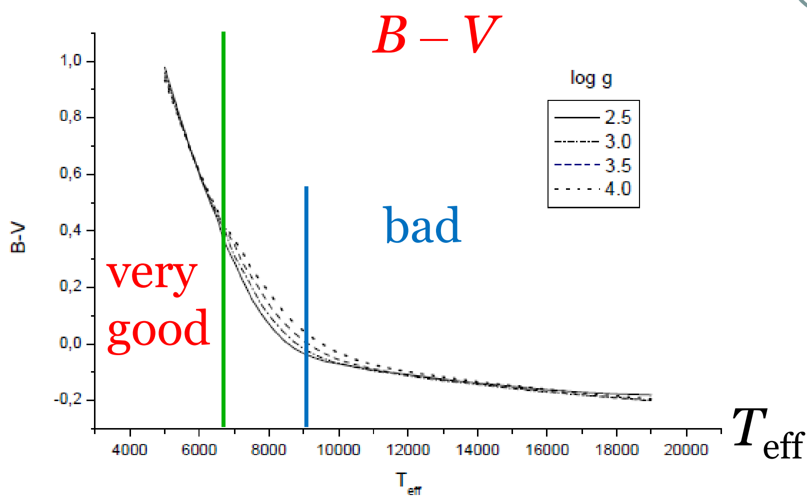
Photometric Methods

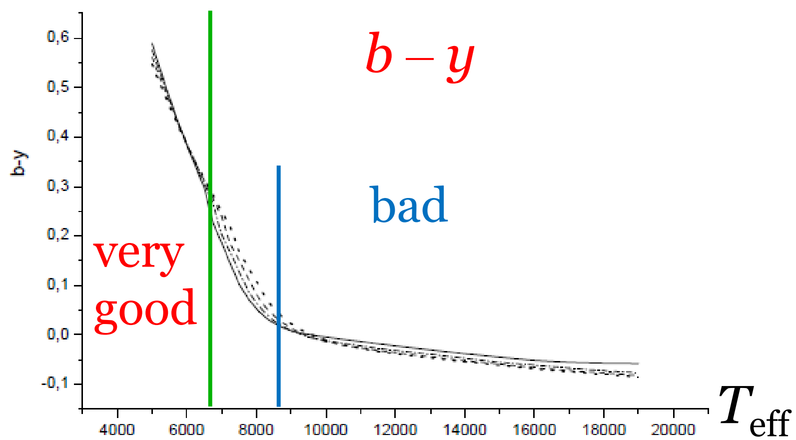
T_{eff} from photometry

- The slope of the Paschen continuum, F_{4000}/F_{7000}
- $\mathrm{c}_1 = (u - v) - (v - b)$ for A0 stars and earlier
- $b - y$, $B - V$, $V - K$ for F stars and later

} $f\,(T_{\text{eff}})$

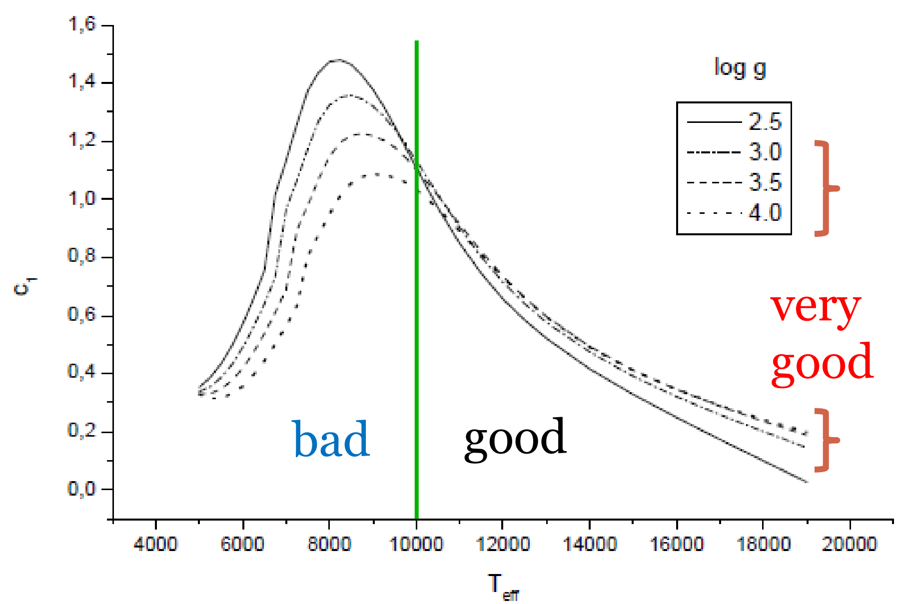
Photometric Methods





Kurucz atmosphere models

$c_1 = (u - v) - (v - b)$

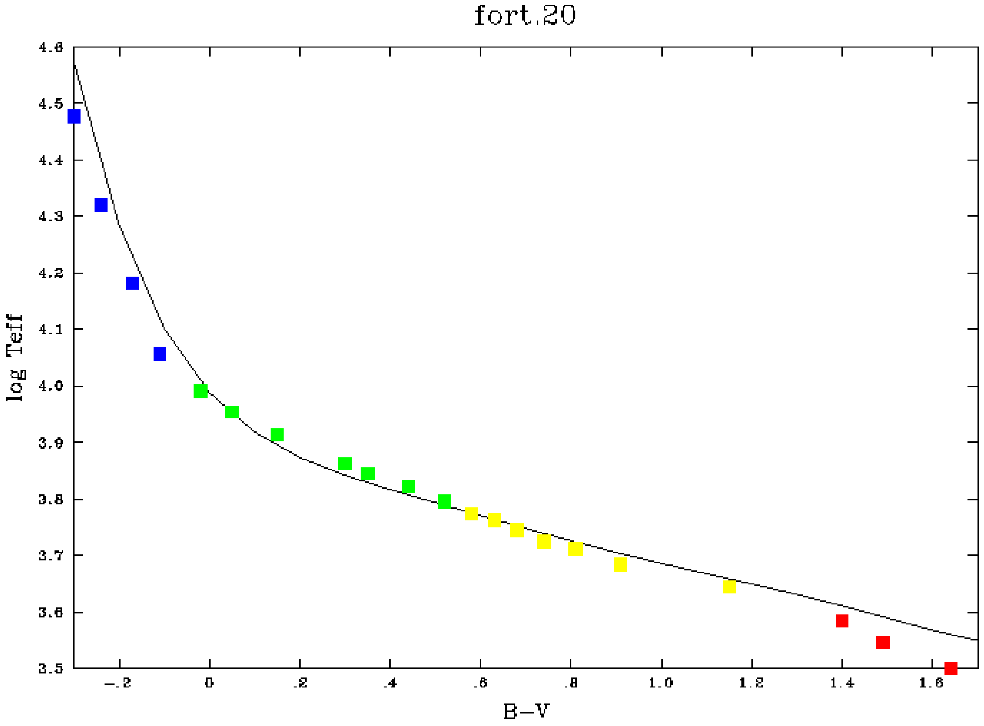


Temperatures from photometry

Observed *B-V* colour index generally allows T_{eff} for normal stars ($0<B\text{-}V<1.5$):

$$\log T_{eff} = 3.988 - 0.881(B-V) + 2.142(B-V)^2 - 3.614(B-V)^3 + 3.2637(B-V)^4 - 1.4727(B-V)^5 + 0.26(B-V)^6$$

Beyond this range most flux is originating in the UV or IR so *B-V* becomes insensitive to temperature.



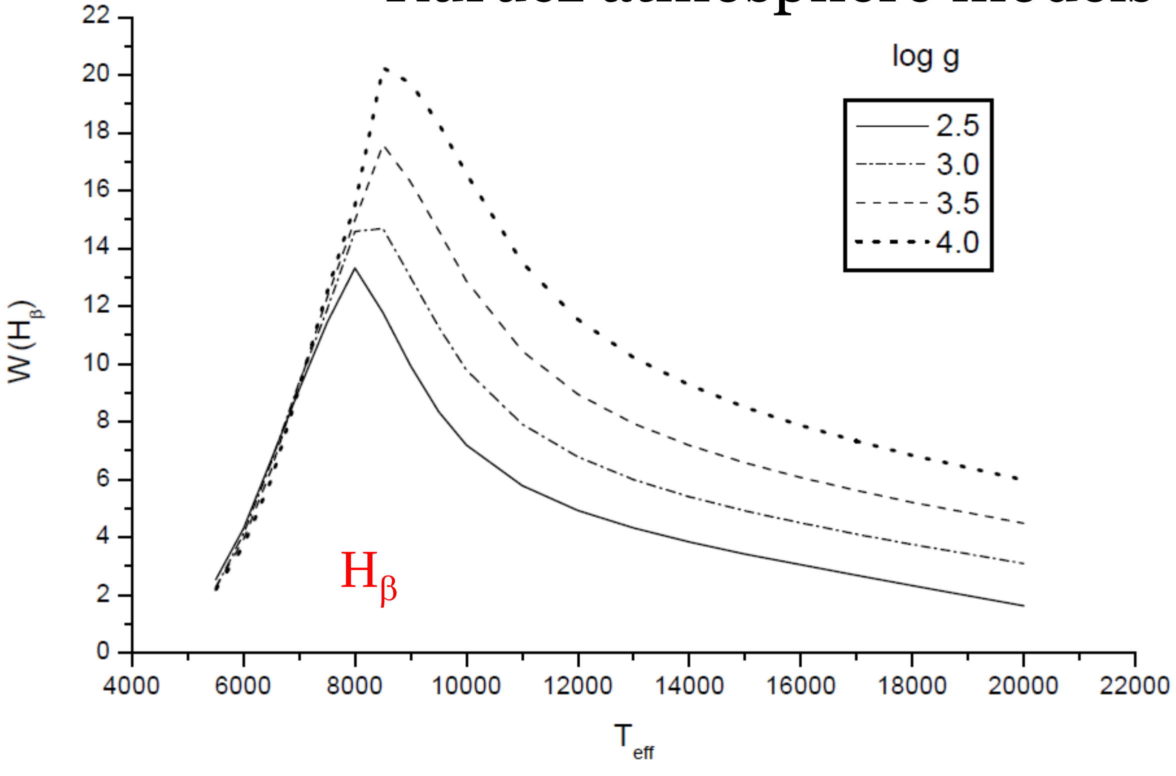
Spectroscopic methods

Equivalent Widths of Balmer lines

Good indicators of T_{eff} when T_{eff}<9000 K

If T_{eff} is higher, then indicators of log g.

Kurucz atmosphere models



Spectroscopic methods

Wings of strong metal lines

Broadening:

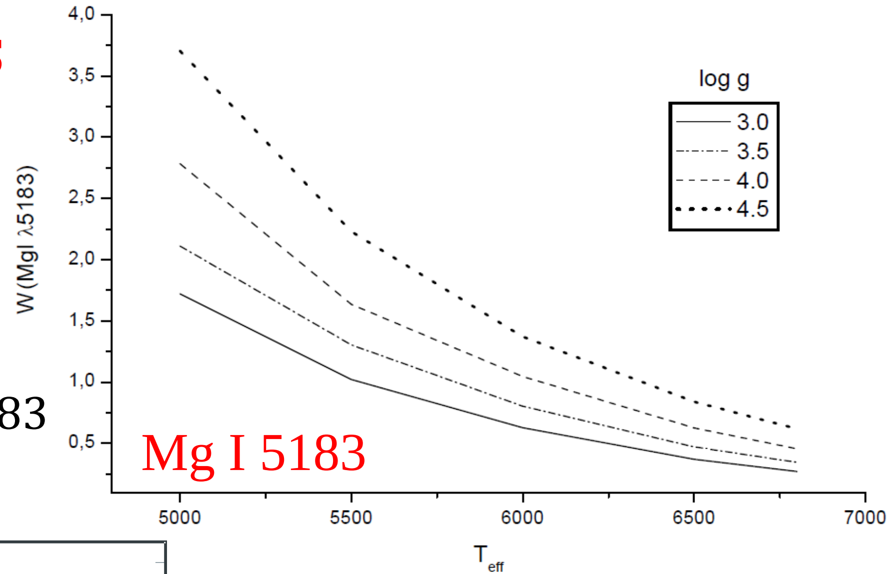
Cool stars - **Van der Waals**

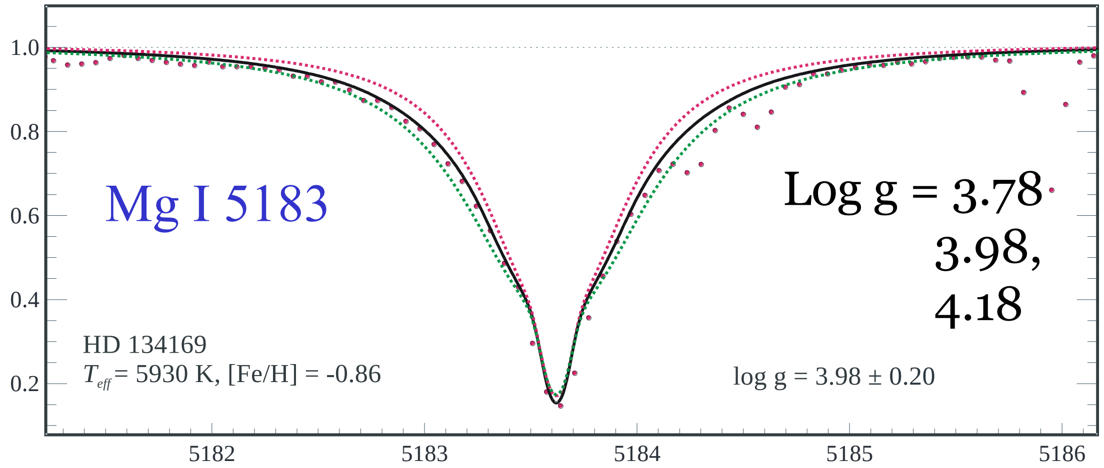
Hot stars - **Quadratic Stark**

Good indicators of *g*:

G, K, M stars: Na D, Ca I 4226, Mg I 5172, 5183

F, A, B stars: resonance lines Ca II, Mg II





For example, Mg I 5183 is a good indicators of log *g* when T_{eff}<6000 K.

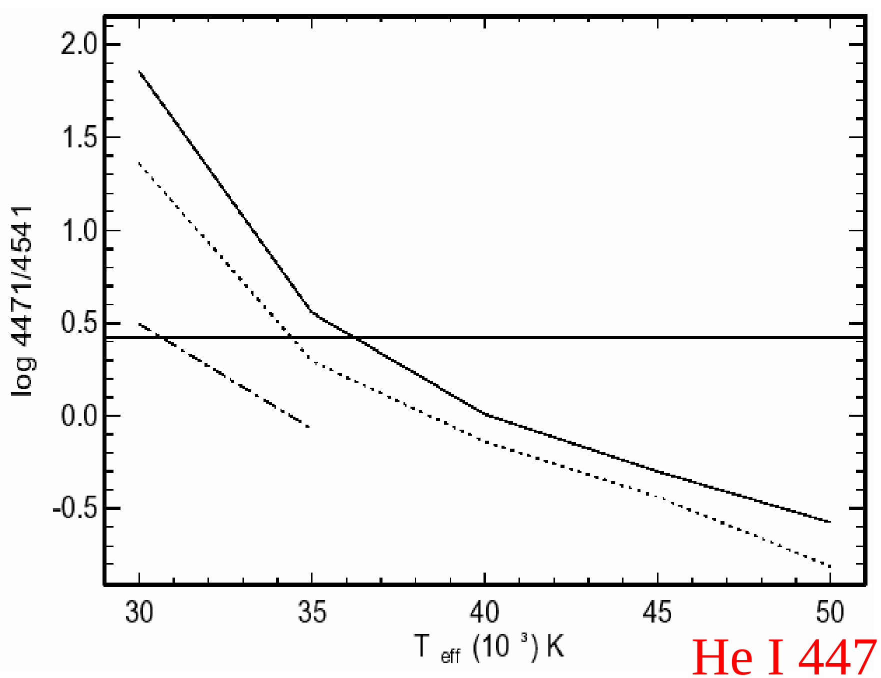
Spectroscopic methods

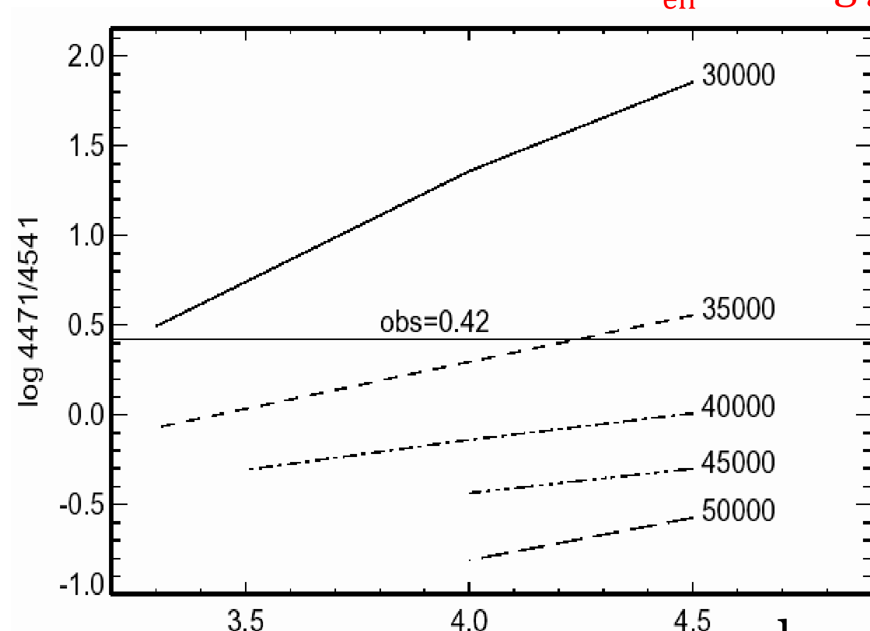
Equivalent Width ratios of species in two consecutive ionization states

G, K, M stars: Fe I and Fe II

O, B stars: He I and He II, Si III and Si IV

He I 4471/ He II 4511 can be an indicator of both $T_{\rm eff}$ and $\log g$

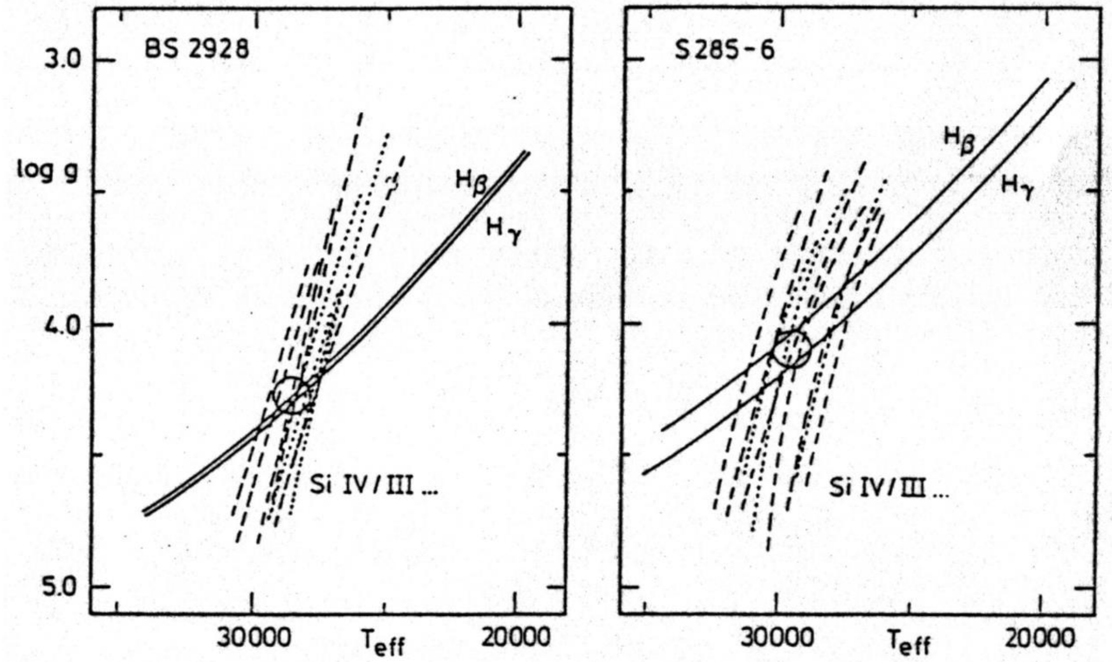


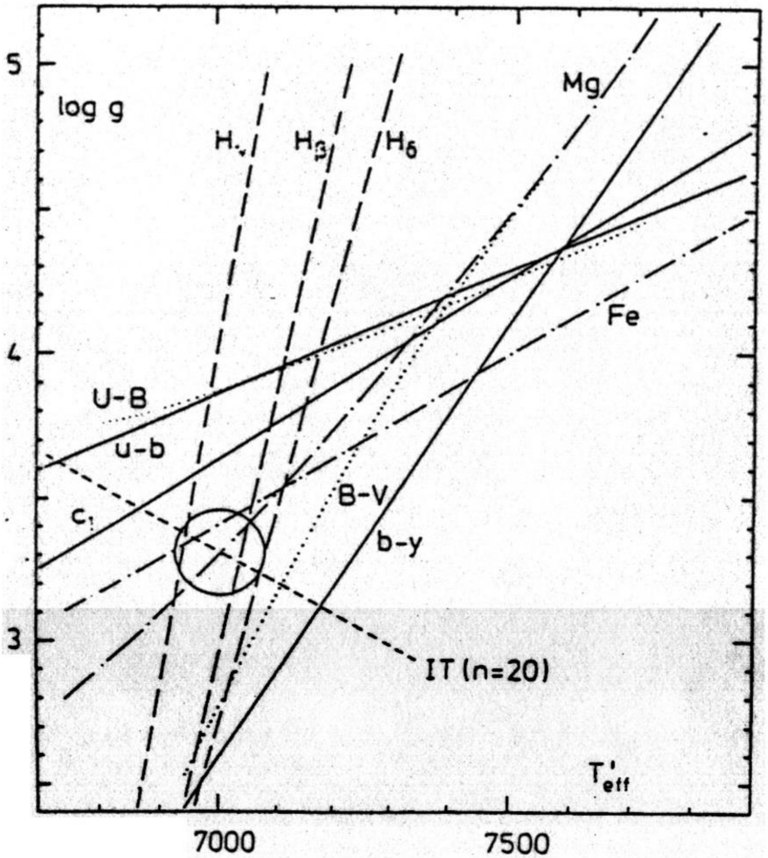


log g

He I 4471/ He II 4511

Examples





The different criteria for determining $T_{\rm eff}$ and $\log g$ are collected in the corresponding parameter plane with the final stellar parameters obtained from the mean intersection point

Summary

- Radii directly measured from interferometry (e.g. VLTI) if distance known from parallax (e.g. Gaia). Currently restricted to K & M giants.
- Masses/radii directly measured from close binaries. Otherwise, reliant upon models…
- Balmer jump sensitive to T_{eff} and N_e in F & G stars. (Discontinuity decreases with increasing N_e due to greater role of H^- ion)
- Balmer jump sensitive to T_{eff} in A & B stars (negligible role of H^- ion)
- Balmer jump absent in O stars (e.s. dominates opacity) so need to use line spectrum.