

Towards the Model Photosphere

343

HYDROSTATIC EQUILIBRIUM
GAS PRESSURE
ELECTRON PRESSURE

Model atmospheres (example)

344

$\log \tau_0$	T (K)	$\log P_g$ (dyne/cm ²)	$\log P_e$ (dyne/cm ²)	$\log \kappa_0/P_e$ (cm ² /g per dyne/cm ²)	x (km)
Solar model, $S_0 = 1.0$, $\log g = 4.438$ cm/s ²					
-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:

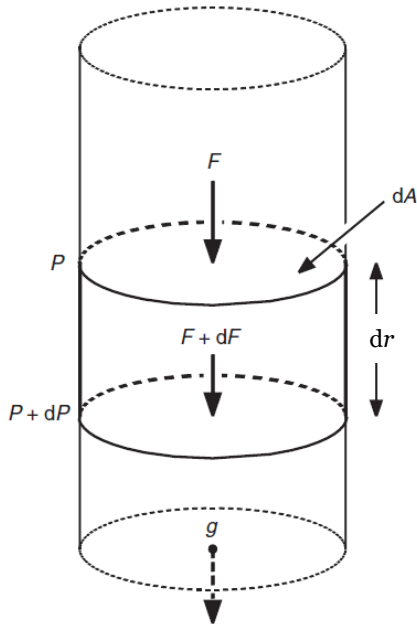
1. **Plane parallel geometry**, making all physical variables a function of only one space coordinate.
2. **Hydrostatic equilibrium**, meaning that the photosphere is not undergoing large scale-accelerations comparable to the surface gravity; there is no dynamically significant mass loss.
3. **Structures** 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

345

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 \times 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

346

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, $P_g = \frac{\rho kT}{\mu m_p} = \frac{\mathfrak{R}\rho T}{\mu}$

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

where $\mathfrak{R} = \frac{k}{m_p} = 8.3 \times 10^7$ erg/mol/K is the gas constant

μ - mean molecular weight

Pressure Scale Height

347

We obtain

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

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

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

where we have introduced the **scale height** H ,

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

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

For a (**fictitious**) 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

348

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

Gas Pressure $P_g(\rho)$

349

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

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

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

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

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

350

- 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):

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

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

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

351

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

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

352

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/cm³, and

$$P_e = n_e kT$$

with n_e = number of electrons/cm³. Of course,

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

In the simplest case of pure hydrogen,

$$N = N(\text{H}) + N(\text{H}^+) + n_e = N(\text{H}) + 2N(\text{H}^+) = P_g / kT$$

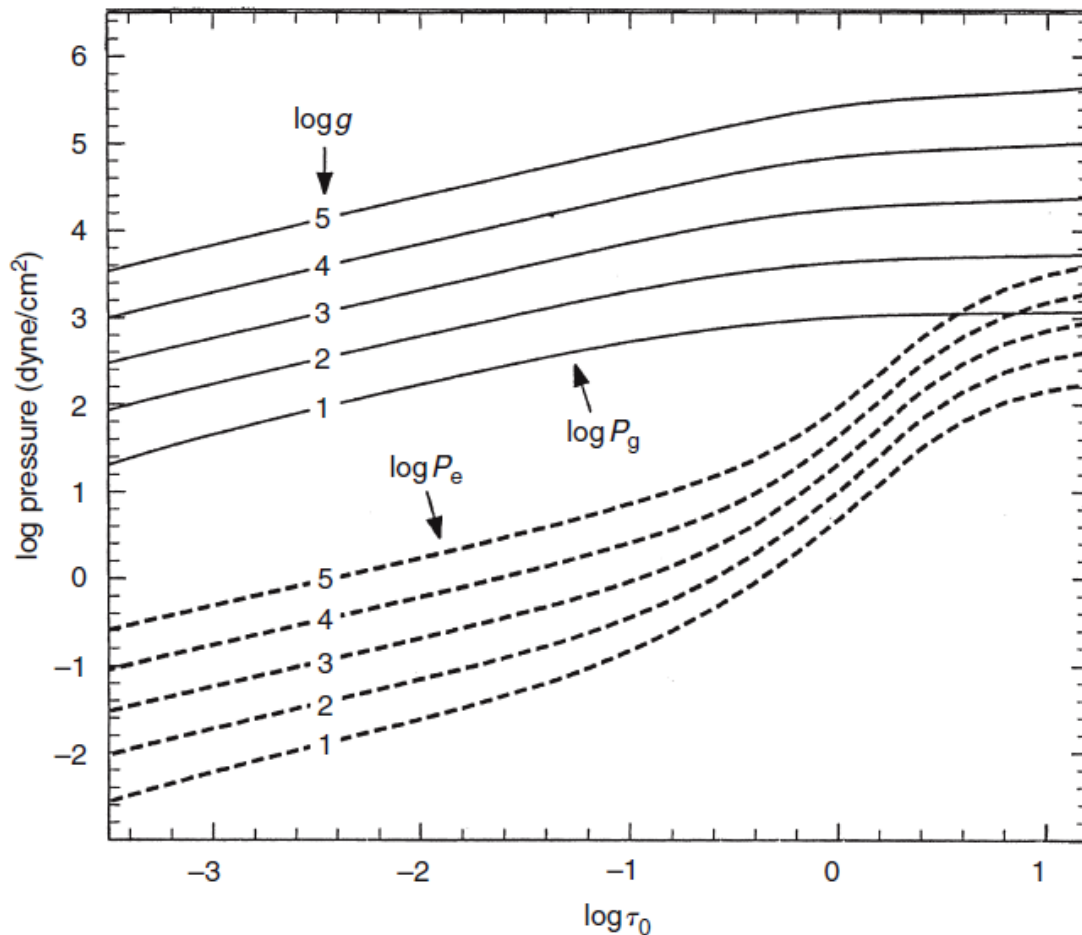
since from **charge conservation** $n_e = N(\text{H}^+)$.

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

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

Numerical examples

353



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?

354

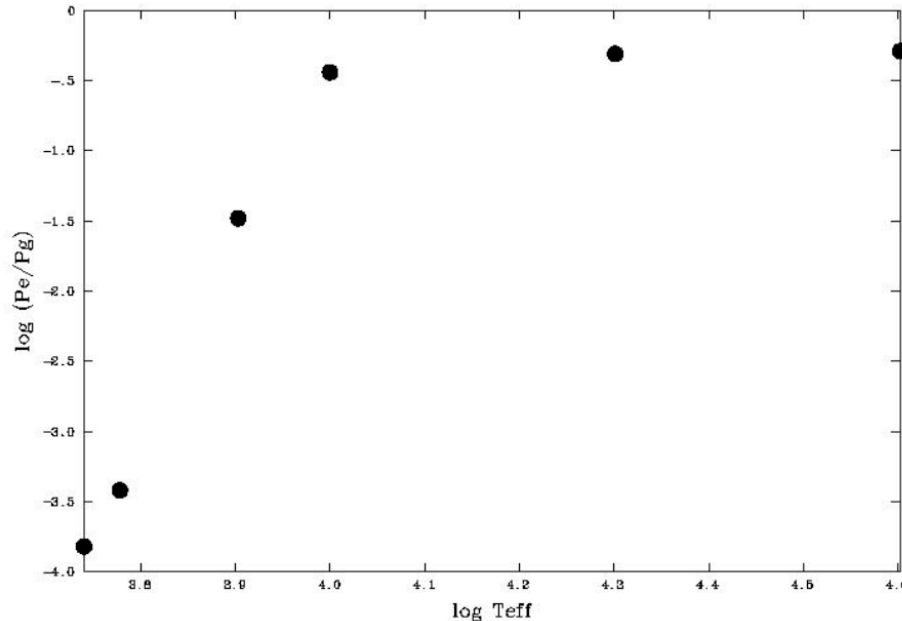
For a pure H atmosphere in the case of the Solar photosphere, the gas pressure greatly exceeds the electron pressure. Although metals are few in number, some are very easily ionized e.g. $\text{Na}/\text{H}=2 \times 10^{-6}$, $\text{Mg}/\text{H}=3 \times 10^{-5}$, $\text{Al}/\text{H}=2.7 \times 10^{-6}$, $\text{Ca}/\text{H}=2 \times 10^{-6}$, $\text{Si}/\text{H}=3 \times 10^{-5}$. 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	13.59844													
2 He	24.58741	54.41778												
3 Li	5.39172	75.64018	122.454											
4 Be	9.32263	18.21116	153.897	217.713										
5 B	8.29803	25.15484	37.931	259.366	340.22									
6 C	11.26030	24.38332	47.888	64.492	392.08	489.98								
7 N	14.53414	29.6013	47.449	77.472	97.89	552.06	667.03							
8 O	13.61806	35.11730	54.936	77.413	113.90	138.12	739.29	871.41						
9 F	17.42282	34.97082	62.708	87.140	114.24	157.17	185.19	953.91	1103.1					
10 Ne	21.56454	40.96328	63.45	97.12	126.21	157.93	207.28	239.10	1195.8	1362.2				
11 Na	5.13908	47.2864	71.620	98.91	138.40	172.18	208.50	264.25	299.9	1465.1	1648.7			
12 Mg	7.64624	15.03528	80.144	109.265	141.27	186.76	225.02	265.96	328.1	367.5	1761.8	1963		
13 Al	5.98577	18.82856	28.448	119.99	153.83	190.49	241.76	284.66	330.1	398.8	442.0	2086	2304	
14 Si	8.15169	16.34585	33.493	45.142	166.77	205.27	246.49	303.54	351.1	401.4	476.4	523	2438	2673
15 P	10.48669	19.7694	30.203	51.444	65.03	220.42	263.57	309.60	372.1	424.4	479.5	561	612	2817
16 S	10.36001	23.3379	34.79	47.222	72.59	88.05	280.95	328.75	379.6	447.5	504.8	564	652	707
17 Cl	12.96764	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	15.75962	27.62967	40.74	59.81	75.02	91.01	124.32	143.46	422.5	478.7	539.0	618	686	756
19 K	4.34066	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	6.11316	11.87172	50.913	67.27	84.50	108.78	127.2	147.24	188.5	211.3	591.9	657	727	818
21 Sc	6.56144	12.79967	24.757	73.489	91.65	111.68	138.0	158.1	180.0	225.2	249.8	688	757	831
22 Ti	6.8282	13.5755	27.492	43.267	99.30	119.53	140.8	170.4	192.1	215.9	265.1	292	788	863
23 V	6.7463	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	6.76664	16.4857	30.96	49.16	69.46	90.64	161.18	184.7	209.3	244.4	270.7	298	355	384
25 Mn	7.43402	15.63999	33.668	51.2	72.4	95.6	119.20	194.5	221.8	248.3	286.0	314	344	404
26 Fe	7.9024	16.1878	30.652	54.8	75.0	99.1	124.98	151.06	233.6	262.1	290.2	331	361	392
27 Co	7.8810	17.083	33.50	51.3	79.5	103	131	160	186.2	276.2	305	336	379	411
28 Ni	7.6398	18.16884	35.19	54.9	75.5	108	134	164	193	224.6	321	352	384	430
29 Cu	7.72638	20.29240	36.841	55.2	79.9	103	139	167	199	232	266	369	401	435
30 Zn	9.39405	17.96440	39.723	59.4	82.6	108	136	175	203	238	274	311	412	454

Gas and electron pressures

355

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

356

T_{eff}	$\text{Log } g$	$\text{Log } P_g(\tau=2/3)$	$\text{Log } P_e(\tau=2/3)$
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

357

- 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 6-7).

Summary

358

- 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

360

Stellar parameters:

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

In most cases, cannot be measured directly

Atmosphere parameters:

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

- Chemical composition
(metallicity, element abundances)

Can help in
measuring L & M

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

Surface Flux, Luminosity and T_{eff}

361

- 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, $F = \sigma T_{\text{eff}}^4$, or alternatively $L/4\pi R^2 = \sigma T_{\text{eff}}^4$ 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)

362

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

363

- We have already introduced interferometry regarding limb darkening (Lecture 17).
- 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 02b/04 (30 January 2004)

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The AT1 Positioned Next to the VLTi Laboratory

ESO PR Photo 02b/04 (30 January 2004)

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Radii from other direct methods

364

- **Occultations**

- Moon used as “knife-edge”
- Diffraction pattern recorded as flux vs. time
- Precision ~ 0.5 mas
- A few hundred radii have been determined

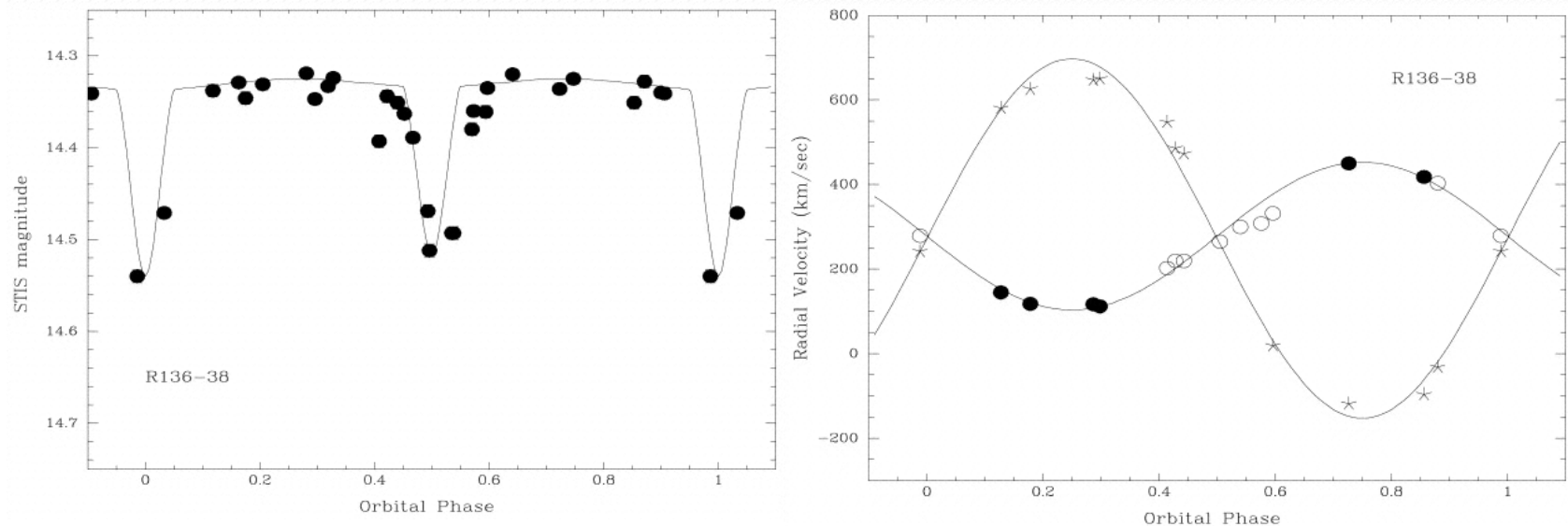
- **Eclipsing binaries**

- 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 ($i=90^\circ$)

Binary Masses

365

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



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)

366

Direct measurements:

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

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

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

Model-dependent methods

367

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

- T_{eff} from Bolometric Corrections
 - Lecture 16
- $\text{Log } g$ from parallaxes

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

- Method of IR fluxes (Blackwell & Shallis 1977)

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

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

Also correct for
monochromatic
fluxes

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

Atmospheric Models

368

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

Specific Intensities (λ)

Emergent Fluxes (λ)

UBVRI...

$(U-B), (B-V), (V-R), \dots$

W_{λ}

Line profiles

Observations

Atmospheric Models (1)

369

- 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

370

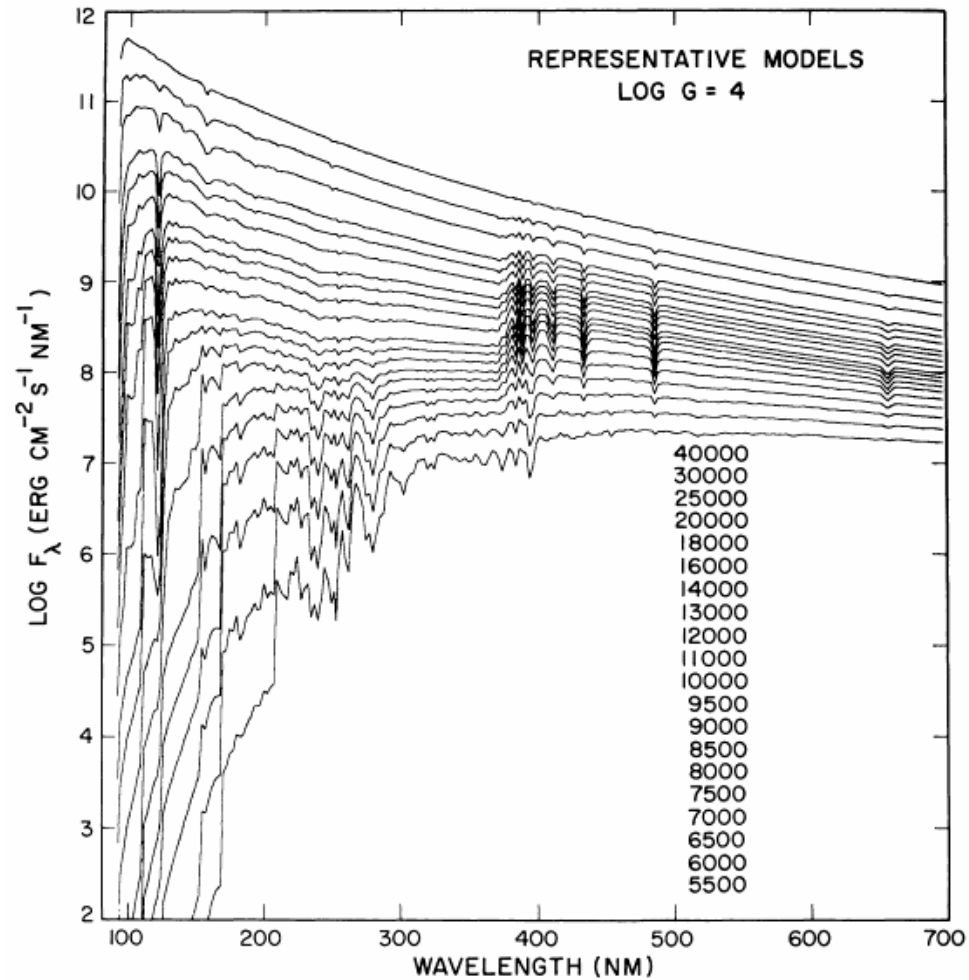


FIG. 16.—The flux F_{λ} redward of the Lyman limit as a function of T_{eff}

Atmospheric Models (2)

371

- To determine T_{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_{eff} than on $\log g$, and another one in the opposite way.
- The more parameters the better.

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

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

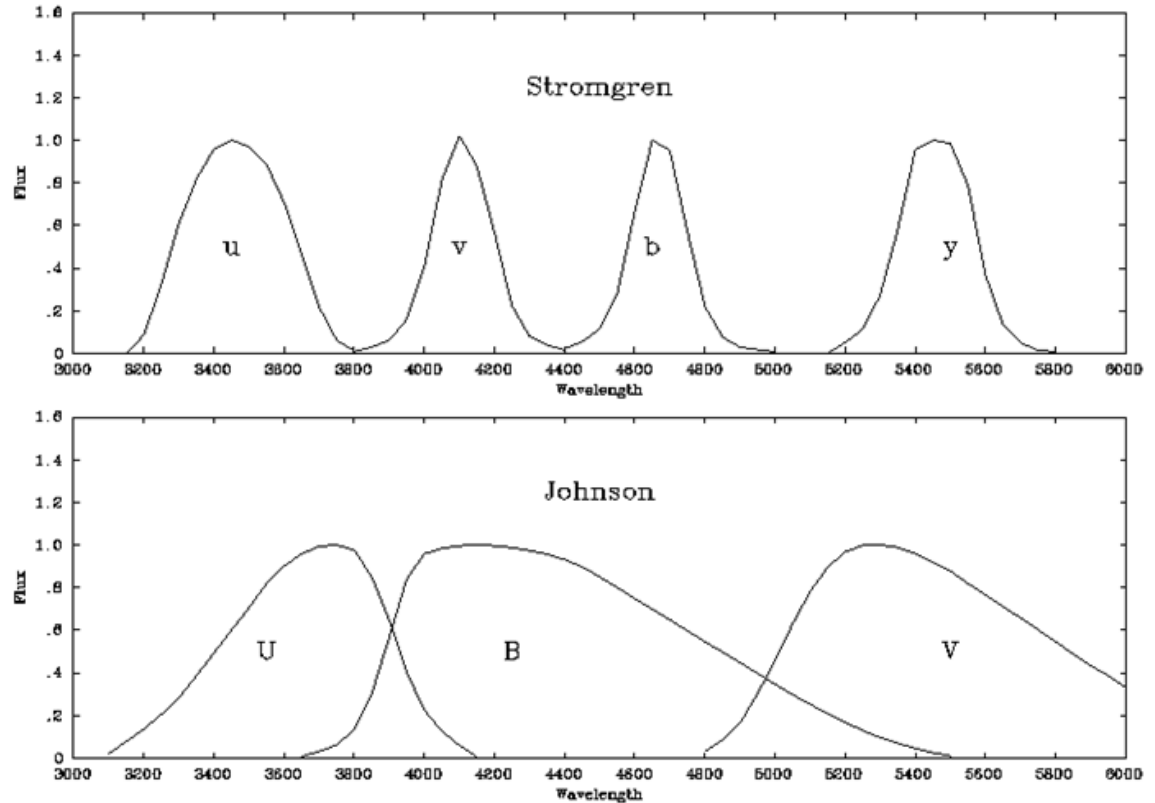
g – a luminosity criterium

Photometric Methods

372

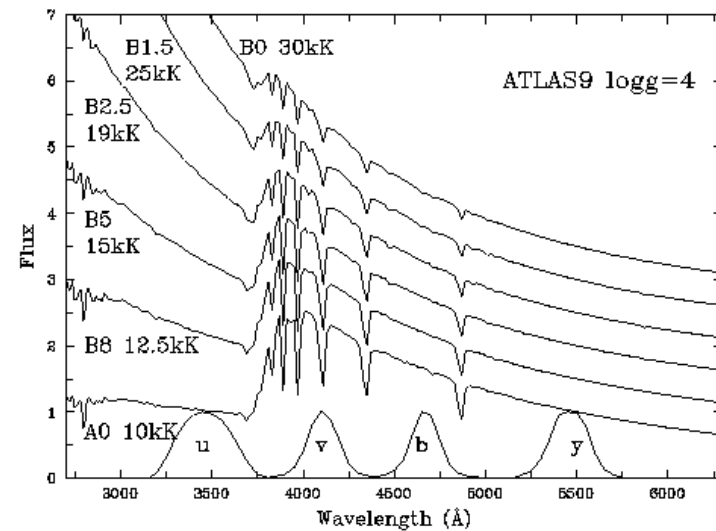
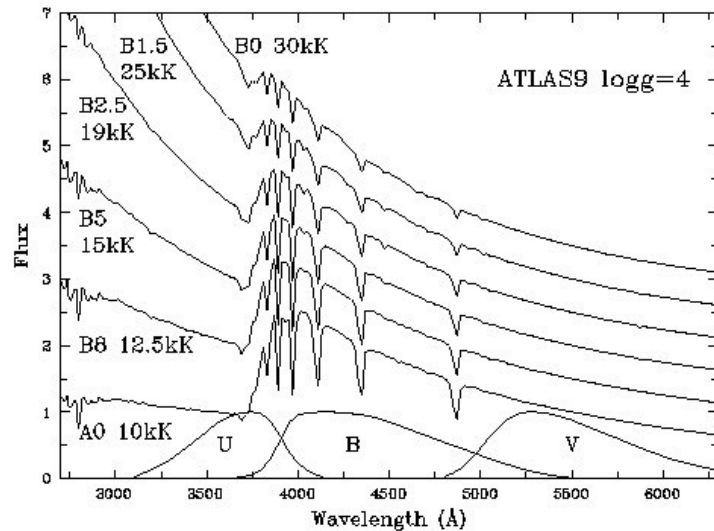
Alternative photometric systems to Johnson *UBV* are available – notably Strömgren (1963) *ubvy*.

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



UBV versus uvby photometry

373



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

Photometric Methods

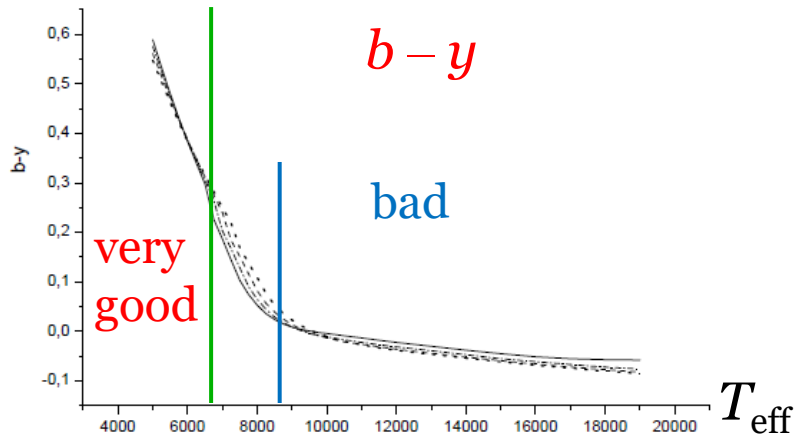
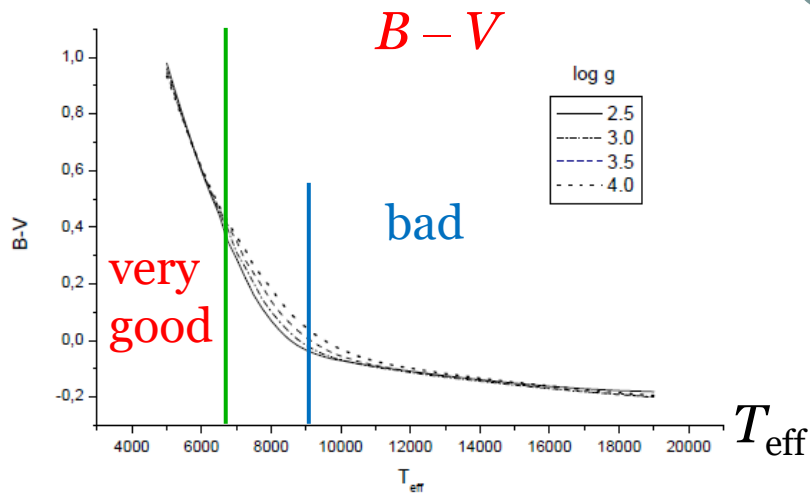
373

T_{eff} from photometry

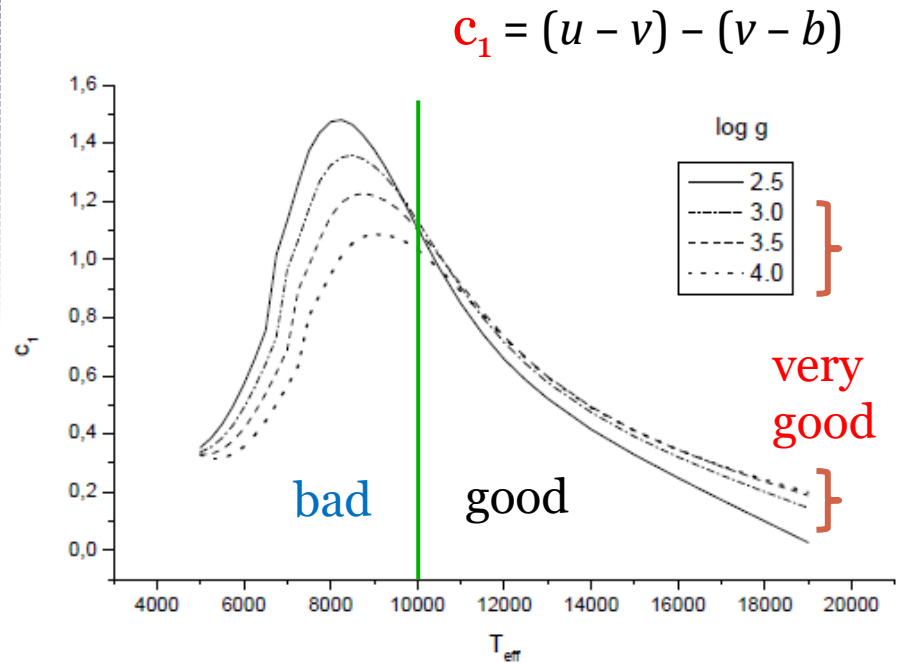
- The slope of the Paschen continuum, F_{4000}/F_{7000}
 - $c_1 = (u - v) - (v - b)$ for A0 stars and earlier
 - $b - y, B - V, V - K$ for F stars and later
- } $f(T_{\text{eff}})$

Photometric Methods

375



Kurucz atmosphere models



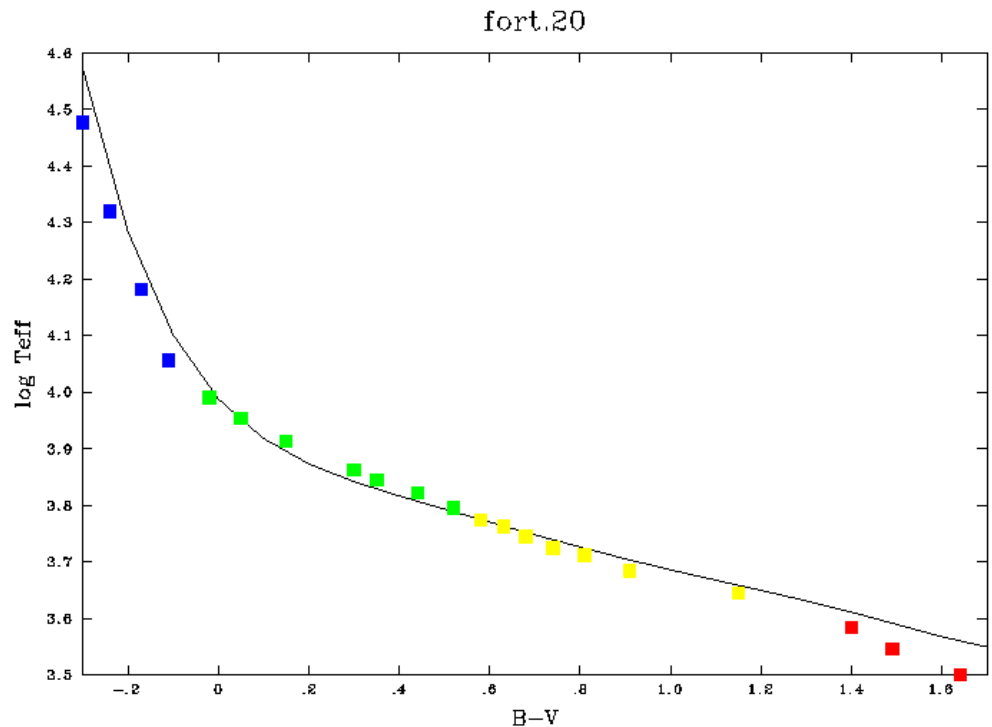
Temperatures from photometry

376

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

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

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



Spectroscopic methods

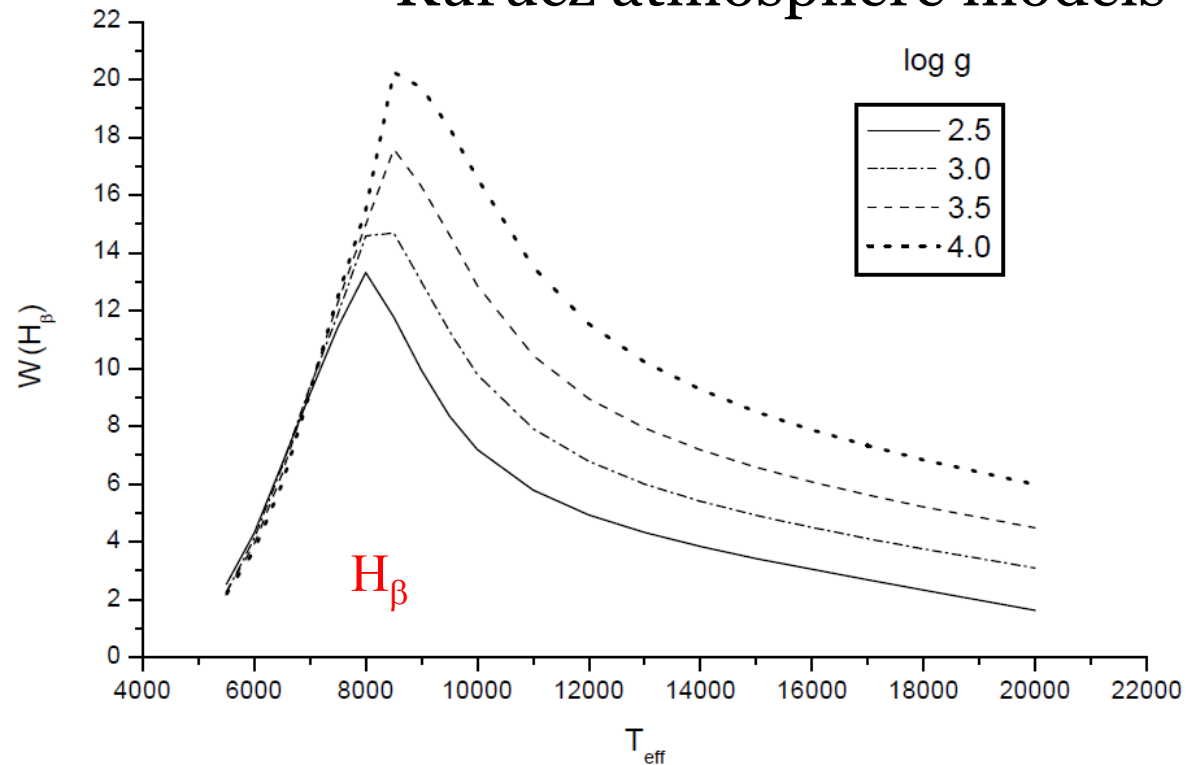
377

Equivalent Widths of Balmer lines

Good indicators of T_{eff}
when $T_{\text{eff}} < 9000$ K

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

Kurucz atmosphere models



Spectroscopic methods

378

Wings of strong metal lines

Broadening:

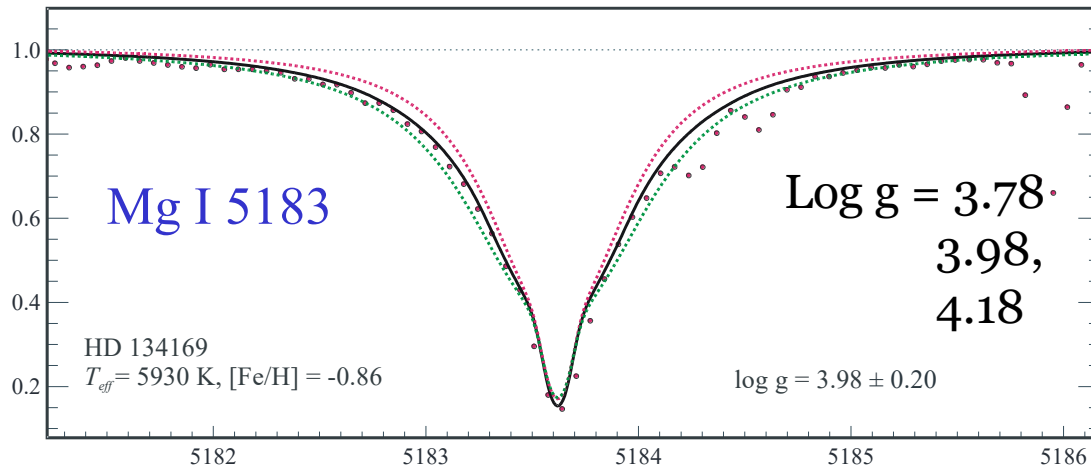
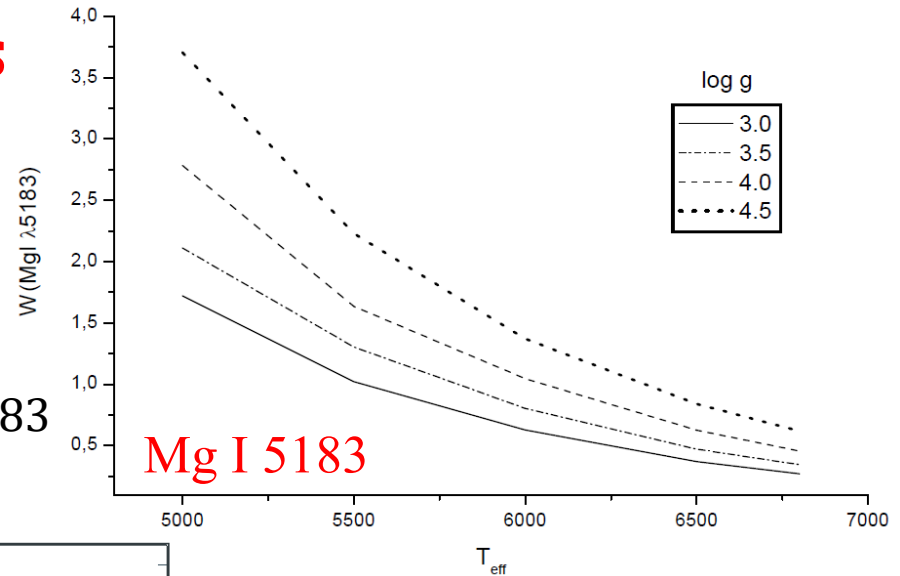
Cool stars - **Van der Waals**

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 **indicator of $\log g$** when $T_{\text{eff}} < 6000 \text{ K}$.

Spectroscopic methods

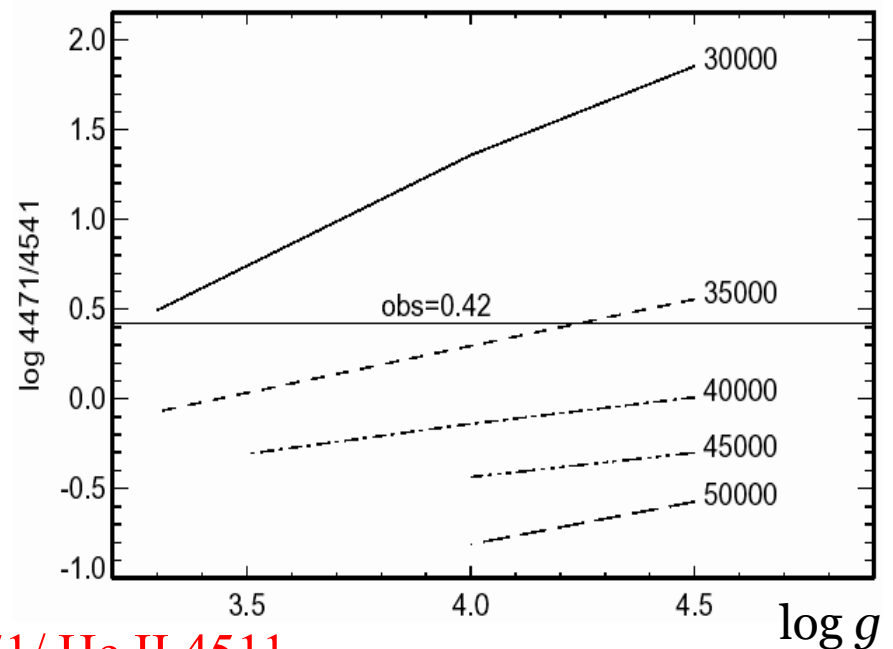
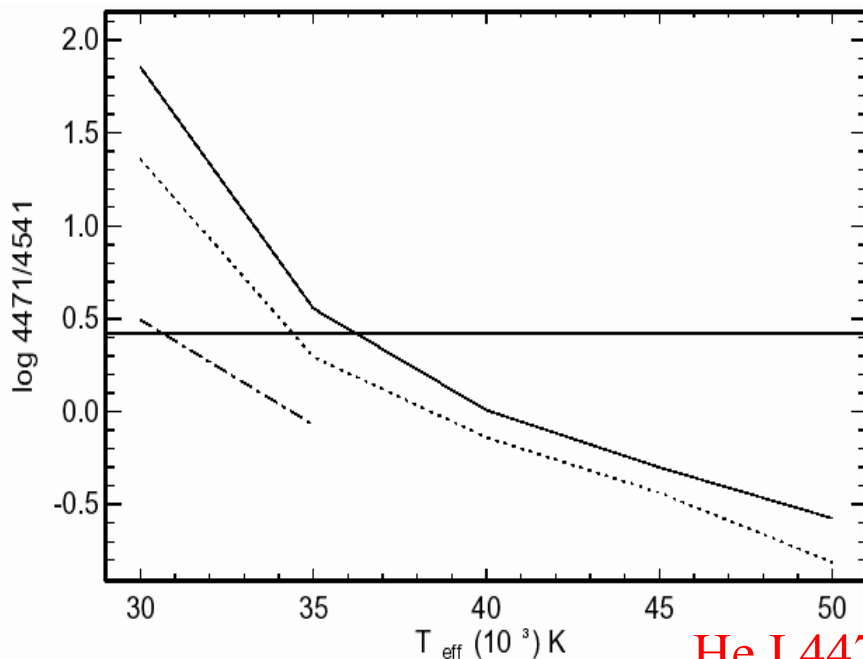
379

Equivalent Width ratios of species in two consecutive ionization states

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

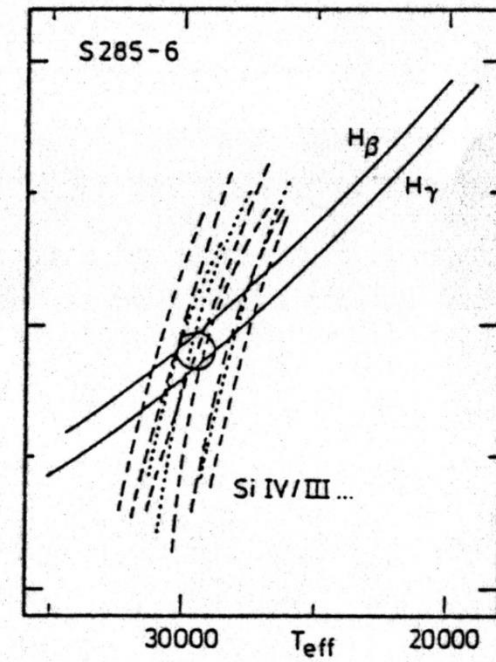
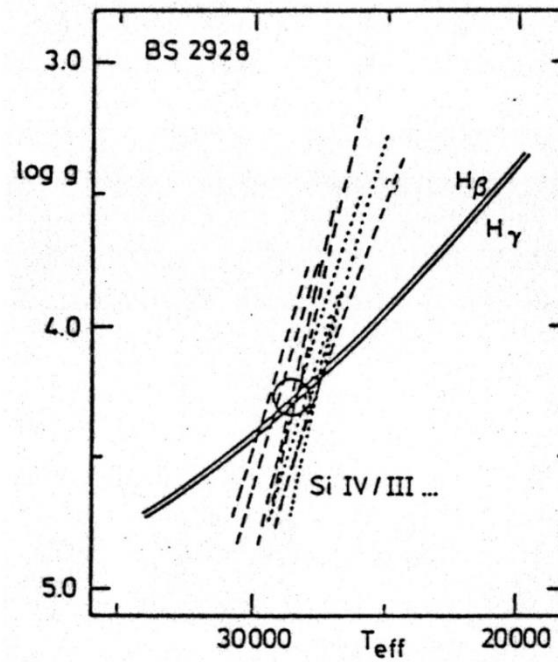
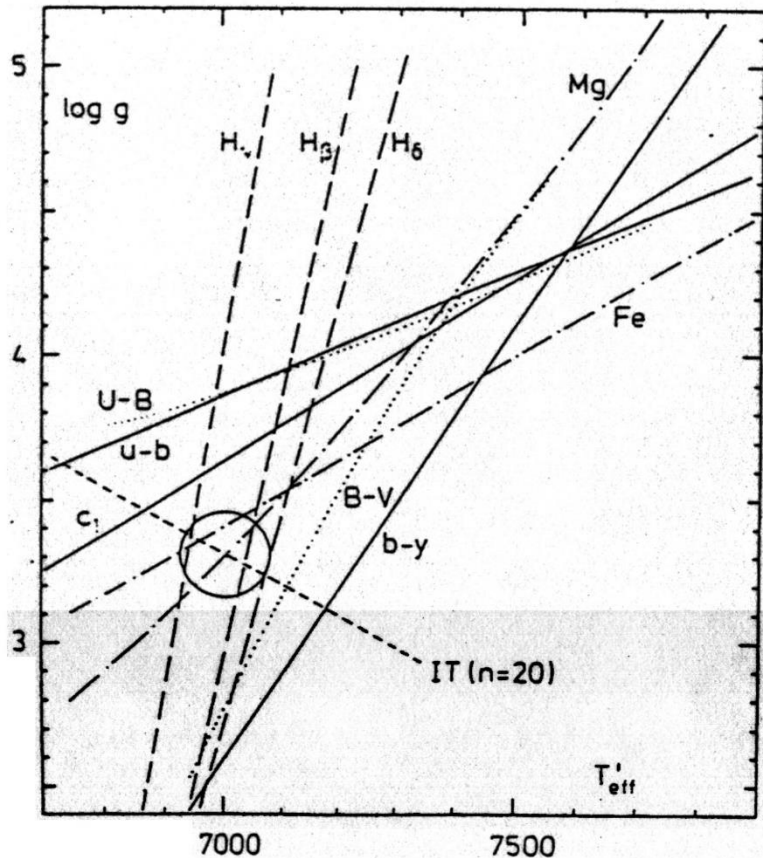
O, B stars: He I and He II, Si III and Si IV

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



He I 4471/ He II 4511

Examples



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

Summary

381

- **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.