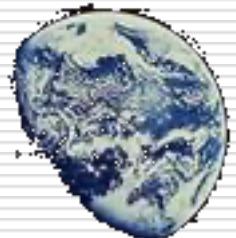


高分辨率恒星光谱分析

施建荣

国家天文台



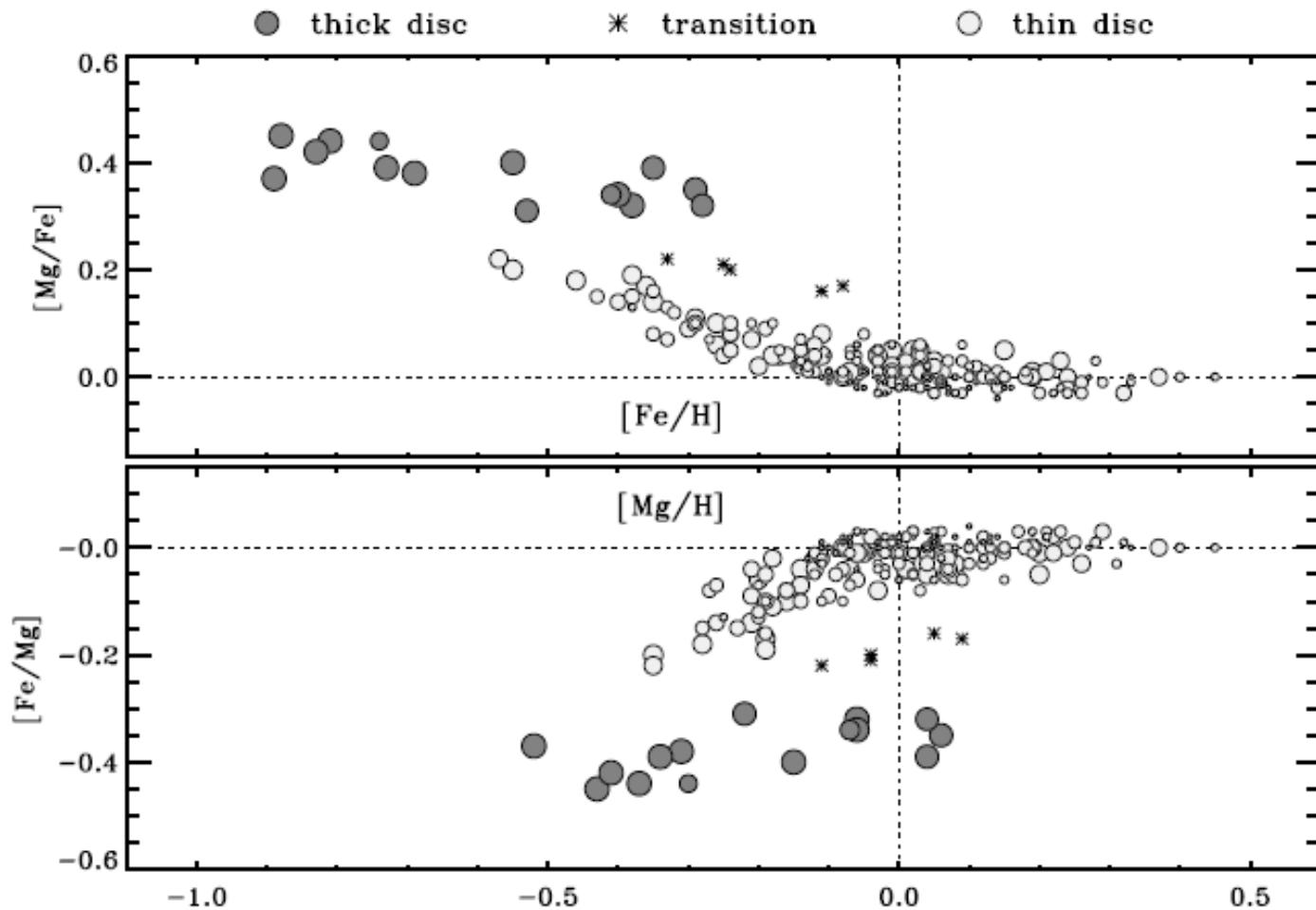
银河系的化学演化

年老恒星是银河系活的化石，它反映了其形成时元素分布模式，通过分析这些恒星表面的元素丰度分布，我们可以了解银河系的形成和演化的历史。

贫金属星——这类特殊的恒星群体就是被誉为记录宇宙年龄的“活化石”。贫金属星含有星系和宇宙演化早期信息，其丰度直接和宇宙的起源与演化相关，是星系和宇宙学研究的重要组成部分，但是由于它们极其暗弱，因此很难测量。

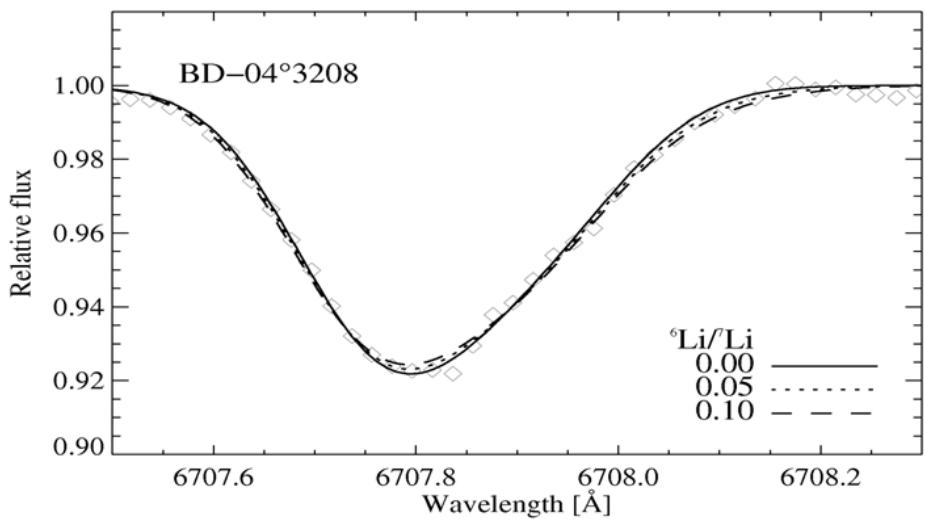


丰度和运动学信息区分不同星族

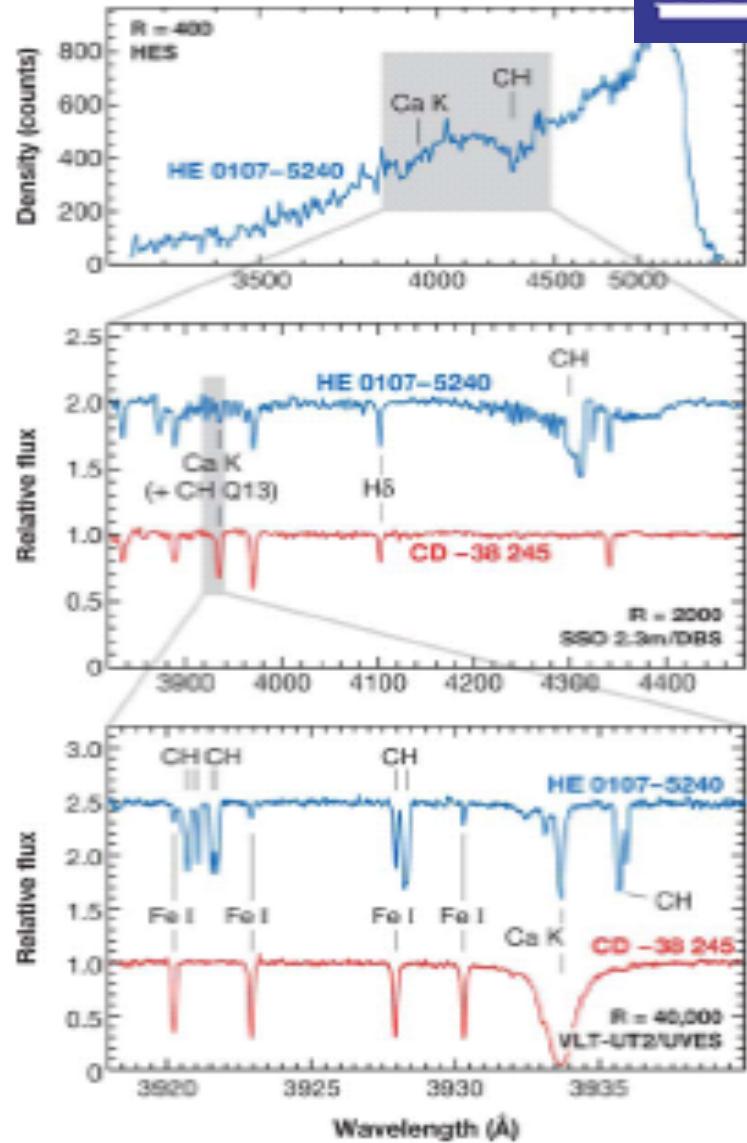


高分辨率恒星光谱分析

为啥高分辨率光谱



同位素比例



高分辨率恒星光谱分析

高分辨率光谱的观测图像
(下图)

处理得到一维光谱 (右)

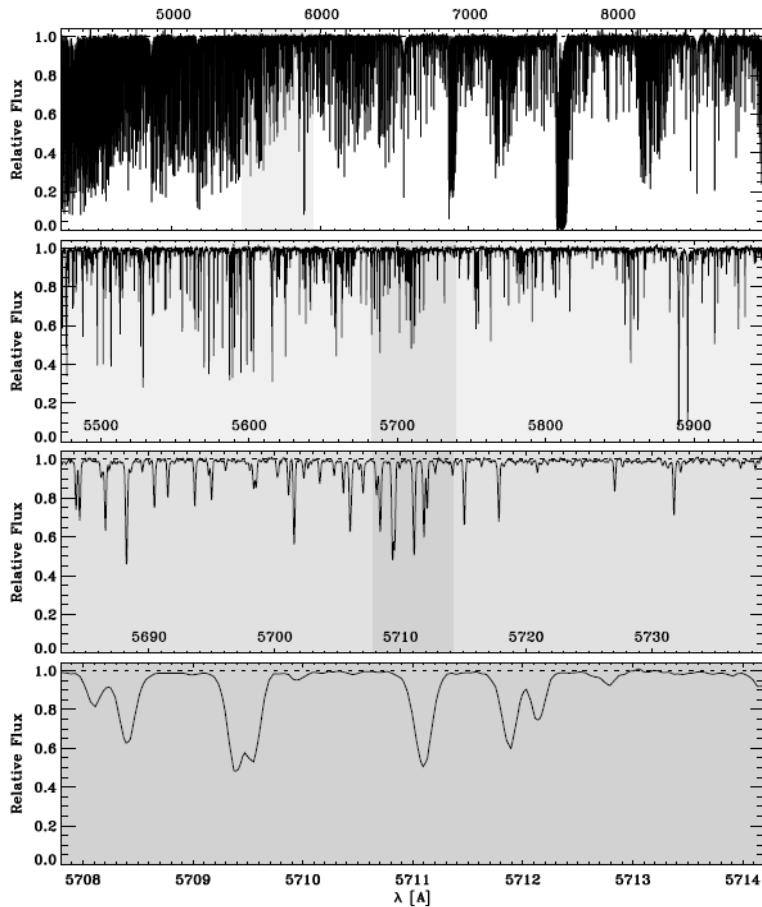
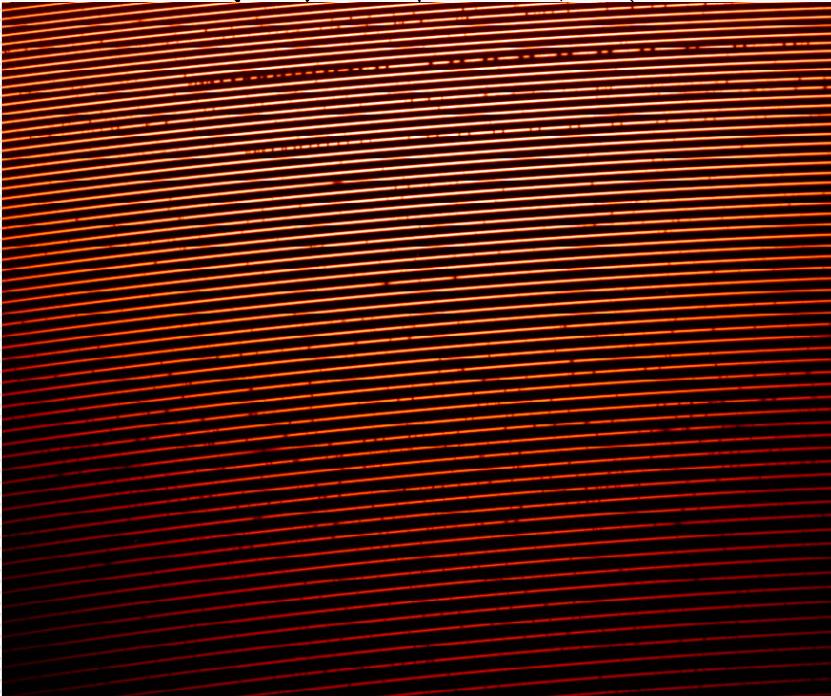
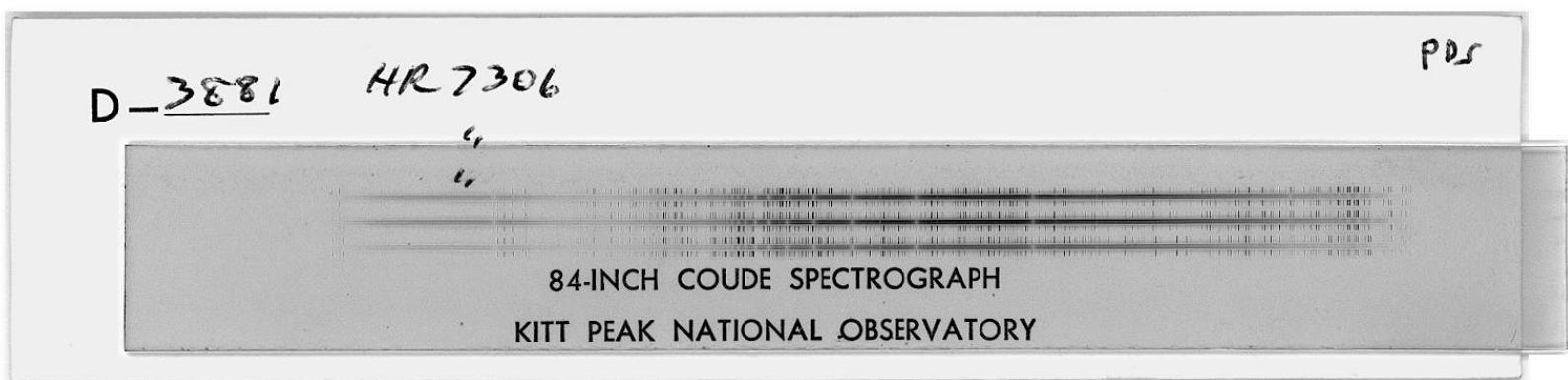
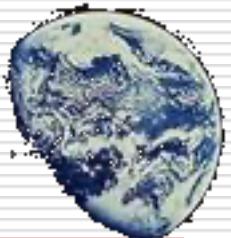


Fig. 1. A FOCES spectrum of the iron-deficient turnoff star ρ CrB with resolution $R \sim 60000$ and wavelength coverage $\lambda \lambda 4200-9000$. The merged échelle spectrum has an equidistant spacing of $\Delta\lambda = 20\text{m}\text{\AA}$ and a total length of $\sim 2 \times 10^5$ data points. The top panel shows the complete spectrum with successive enlargements below.

高分辨率恒星光谱分析



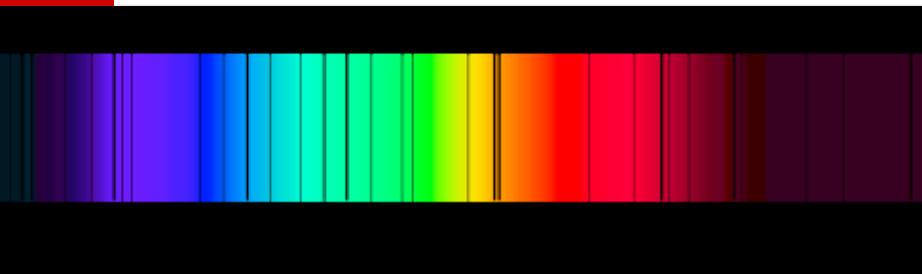
Helmut Abt在1973年9月测试观测了恒星HR7306的高分辨率光谱，以确定新完成的折轴光谱仪的效率



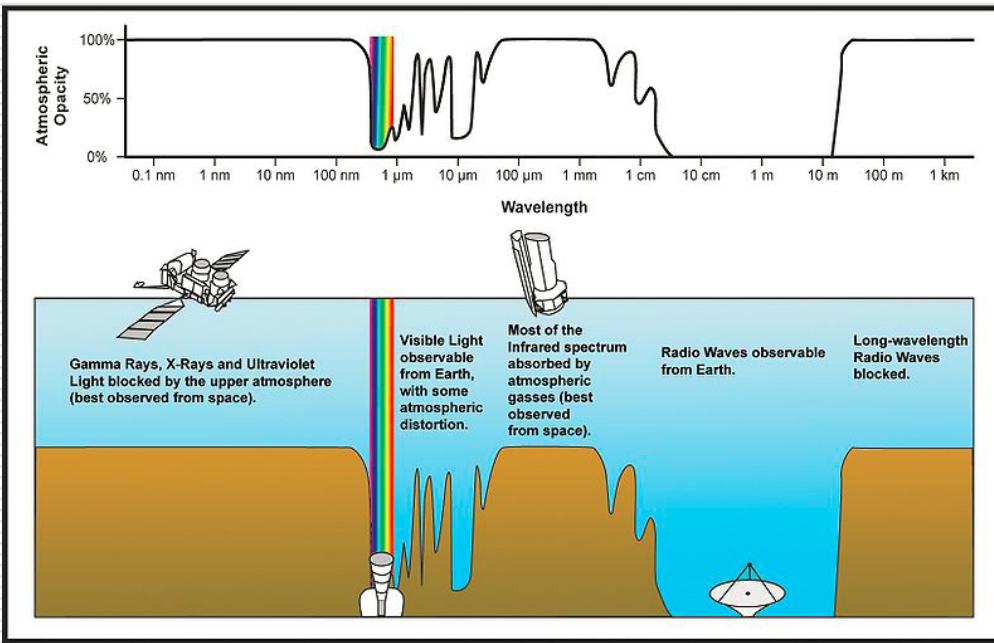
光谱包含哪些信息

➤ 吸收谱线

- 谱线的形成是由于原子和分子的吸收
- 测量光球中的元素丰度

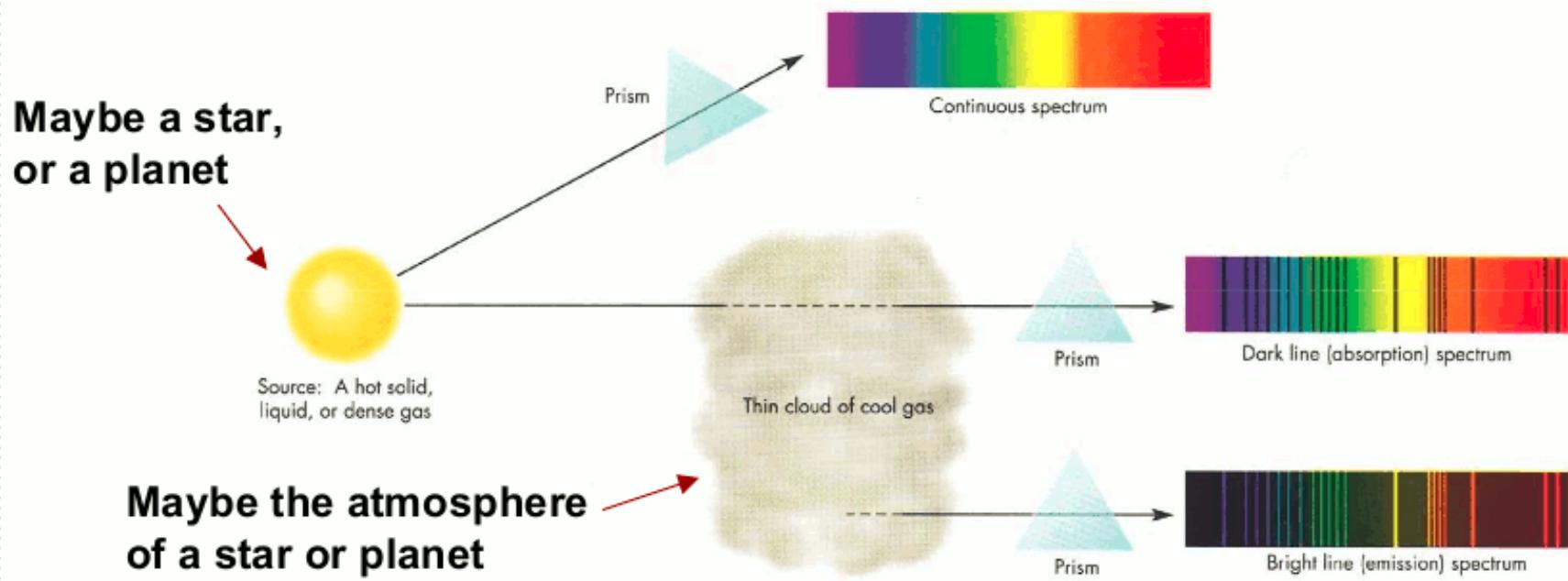


➤ 光谱包含的信息 光球中的物理条件



恒星大气吸收谱线的形成

在一个热源前面的一个冷的薄气体层会形成吸收线。对于连续谱， τ 很小，因此我们看到的背景目标。在谱线波长处， τ 比较大，我们能看到低温气体的强度特征。由于它比中心的温度低，因此我们看到的是吸收谱线。

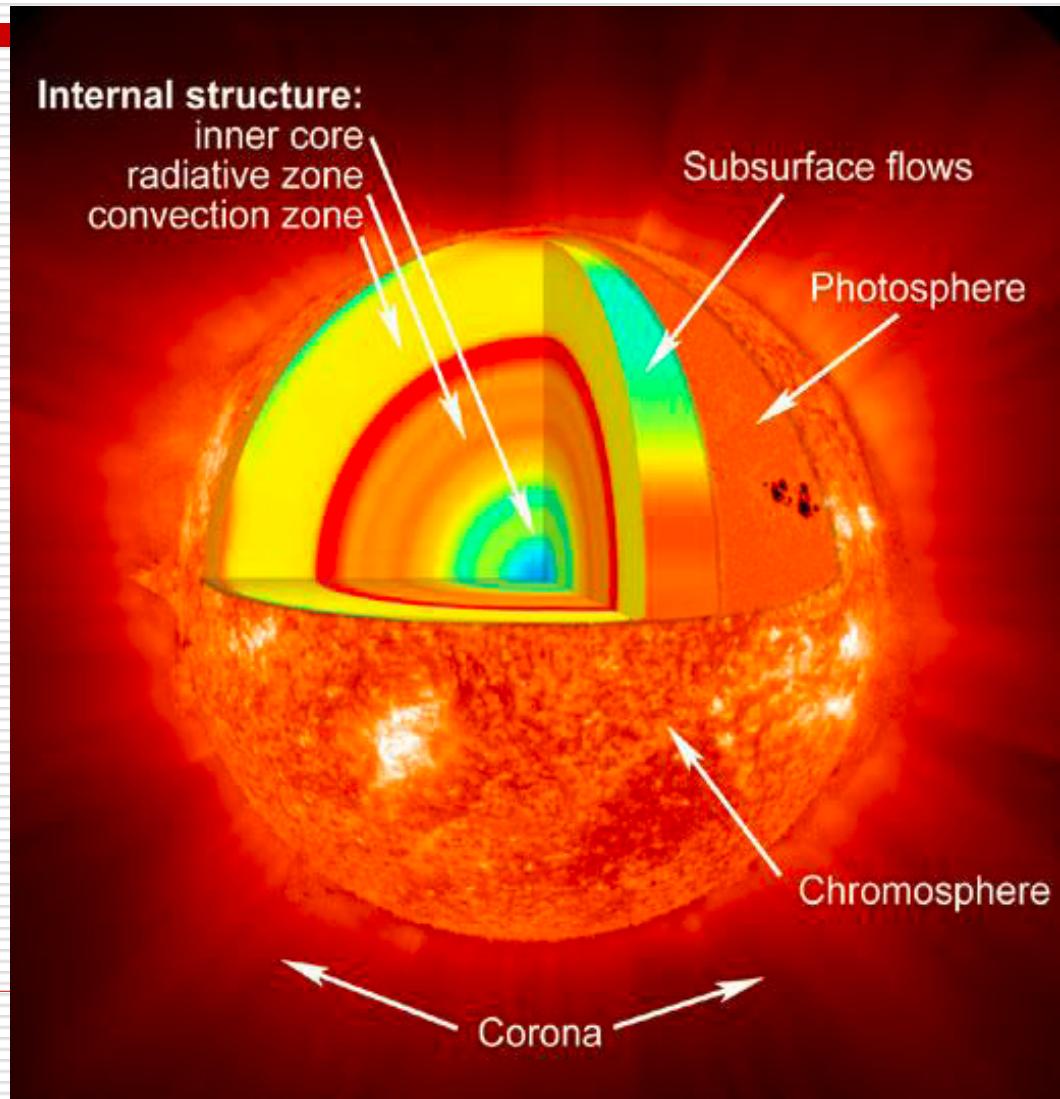


恒星大气

恒星大气层是指恒星表面能将其产生的辐射转移出来的气体层。厚度约为几百到几千公里

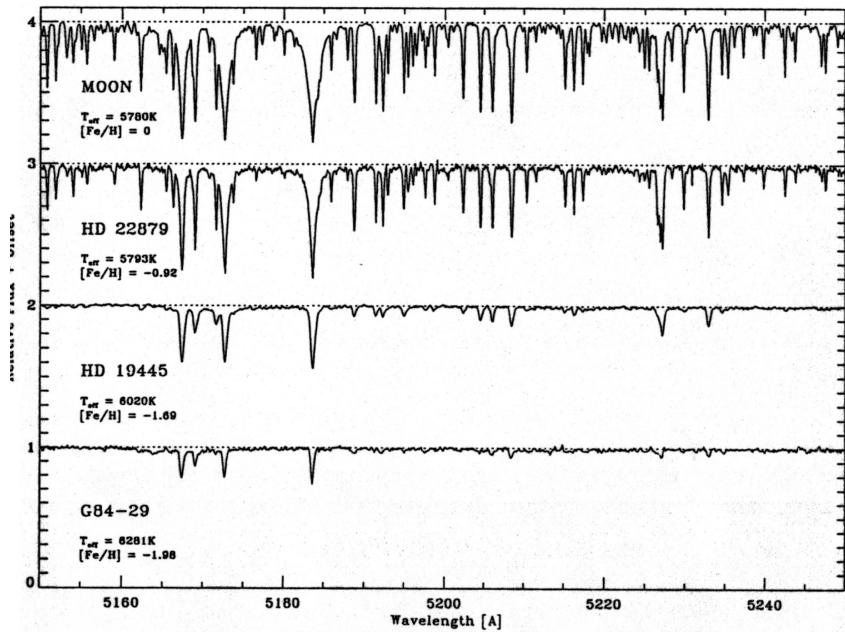
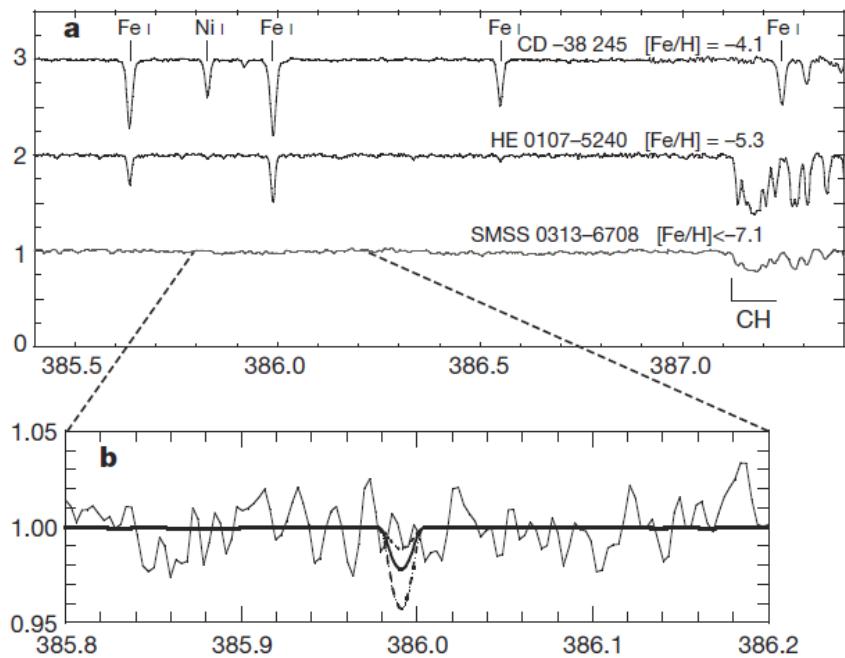
(Photosphere)

2024-7-5



不同金属丰度恒星光谱

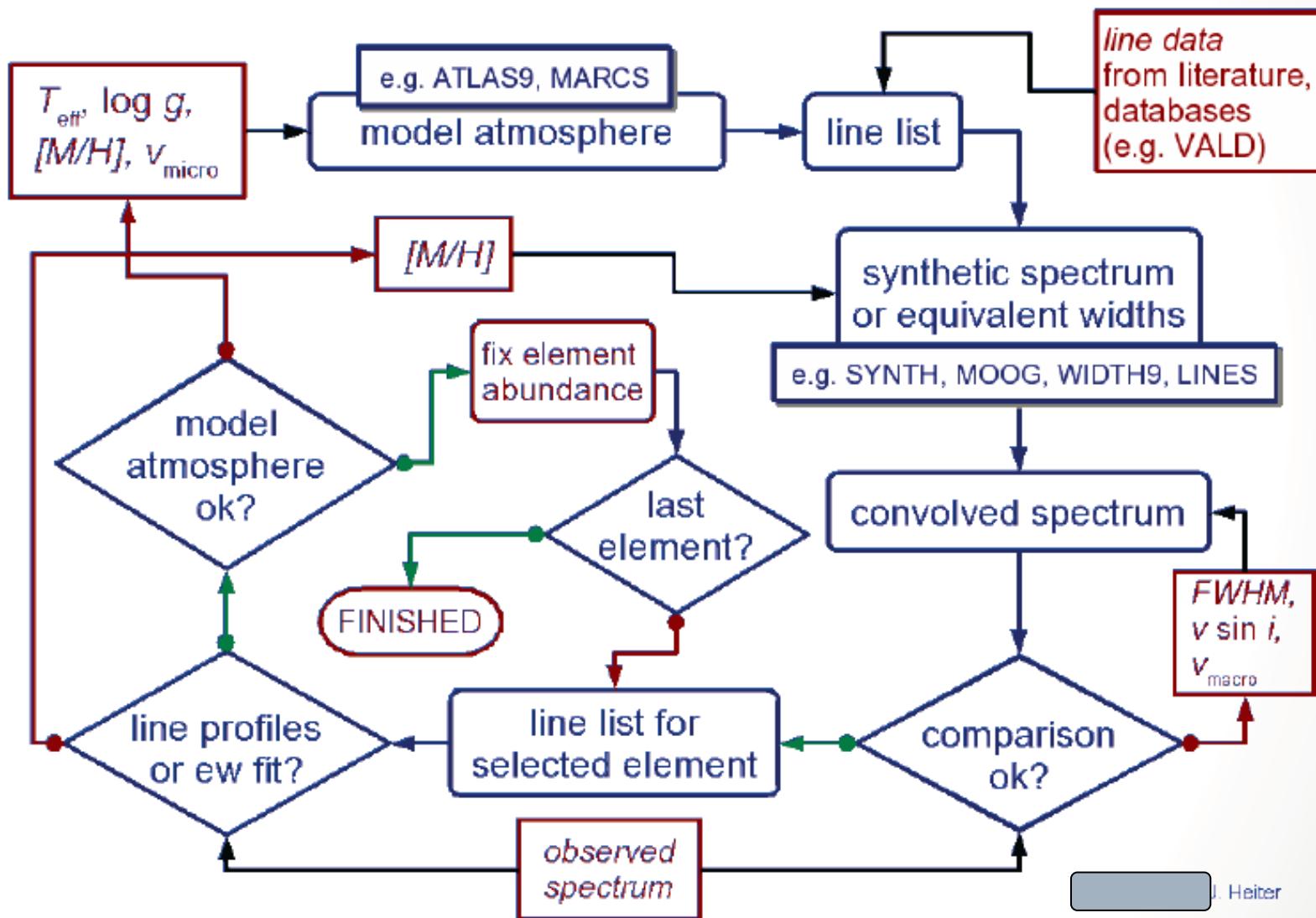
随着金属丰度的降低，
谱线明显变弱



Keller et al. 2014 nature 506, 463



高分辨率恒星光谱分析



如何获取元素丰度信息?

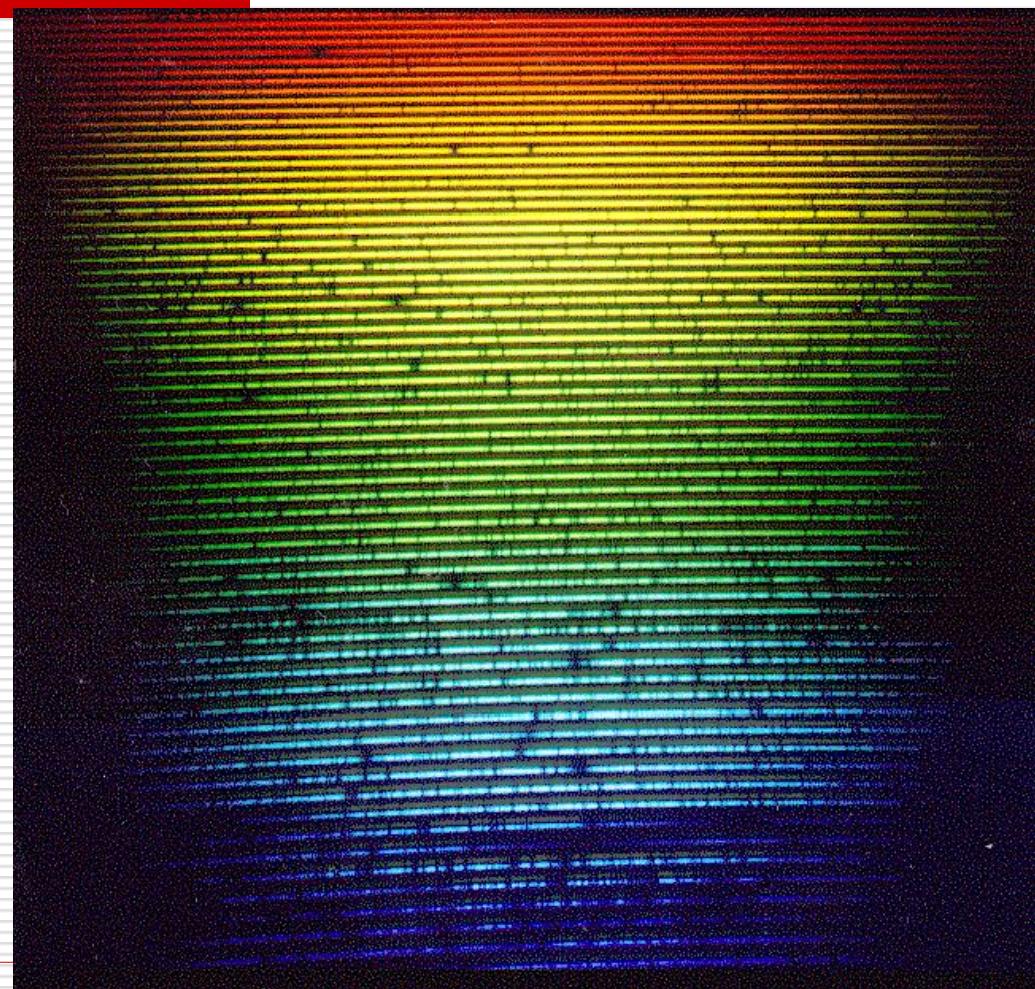
首先需要:

恒星信息(光谱型或测光分类)

恒星大气性质

→ 谱线形成

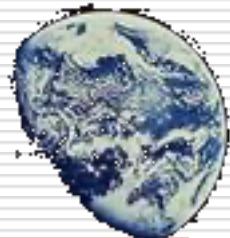
- 有效温度
- 表面重力
- 金属丰度



高分辨率恒星光谱定量分析

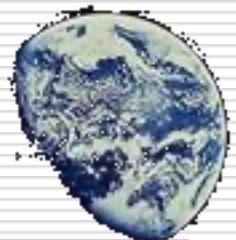
在分析观测光谱之前，必须确定恒星大气模型：即： T_{eff} $\log g$ 、 $[\text{Fe}/\text{H}]$ 和 ξ

- 有效温度 T_{eff} ,
确定方法 \Rightarrow 理论或经验
- 表面重力 $\log g$
- 金属丰度 $[\text{Fe}/\text{H}]$, 迭代改进
- 微观湍流速度 ξ .

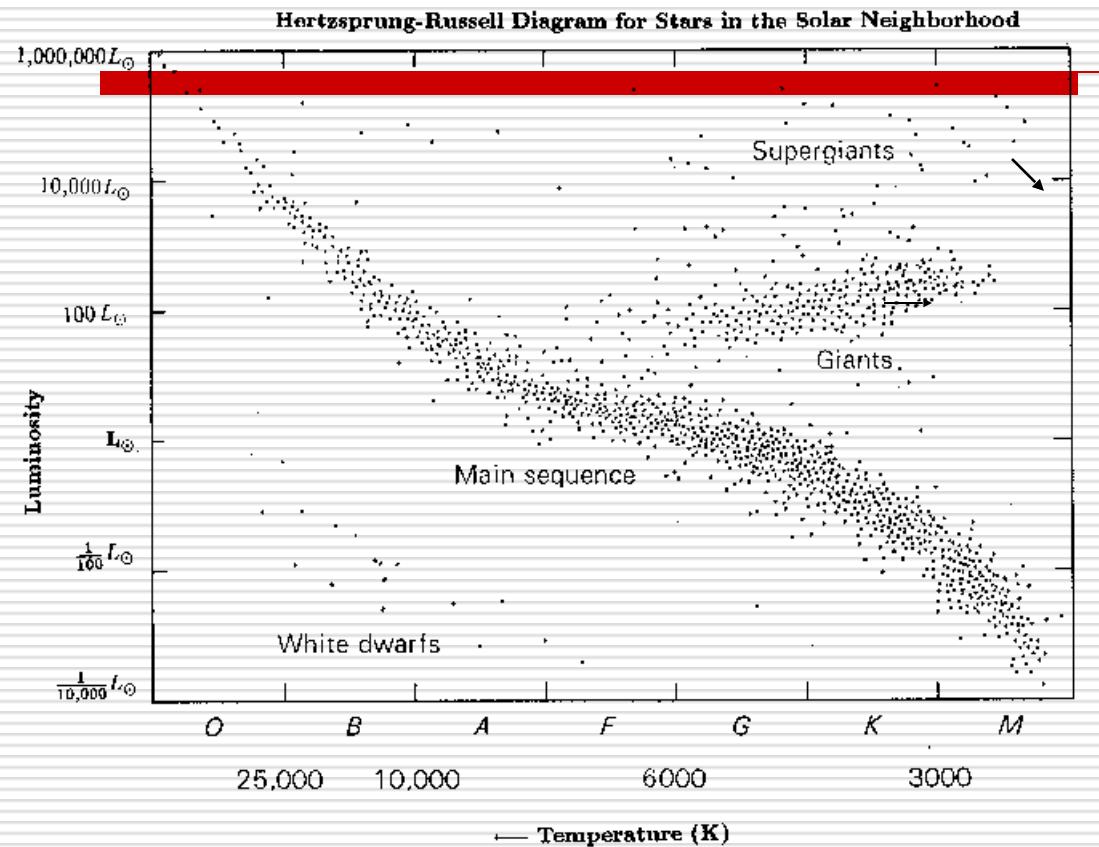


高分辨率恒星光谱定量分析

- “非模型依赖”方法：确定有效温度和表面重力
- 模型依赖方法
 - 测光方法
 - 光谱方法（证认谱线）



赫罗图



恒星物理就是了解赫罗图.

有三种表示方法:

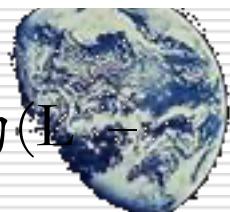
a) 颜色-星等

$M_V - (B - V)$ 图;

b) $L - T_{\text{eff}}$ 图用来反映恒星内部变化;

c) $\log g - T_{\text{eff}}$ 图在高分辨率光谱分析中常用

恒星大气理论提供了一种从观测到的($S_p - M_V$) 与理论的($L - T_{\text{eff}}$) 或 ($\log g - T_{\text{eff}}$) 等的颜色星等图关系



恒星大气参数

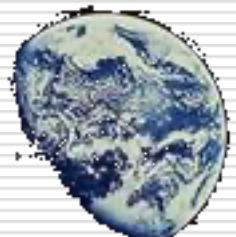
1. 有效温度 T_{eff} : 辐射出相同光度黑体所呈现的温度;
2. 表面重力: 反映密度分布的量(cgs单位: $\log g$)
3. 金属丰度 Z 或Fe含量

对太阳 $Z = 0.0134$

[Fe/H]:
$$\left[\frac{Fe}{H} \right] = \log \left(\frac{N(Fe)}{N(H)} \right)_* - \log \left(\frac{N(Fe)}{N(H)} \right)_{\text{sun}}$$

和 [α/Fe]:
$$\left[\frac{\alpha}{Fe} \right] = \log \left(\frac{N(\alpha)}{N(Fe)} \right)_* - \log \left(\frac{N(\alpha)}{N(Fe)} \right)_{\text{sun}}$$

α 是α元素，或者其它任何元素



丰度标度

丰度标度: 质量比例 $X=H; Y=He, Z=\text{所有其它元素}$
 $(=\text{金属})$

$$X+Y+Z=1$$

例子: $X_{\odot}=0.7381, Y_{\odot}=0.2485, Z_{\odot}=0.0134$

(Asplund et al. 2009)

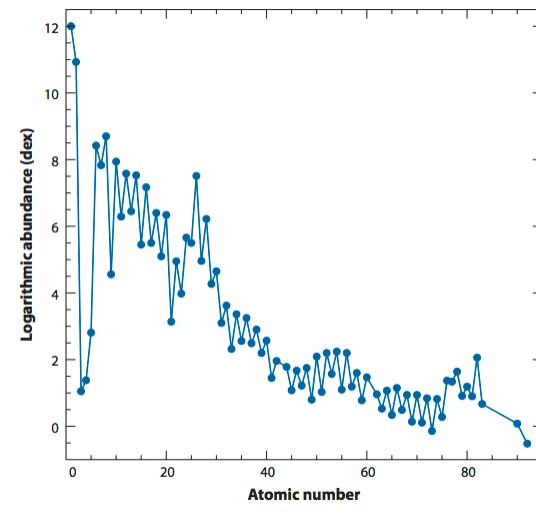
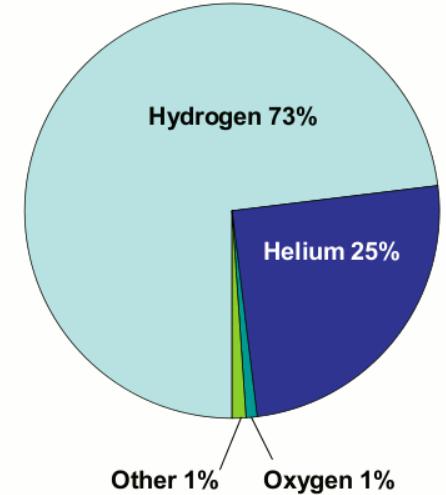
12 标度: $\log \varepsilon(X) = \log(n_X/n_H) + 12$ ($\log \varepsilon(H) \equiv 12$)

例如: $\log \varepsilon(O)_{\odot} \approx 8.7 \text{ dex}$ (O 比 H_{\odot} 约少 2000 倍)

[] 标度 $[X/H] = \log(n_X/n_H)_* - \log(n_X/n_H)_{\odot}$

例如: $[\text{Fe}/H] = -2 \rightarrow$ 这颗星中的 Fe 比太阳中少 $1/100$

$[\text{Fe}/H] = 0.5 \rightarrow$ 这颗星中的 Fe 比太阳多 3.16 倍



有效温度

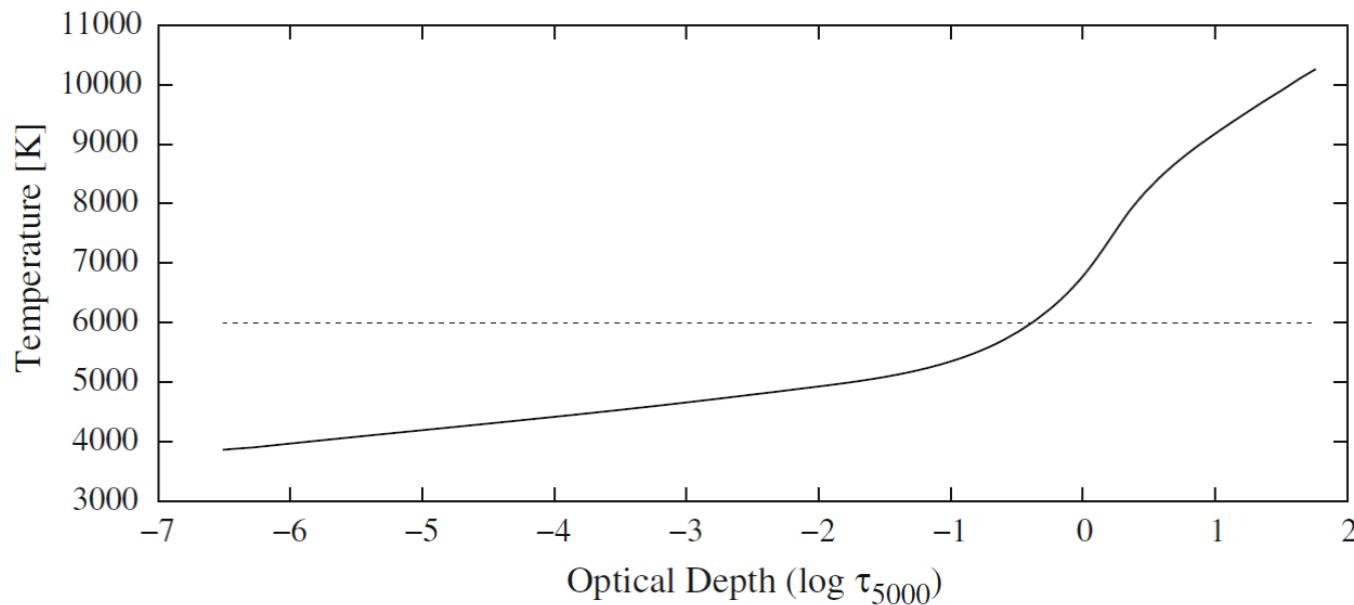
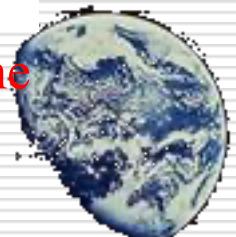


Fig. 1 The depth dependence of atmospheric temperature with monochromatic optical depth at 5,000 Å. Based on model atmosphere with $T_{\text{eff}} = 6,000$ K. The horizontal dashed line indicates a temperature of 6,000 K which intercepts the model at optical depth around $\log \tau_{5000} = -0.5$, corresponding the depth of formation of the continuum flux

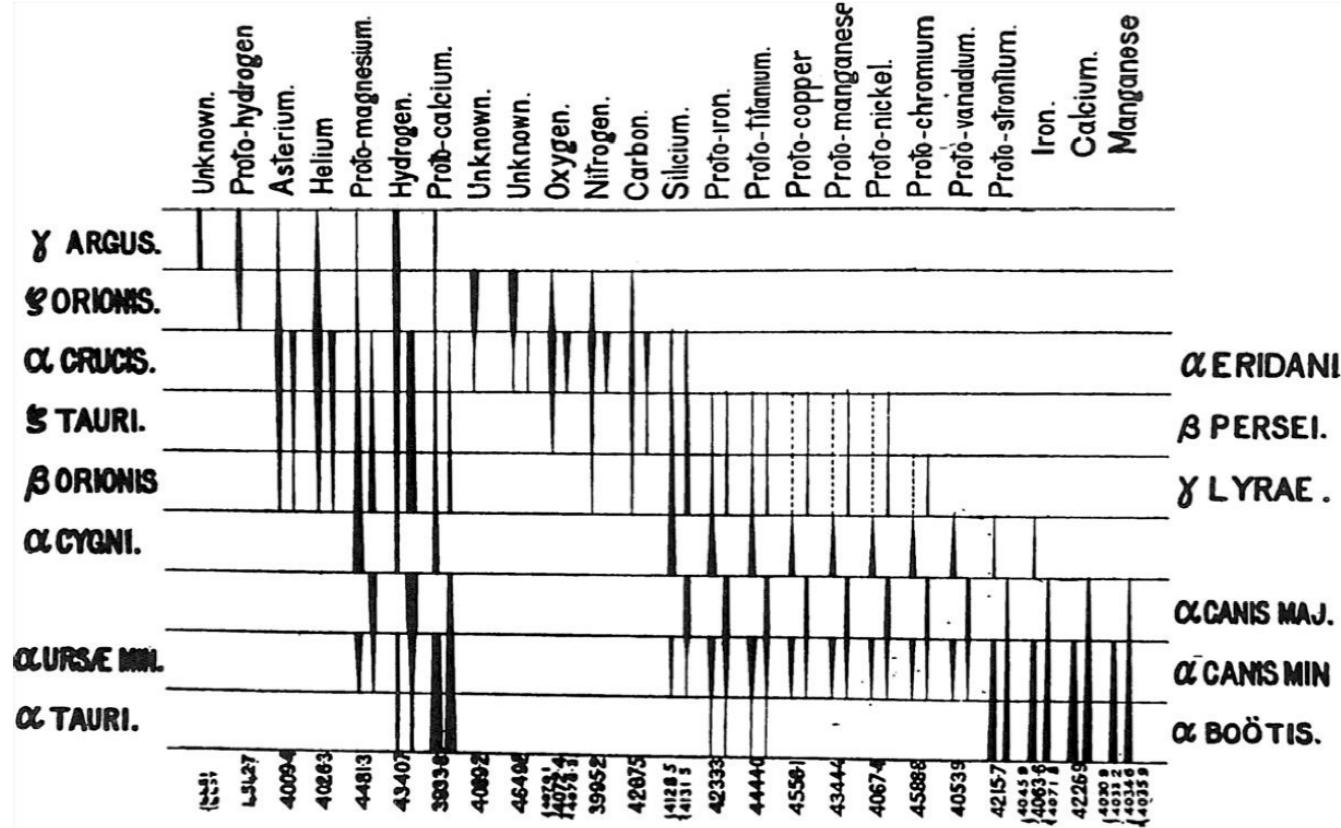
It is the temperature of an equivalent black body that gives the same total power per unit area.



辐射出相同光度黑体所呈现的温度

恒星光谱分析的历史

利用恒星光谱中的吸收线确定元素丰度时，需要解决一些重要问题。
首先：恒星温度



恒星光谱分析的历史

二十世纪初，Potsdam的Wilsing & Scheiner (1909)利用眼睛观测，而 Tübingen的Rosenberg则利用照相技术首先开始确定恒星温度。他们的温度完全是基于颜色的；

Sampson首先注意到恒星光谱存在偏离黑体情形，定义了有效温度
(1925)

Balmer跳变被用来确定温度
Barbier & Chalonger (1941)

212

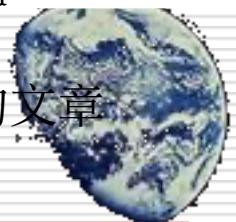
Prof. R. A. Sampson,

LXXXV. 3,

Effective Temperatures of Sixty-Four Stars. By Professor R. A. Sampson, F.R.S. (Plates 9, 10, 11.)

The following paper is the continuation of one published in *Monthly Notices*, 83, 1923 January, "On the Estimation of the Continuous Spectrum of Stars," in which the Koch microphotometer was used to reproduce and measure the density of a spectrogram throughout its length, and theory was then applied to eliminate the various irrelevant factors entering these measures. Thus was derived, relative to Polaris, taken as standard, the radiation curve of the star and its effective temperature. Reference may be made to that paper for details which need not be recalled here, except where there is some variation. It may, however, be said that the spectra are taken with an objective prism of 12° angle in front of a 6-inch photovisual object glass, giving a sharp focus from (B) to (K), with a dispersion over all of 1 mm. = 121 Å. This spectrum is reproduced automatically as a graph—termed the

Sampson 1925在MNRAS上发表的文章



与模型无关的有效温度和表面重力确定方法

◆ 食双星和光谱双星的表面重力

$$g = \frac{GM}{R^2}$$

M质量可以从视向速度曲线获取;
半径可以分析光变曲线得到

◆ 利用绝对流量确定有效温度

仅有的与模型无关的确定有效温度的 T_{eff} 方法是观测它的绝

对流量 f 和角半径 q .

$$F = \int_0^\infty F v d\nu = \sigma T_{\text{eff}}^4 \quad f = 4\pi R^2 F / 4\pi d^2; \quad \theta = R/d;$$

$$f = \theta^2 \sigma T_{\text{eff}}^4$$

R - 半径
 d - 距离



利用绝对流量确定温度

角半径 只有邻近最亮的恒星才能确定角半径

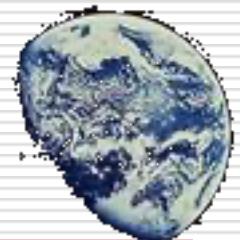
- 干涉仪;
- 光斑干涉;
- 食双星法;
- 月掩星.

举例:

$$d = 1.3 \text{ pc}, R = 700000 \text{ km}$$
$$q = 0.004 \text{ arcsec}$$

绝对流量法的误差来源:

- 低于Lyman边缘的辐射被星际气体完全吸收;
- 对于 $d > 100 \text{ pc}$ 的恒星在912 – 3000 Å之间被严重红化;
- 绝对流量定标。



角直径观测的精度

大约有200多颗恒星有干涉半径精度好于10 %

Table 3. Measures of the angular diameter of Arcturus, K2 II, $d = 11$ pc

Technique	Author	Wavelength (nm)	Diameter (arcsec)	Notes	Effective temperature (K)
A	Pease (1931)	575	0.020	(1)	4419
A	Pease (1931)		0.022	(2)	4213
A	Beavers (1965)		0.024		4034
B	Currie, Knapp & Liewer (1974)	500	0.026 ± 0.007	(3)	3876^{+658}_{-436}
C	Gezari <i>et al.</i> (1972)	500	0.022 ± 0.030	(4)	4213^{+321}_{-260}
C	Worden (1976)	420	0.027 ± 0.010	(5)	3803^{+990}_{-554}
C	Worden (1976)		0.019 ± 0.006	(4)	4534^{+974}_{-582}

Technique
A Michelson interferometer.
B Amplitude interferometry.
C Speckle interferometry.

$$\text{平均角直径} = 0.023 \pm 0.003 \text{ arcsec}$$

Notes:

(1) Probably uniform disk value.

(2) Corrected for limb darkening by present authors (Section 4).

(3) Total uncertainty.

(4) For uniform disk (UD).

(5) For limb darkened disk (LD).

Blackwell & Shallis 1977

“非模型依赖” 方法

◆ 利用绝对热星等 (M_{bol}) 确定有效温度

$$M_{bol} = M_V - BC;$$

$$M_V = m_V + 5 - 5 \log d \text{ (pc)}$$

BC 是热改正来自V波段外流量的贡献（这个值利用恒星大气模型计算得到）；
 m_V 是视星等; M_V 是绝对视星等;

举例:

太阳 $m_V = -26^m.75$; $M_V = 4^m.82$; $M_{bol,sun} = 4^m.74$; $BC = 0^m.08$

基本方程:

$$[T_{eff}] = 0.1 M_{bol,sun} + 0.1 BC - 0.1 M_V - 0.5 [R]$$

观测量:

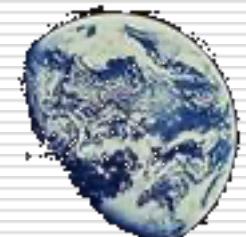
a) m_V ;

$$R = \theta d$$

b) q ;

c) d

$$[X] = \log X / X_{sun}$$



红外流量方法 (IRF) (Blackwell & Shallis 1977)

$$\theta^2 = f/F = f_\nu/F_\nu$$

思路:

这一关系对所有的频率都适用.

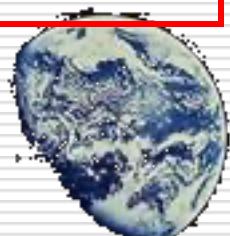
在IRF方法中角直径是通过观测多个IR波段的单色光流量 f_{IR} 得到.

恒星表面的初始流量, F_{IR} , 可以利用恒星大气模型计算得到。模型的选择对结果影响不大

- 红外流量对温度的依赖性很小;
- 谱线导致的不透明度比较小;
- 连续不透明度很清楚.

恒星的绝对流量 f 通过测量或从 m_V 得到.

$$T_{eff}^4 = \frac{f}{\sigma} \frac{F_{IR}}{f_{IR}}$$



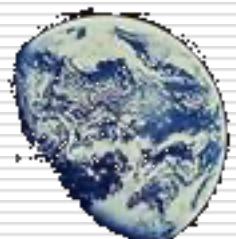
T_{eff} 和 θ 通过迭代得到

红外流量方法

- ◆ 这种方法不局限于已知距离的恒星
- ◆ 它依赖于恒星大气类型和
- ◆ 非常敏感于星际红化

红外流量方法已经成为确定有效温度 T_{eff} 的一种标准方法

Alonso et al. (1996) 发表了1000多颗恒星的 $T_{\text{eff}}(\text{IRF})$

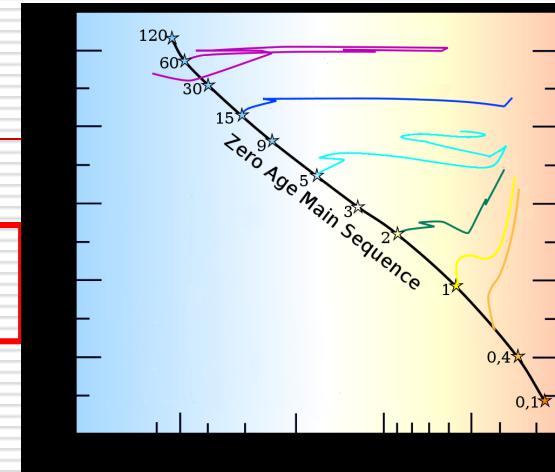


利用三角视差确定表面重力

$$g = \frac{GM}{R^2} = \frac{GM\sigma T_{eff}^4 4\pi}{L}$$

$$[g] = [M] + 4[T_{eff}] + 0.4(M_{bol} - M_{bol,sun})$$

$$M_{bol} = Vmag + 5 + 5 \log \pi'' + BC - Av;$$



$\pi'' = 1/d$ (pc) 是来自 Hipparcos (1997) 的三角视差测量;

T_{eff} 已经知道; BC 热改正 (Alonso et al. 1999, A&As, 140, 261)

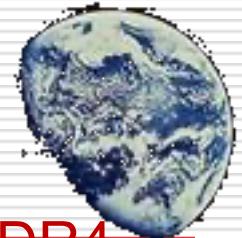
A_V 是 V 波段消光

质量 M 来自恒星演化轨迹的结果;

最好选择刚刚离开主序的恒星 (位置比较容易确定)

这种方法局限于近邻恒星, 这些恒星有精确的三角视差

($d < 200$ pc) Gaia DR3 (2022) $d < 4$ kpc 未来: Gaia DR4



依赖于模型的测光方法

测光方法利用了多波段的测光数据

Paschen连续谱的斜率, F_{4000}/F_{7000} , 敏感于有效温度 T_{eff}

敏感于温度的**颜色**有

- c_1 (或考虑了红化后的 $[c_1]$) 对热星,
- $b-y$, $B-V$, 或 $V-K$ 对冷星 晚于F型

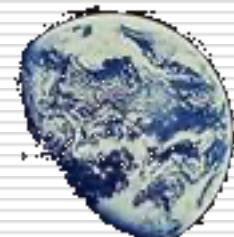
从Strömgren的ubvy或Johnson UBVRIJHK系统.

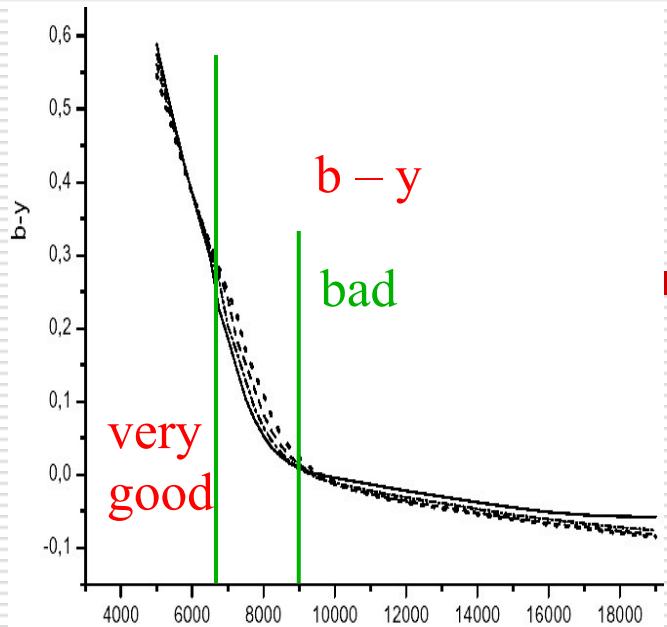
$(B - V)$ 反映 F_{4400}/F_{5500} 比值而 $(b - y)$ 反映 F_{4700}/F_{5550}

$c_1 = (u - v) - (v - b)$ 体现了 $(F_{3500}/F_{4100}) / (F_{4100}/F_{4700})$ 比值

测光方法依赖于如何校准

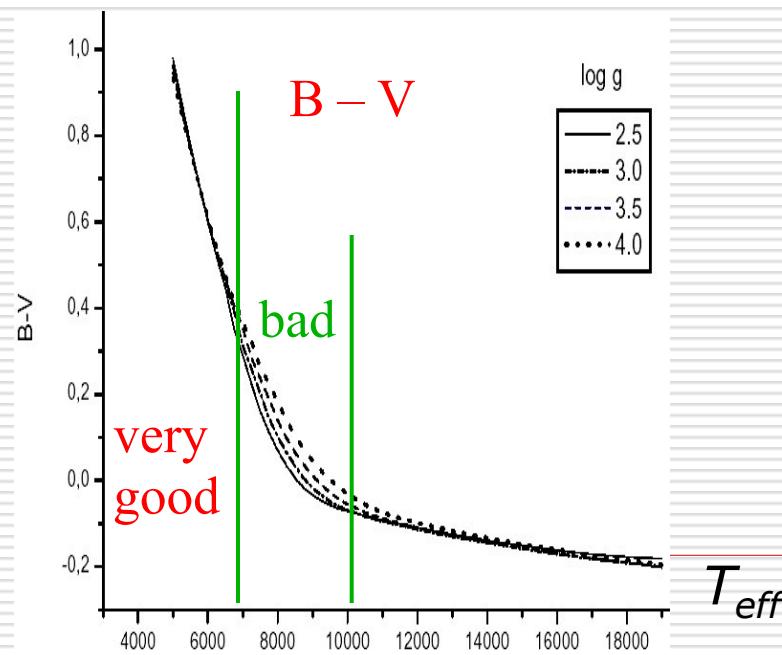
- 利用恒星大气模型 Alonson+ 1996 dwarf
- 或利用红外流方法得到的温度 1999 giant



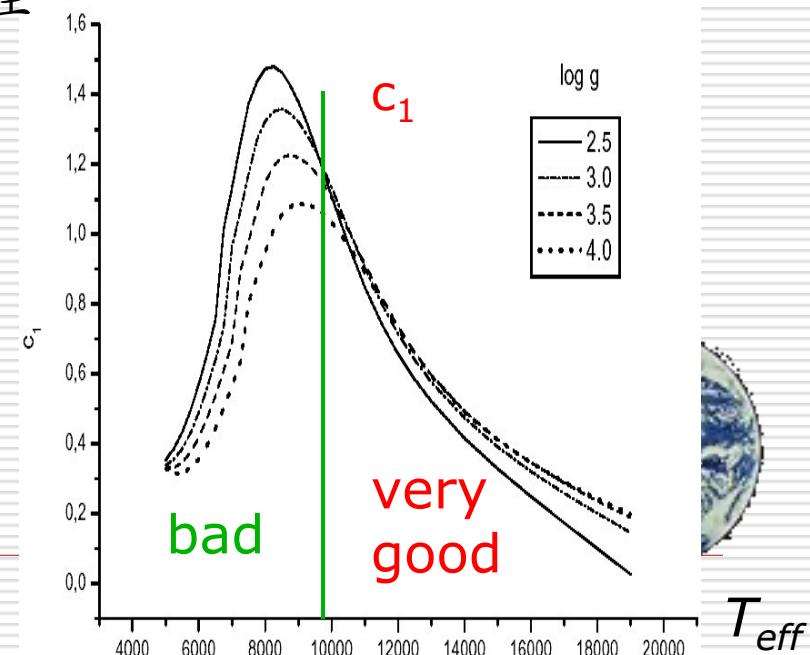


理论：颜色 - T_{eff} 关系

这一校准包括利用如Kurucz
(1992)等理论模型计算得到



B-V与 T_{eff} 相关性很差，因为颜色与
金属丰度有很强的相关性，还与
表面重力和微观湍流速度有一定
的相关性



色指数 - T_{eff} 关系

◆ 其他一些颜色温度关系

➤ 矮星

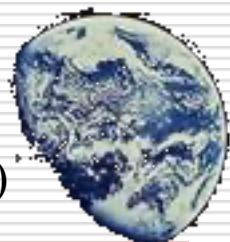
- Peterson et al.: ApJ 231, 762 (1979)
- Carney: AJ 88, 623 (1983)
- Fernley: MNRAS 239, 905 (1989)
- Bell & Gustafsson: MNRAS 236, 653 (1989)
- Sekiguchi et al.: AJ 120, 1072 (2000)

➤ 巨星

- Stone: PASP 95, 27 (1983)
- Di Benedetto: A&A 339, 858 (1998)
- Bessell et al.: PASP 111, 1421 (1999)
- Sekiguchi et al.: AJ 120, 1072 (2000)

➤ 矮星和巨星

- González Hernández, J. I., Bonifacio, P.: A&A 497, 497(2009)
- Casagrande, L. et al.: A&A 512, A54(2010)
- Huang, Y. et al. : MNRAS 454, 2863(2015)

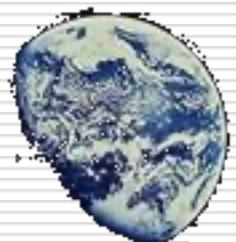


金属丰度确定

◆ F-型恒星

$$\begin{aligned}[Fe/H] = & 1.052 - 73.21m_1 + 280.9m_1(b-y) + 333.95m_1^2 \\ & (b-y) - 595.5m_1(b-y)^2 + [5.486 - 41.26m_1 - \\ & 7.963(b-y)] \cdot \log[m_1 - 0.6322 + 3.58(b-y) \\ & - 5.20(b-y)^2]\end{aligned}$$

适用范围： $0.22 \leq (b-y) \leq 0.38$; $0.03 \leq m_1 \leq 0.21$
 $0.17 \leq c_1 \leq 0.58$; $-3.5 \leq [Fe/H] \leq 0.2$



金属丰度确定

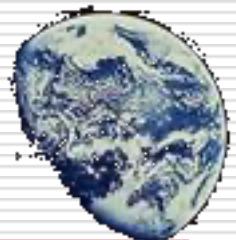
◆ G-型恒星

$$\begin{aligned} [\text{Fe}/\text{H}] = & -2.0965 - 22.45m_1 - 53.8m_1^2 - 62.40m_1(b-y) \\ & + 145.5m_1^2(b-y) + [85.1m_1 - 13.8c_1 - 137.2m_1^2] \cdot c_1 \end{aligned}$$

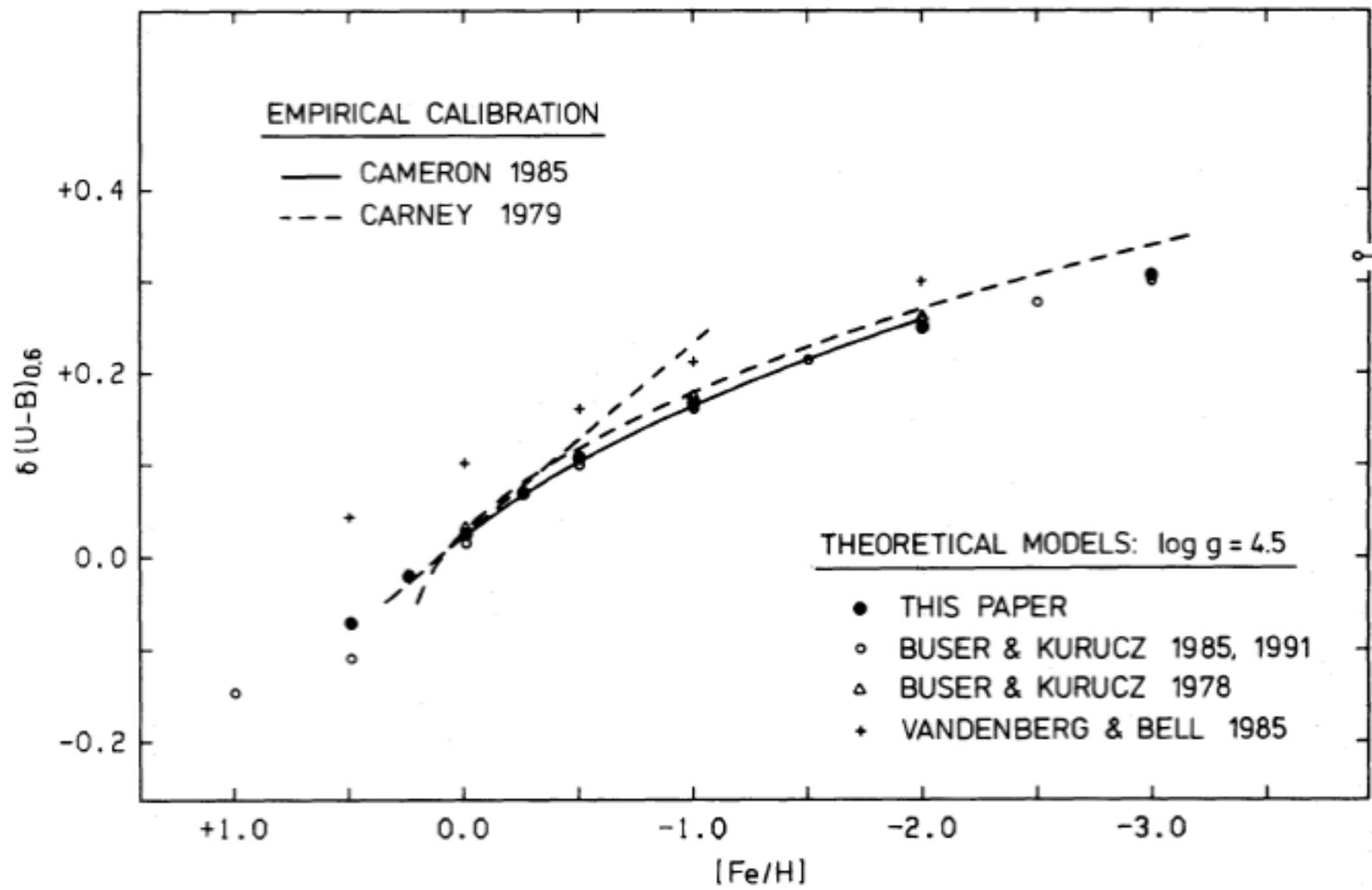
适用范围： $0.37 \leq (b-y) \leq 0.59$; $0.03 \leq m_1 \leq 0.57$

$0.10 \leq c_1 \leq 0.47$; $-2.6 \leq [\text{Fe}/\text{H}] \leq 0.4$

$$\sigma[\text{Fe}/\text{H}] = 0.16$$



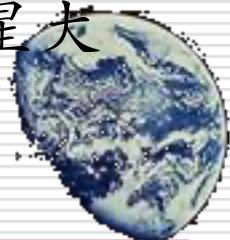
金属丰度确定



测光方法: +++ ---

+ 对非常近的恒星有效

- $(B - V)$ 与 T_{eff} 相关性很差, 因为这一关系与金属丰度相关
- 颜色星等关系 不是很准确 因为需要可重复的数据. 如果测光数据不是较差的(不是对目标所有波段同时观测), 颜色的精度不会好于 0.02 星等
- 恒星的颜色由于星际尘埃的存在, 会受红化的影响, 我们只有关于色余 E_{B-V} 近似的知识
- 连续谱辐射是在相对很薄的恒星大气层 ($\tau = 1$ 附近) 辐射出来的, 因此, 这些颜色不能反映整个恒星大气的物理结构
- 这里没有一个色指数随 $\log g$ 简单变化



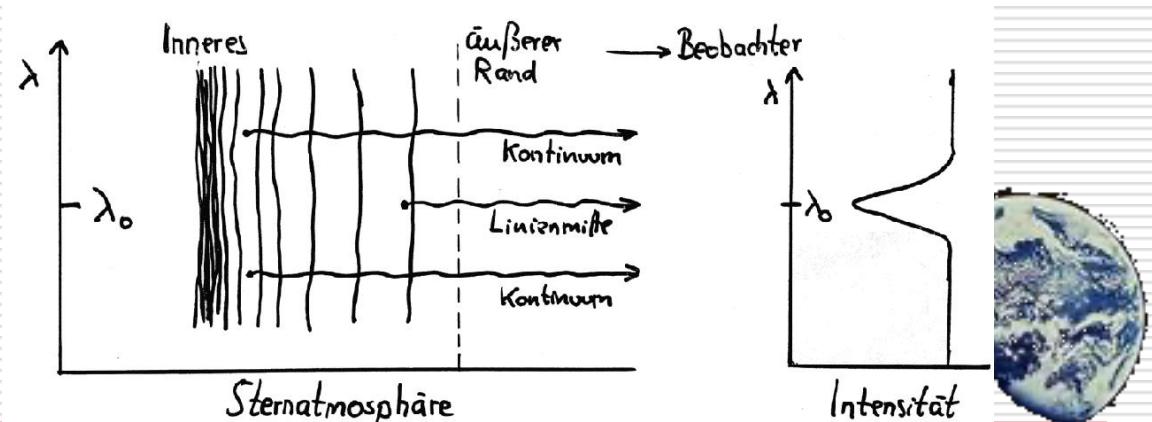
光谱方法

基于谱线敏感于恒星参数, T_{eff} , $\log g$, 元素丰度, ξ_t

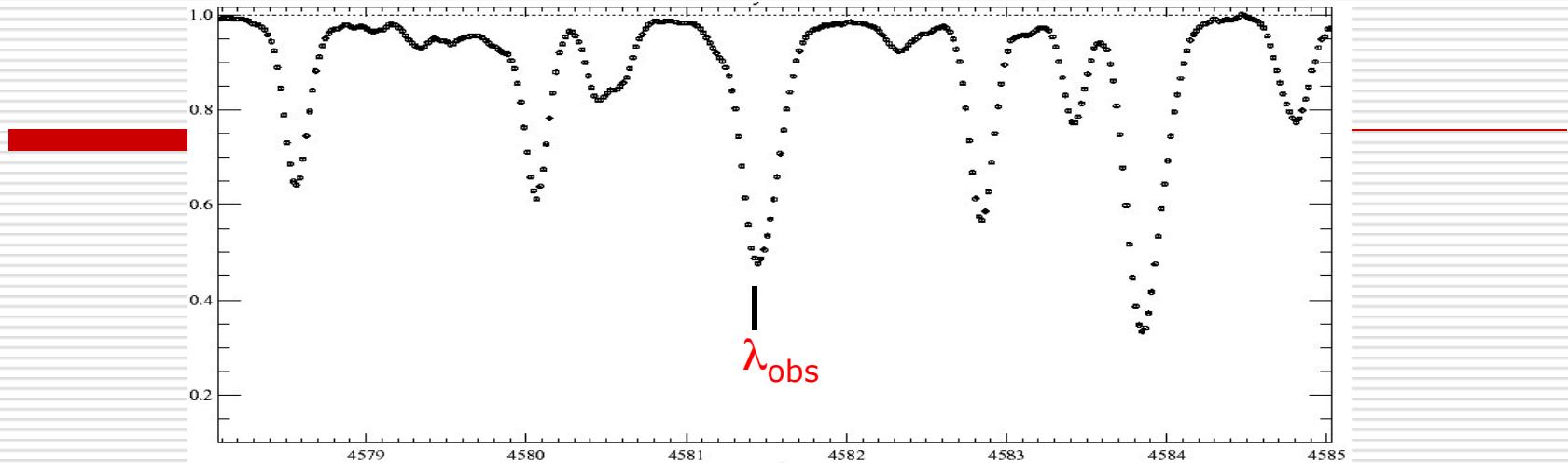
与连续谱相反, 谱线的辐射来自比较大的光深范围, 它们的线翼来自恒星大气的内部, 而线心来自恒星大气的高层.

这种方法基于

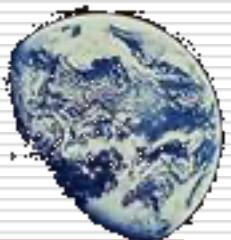
- ◆ 高分辨率 ($R = \lambda / \Delta\lambda > 20000$) 光谱观测;
- ◆ 谱线证认: 定量分析何种元素的那个跃迁形成的谱线;
- ◆ 定量分析谱线.



谱线证认



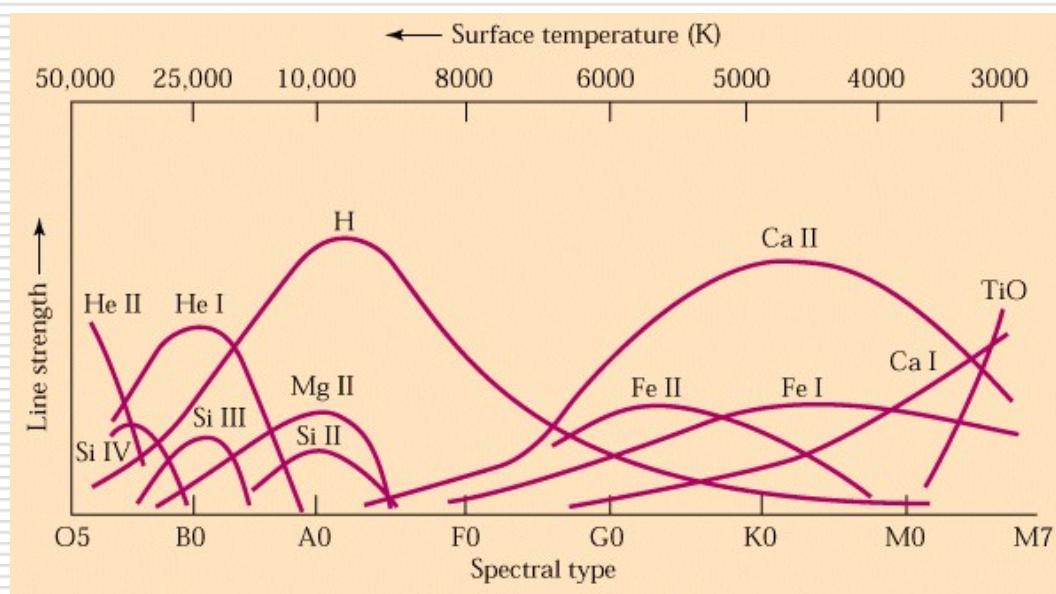
1. 确定谱线的中心波长, λ_{obs}
2. 寻找最有可能的跃迁 利用光谱线表
 - a) Moore C.E. 1972 “A multiplet table of astrophysical interest, Revised edition” NSRDS-NBS, 40
 - b) SAO Kurucz CD-ROM N 18 以及其他
3. 谱线证认依赖于标准和对恒星参数知识的了解



证认谱线：标准

$$W_\lambda \sim N_r / N_A \epsilon_A g_i f_{ij} e^{-Ei/kT}$$

(1) (2)+(3) (4)

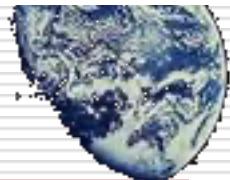


(1) N_r / N_A 非常敏感于 T_{eff}
所考虑的离子在恒星大气
中是否足够多到能产生这条谱
线?

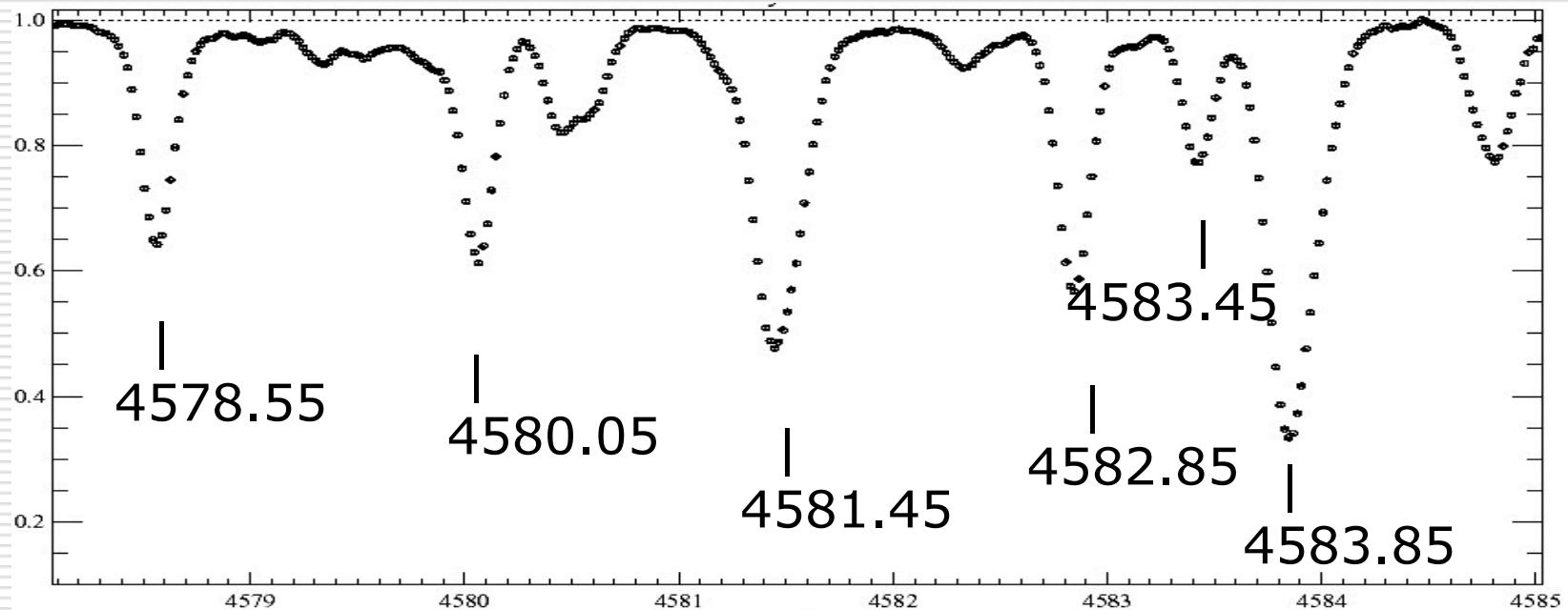
(2)+(3) 线性依赖于化学元素
丰度和 gf 值

(4) 谱线低能级的激发电势越高则越弱;

(5) 来自同一个multiple的谱线有： $W_1 / W_2 = (gf)_1 / (gf)_2$

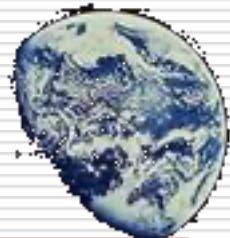


举例：Procyon $T_{\text{eff}} = 6500 \text{ K}$, $\log g = 4.0$

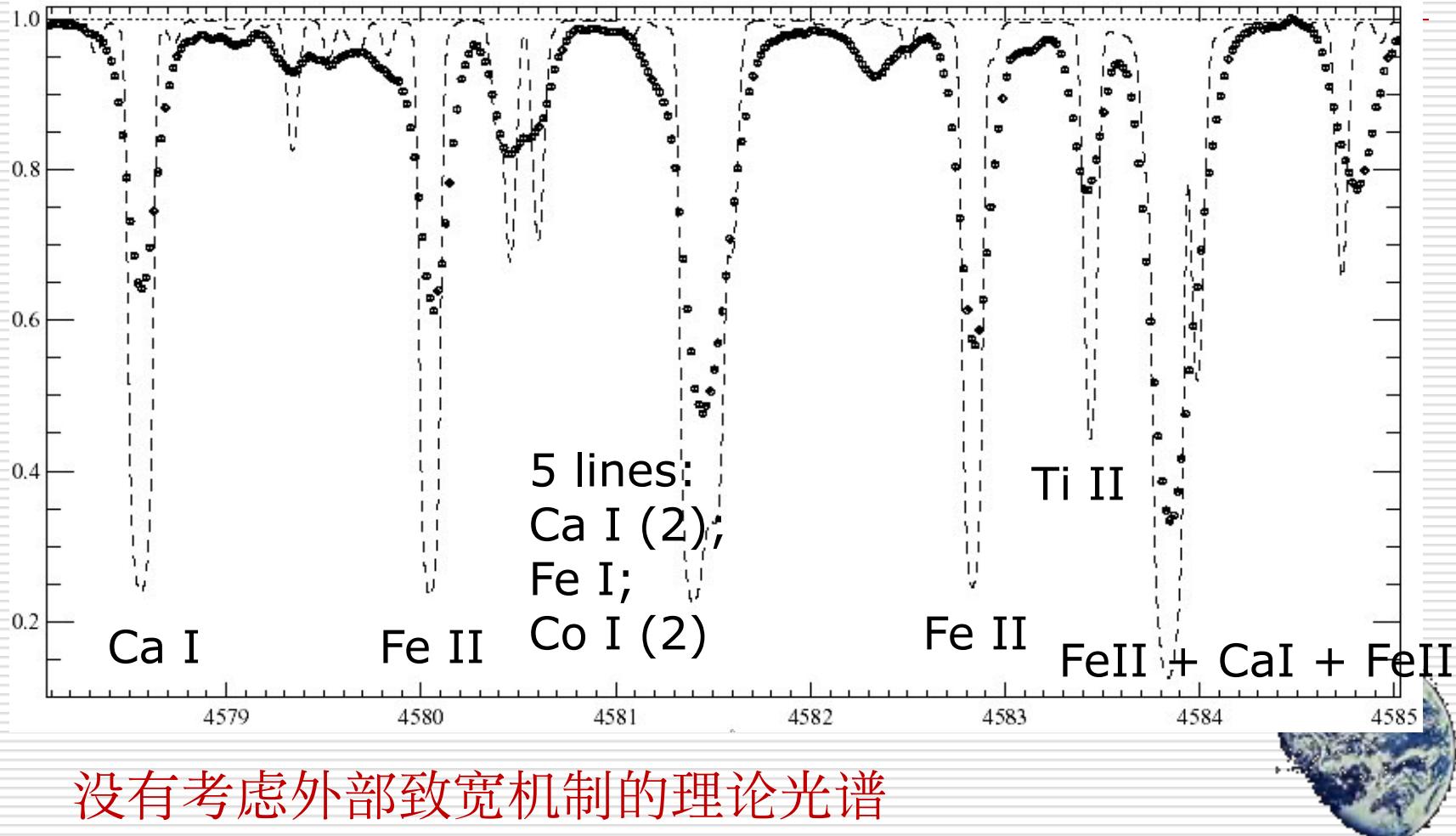


波长精度 $\Delta\lambda = 0.05 \text{ Å}$; 从表中可以得到 $\lambda / \text{离子} / E_i (\text{eV}) / \log gf$

- | | |
|--------------------------------|---------------------------------|
| 1) 4578.560/Ca I/ 2.51/ -0.17; | 3) 4581.400/Ca I/ 2.51/ -0.08; |
| .560/V II/ 3.76/ -7.07; | .414/Ni I/ 3.60/ -2.57; |
| .596/V I/ 1.87/ -3.62; | .428/Cr I/ 3.41/ -4.68; |
| 2) 4580.043/Cr I/ 0.94/ -1.30; | .454/Fe II/ 9.90/ -4.06; |
| .050/La II/ 0.71/ -1.52; | .467/Ca I/ 2.52/ -0.90; |
| .050/Fe II/ 2.57/ -3.72; | .487/Co I/ 3.78/ -0.48; |
| .058/Cr II/ 10.6/ -2.36; | 4) 4582.833/Fe II/ 2.83/ -3.22; |
| 5) 4583.440/Ti II/ 1.16/ -2.68 | |



举例：与恒星大气模型的计算结果比较

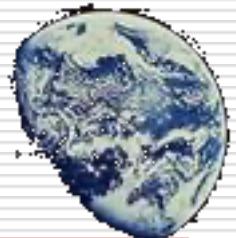


光谱方法: Balmer 谱线

Balmer谱线的重要性

无论是冷星还是热星，由于几乎所有的恒星大气中氢占主导，因此中性氢的Balmer谱线对参数信息有贡献；结合它的电离温度，有理由在光谱分类的过程中考虑它们。

- 一般地说, hydrogen一般有两者状态, 只有很少部分处于两者之间
- 温度 $T_{\text{eff}} \geq 8000 \text{ K}$ 的热星中, 它是电离的
- 温度 $T_{\text{eff}} < 8000 \text{ K}$ 的冷星中, 它是中性的



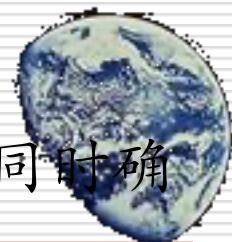
T_{eff} 利用Balmer谱线

冷星中的Balmer谱线谱线不是很依赖于其它参数，除了温度 T_{eff} ；

因此，我们可以仅仅从冷星的Balmer谱线确定 T_{eff} （注意：依赖于混合程参数）；

这一情形在温度范围是 $8000 \leq T_{\text{eff}} \leq 10000$ K A型星中会变得不一样，这时Balmer谱线同时依赖于温度和表面重力；

这样，如果有高信噪比(S/N)的光谱， T_{eff} 和 $\log g$ 可以同时确定，通过比较理论与观测光谱。



T_{eff} 利用 Balmer 谱线

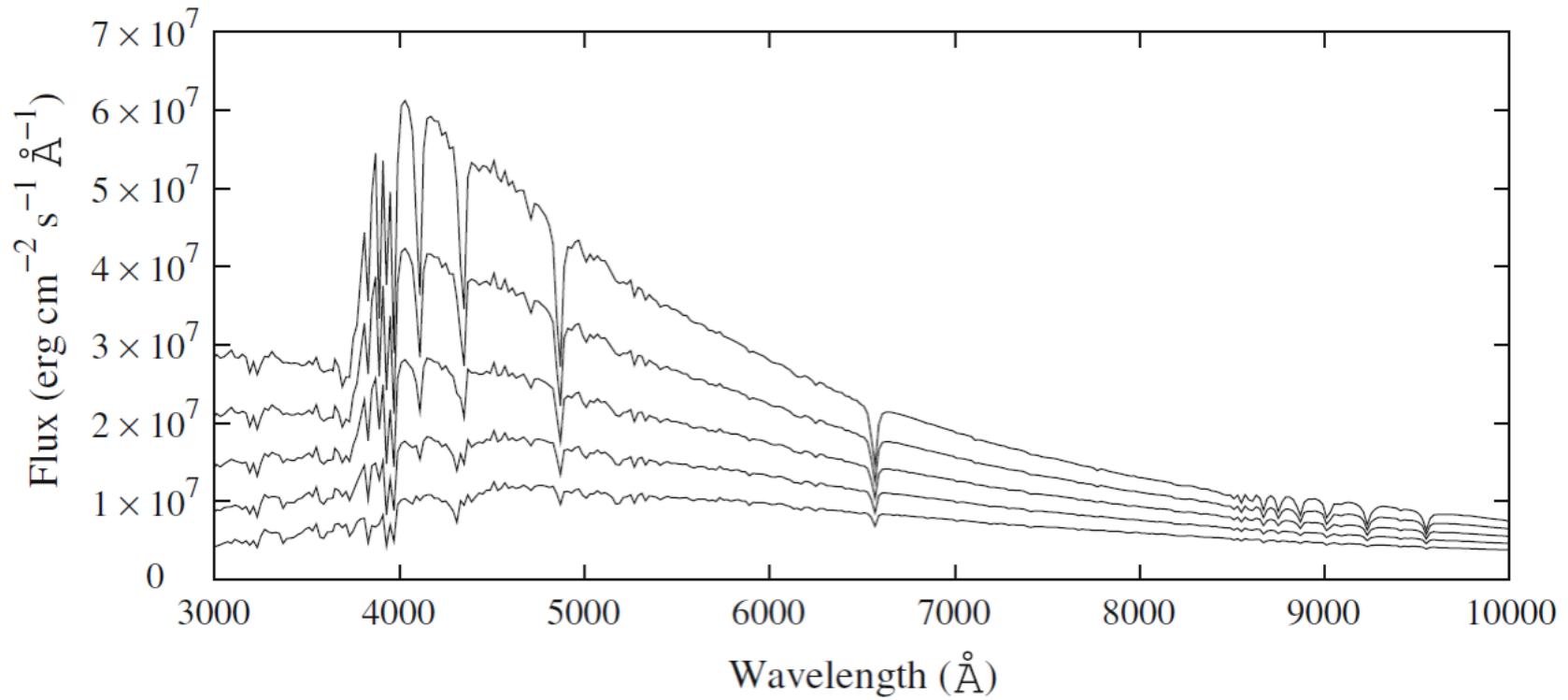


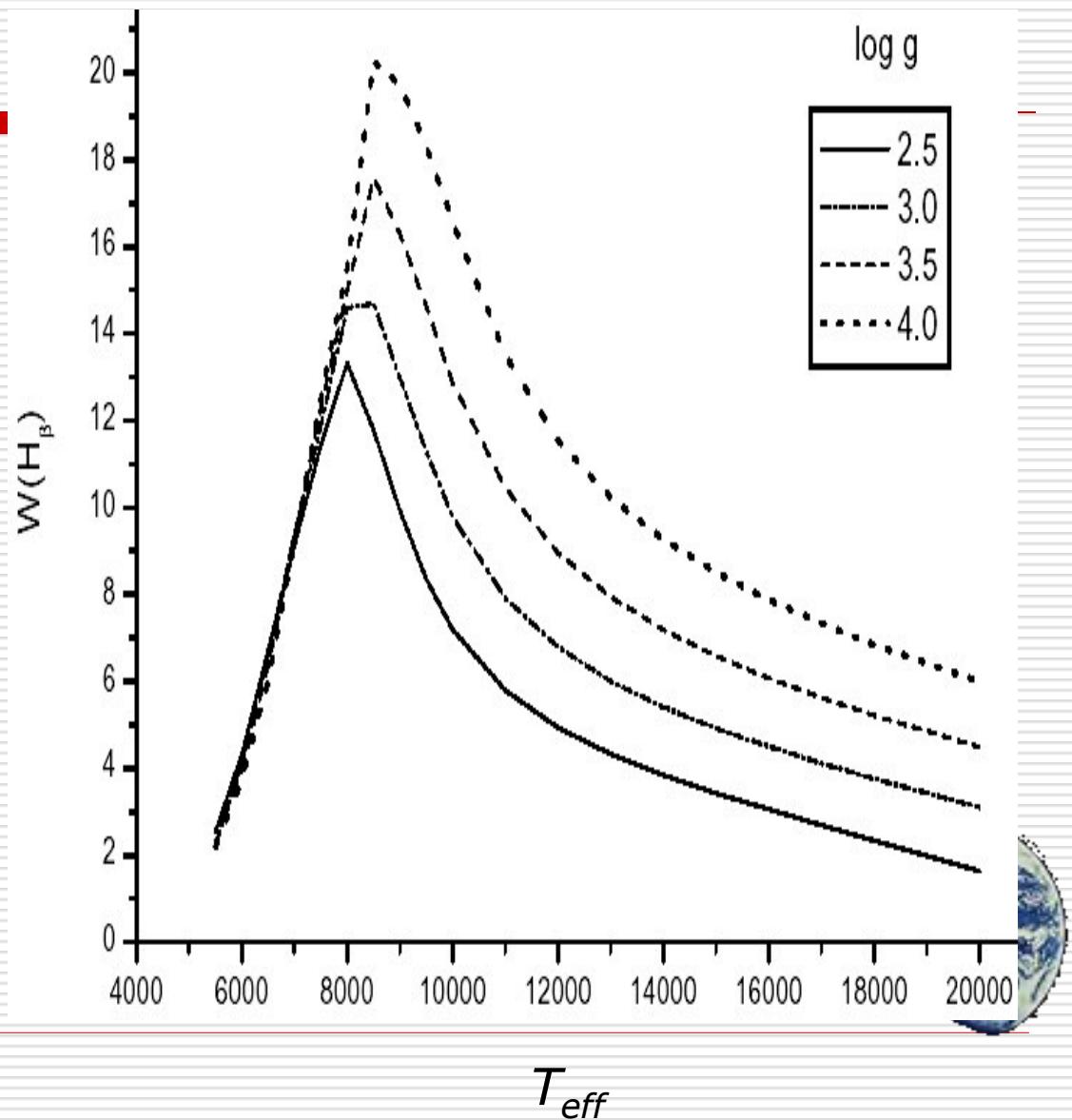
Fig. 2 The variation of stellar flux with T_{eff} , ranging from 6,000 K (bottom) to 8,000 K (top) in steps of 500 K



光谱方法: Balmer 谱线

Balmer 谱线:

T_{eff} 比A5晚的恒星
 $\log g$ O - B 恒星

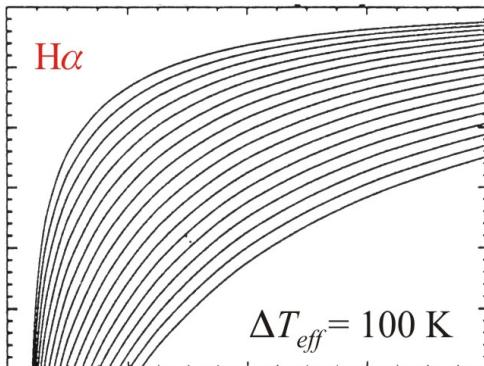


T_{eff} 利用Balmer谱线

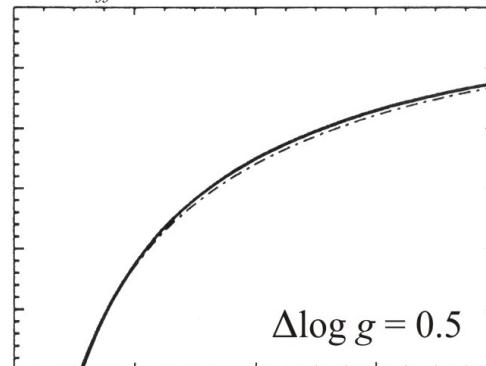
H_{α} 和 H_{β} 谱线随恒星参数的变化

T_{eff} (左图, 5000 – 6500 K), $\log g$ (中间图, 3.0 – 4.5) 和
[Fe/H] (右图, 0.5 – (-3.0))

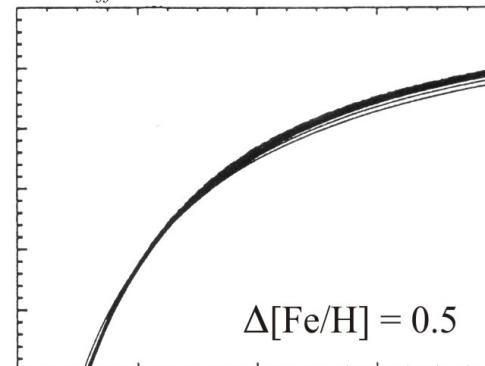
(a) $\log g = 4.0$, [Fe/H] = 0



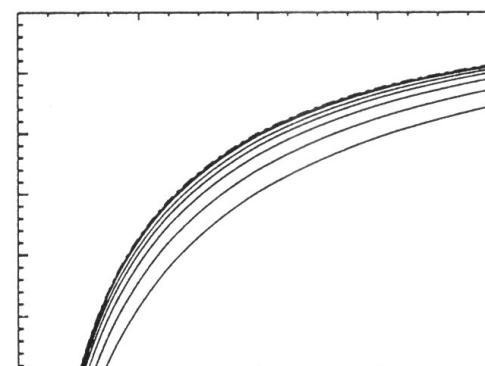
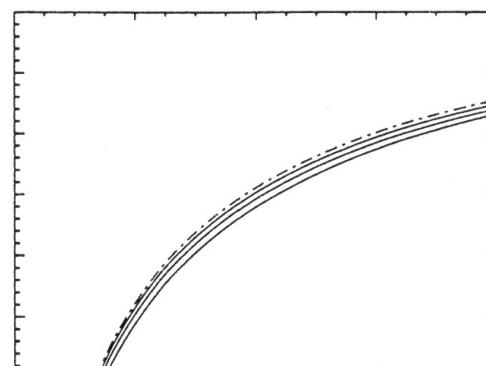
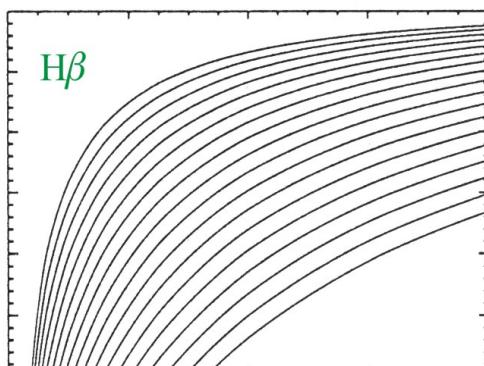
(b) $T_{\text{eff}} = 6000 \text{ K}$, [Fe/H] = 0



(c) $T_{\text{eff}} = 6000 \text{ K}$, $\log g = 4.0$

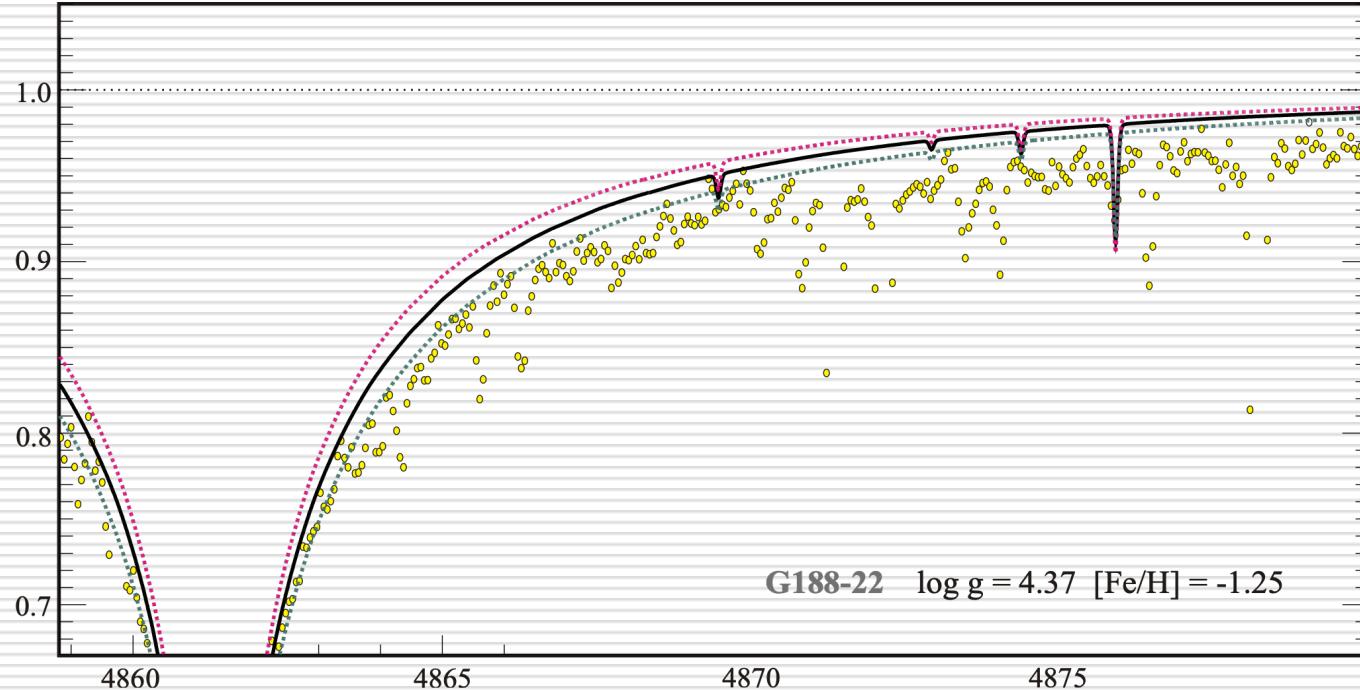


$H\beta$

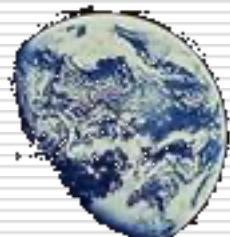


T_{eff} 利用Balmer谱线

如图所示典型的如何确定温度的例子：高自行恒星G188-22恒星光谱以及噪声



与利用直径、红外流量或色指数确定温度相比，
Balmer谱线是最好的确定恒星有效温度 T_{eff} 的参量。

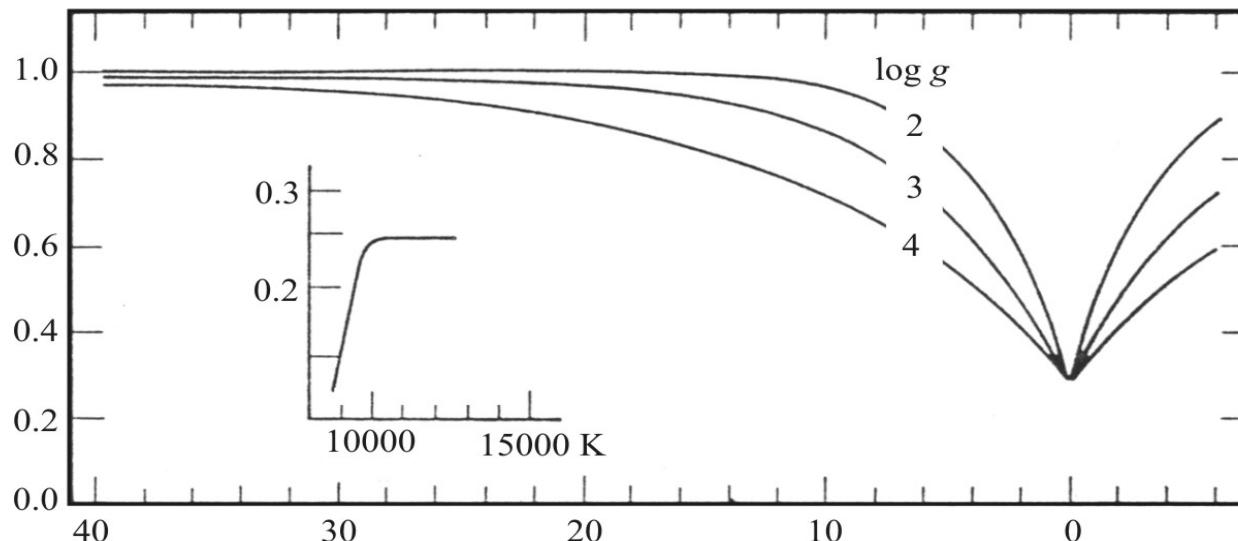


T_{eff} 利用Balmer谱线

在其它光谱型恒星中Balmer谱线或者敏感于温度，或者敏感于表面重力；

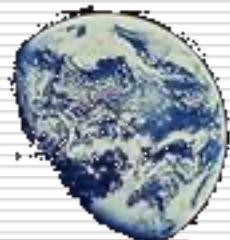
H γ 谱线的线翼强的Stark致宽效应依赖敏感于表面重力。

H γ

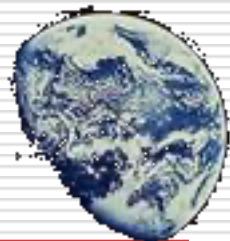
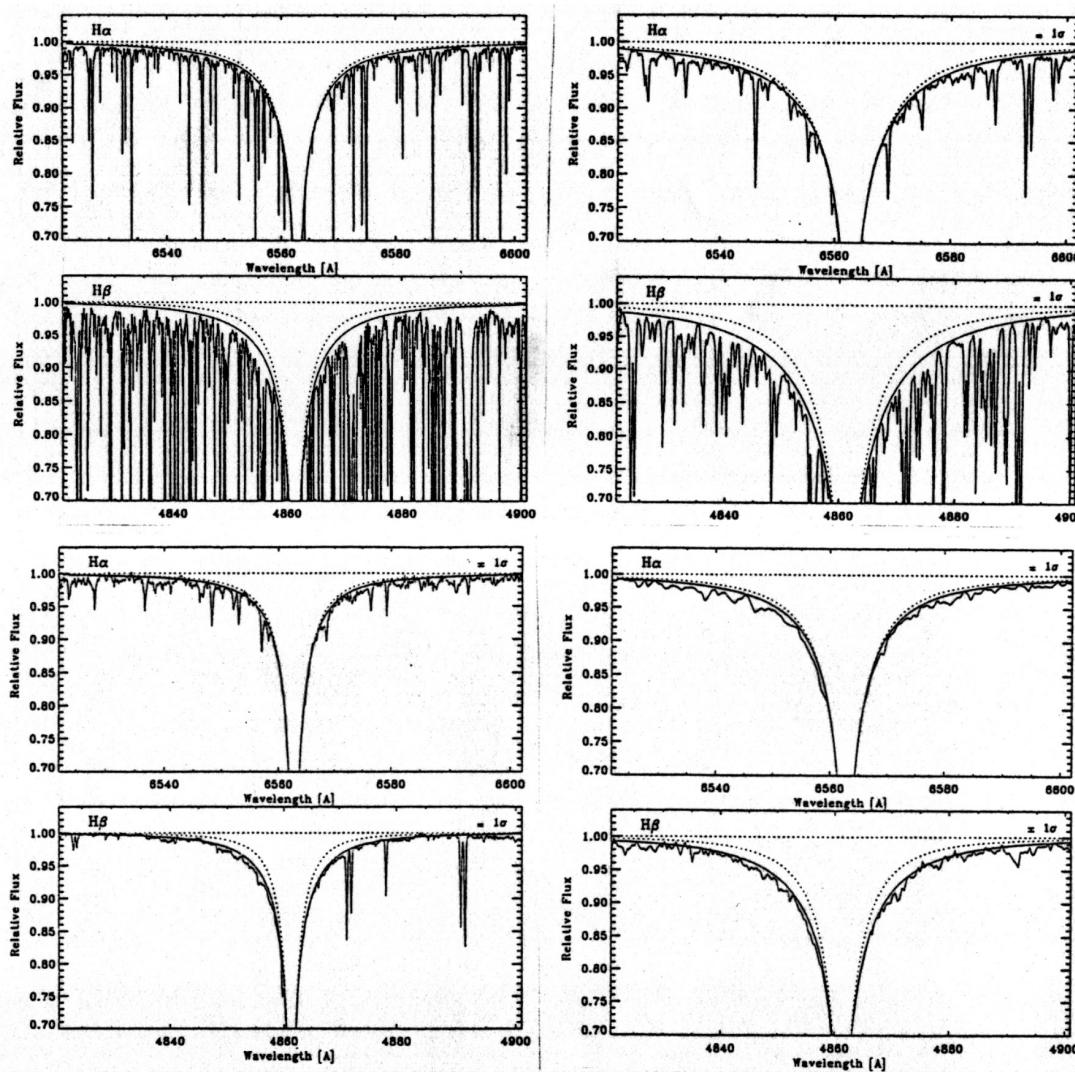


In a medium B-type star for various $\log g$

Insert shows the gradient increasing with temperature. An increase is nearly step-like.

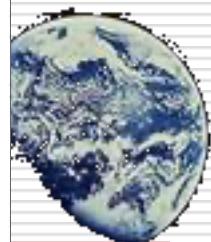
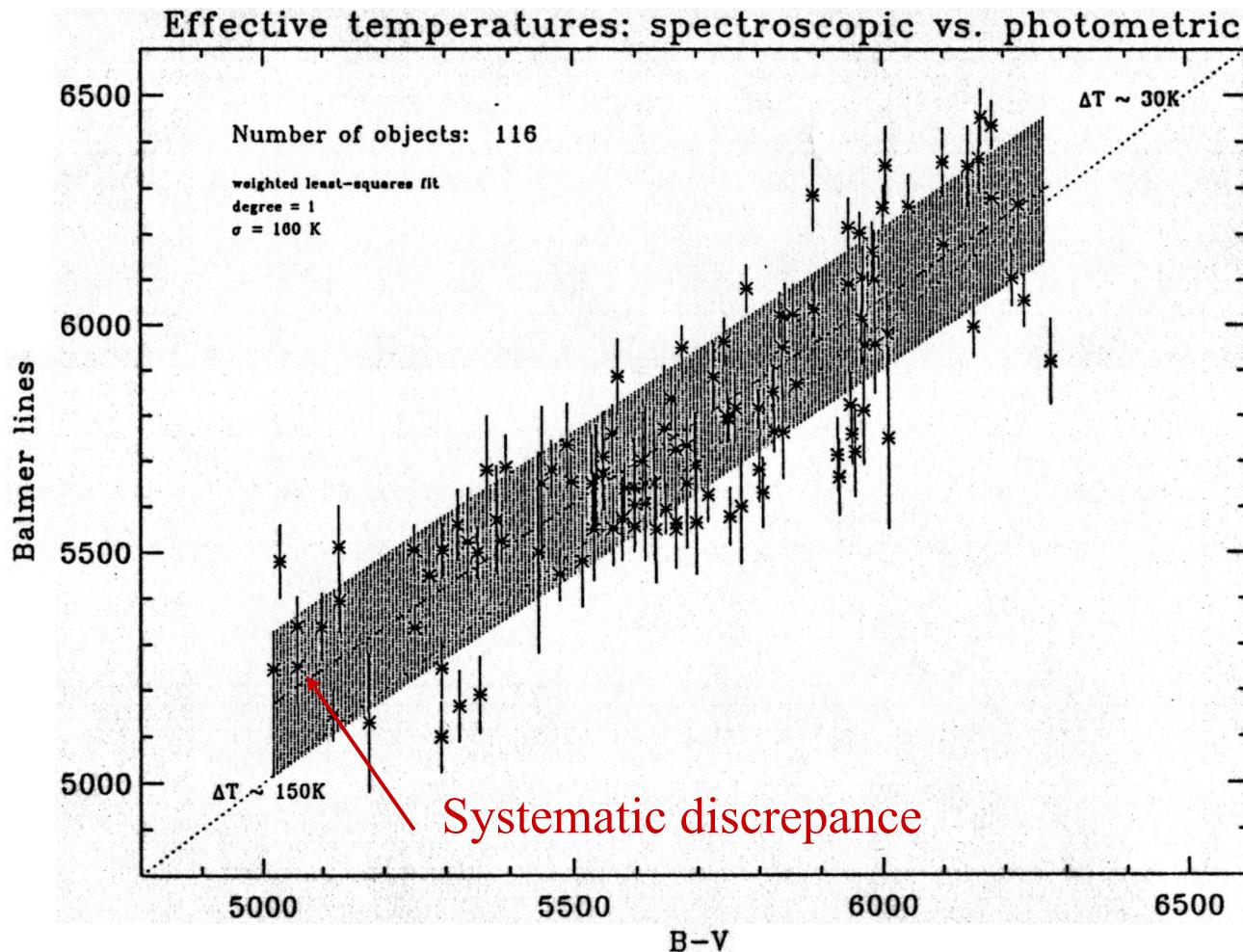


不同表面重力和金属丰度下的谱线轮廓



T_{eff} 利用 Balmer 谱线

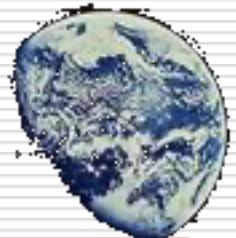
rms error = 160 K



T_{eff} 利用Balmer谱线

一旦选择合适的混合程参数保证所有的Balmer谱线得到相同的温度, 这些观测到的轮廓可以让我们得到精确的温度.

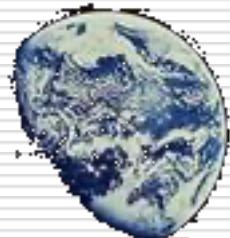
利用太阳和冷星有相同的Stark谱线轮廓, 可以得到精度非常高的相对温度 $T_{\text{eff}} - T_{\text{eff}, \odot}$, 如果采用相同的恒星大气模型.



电离平衡作为温度或重力的标志

Saha方程同时依赖于电子密度和温度. 因此, 原则上恒星大气中的电离平衡应该包含 T_{eff} 和 $\log g$ 的信息。

来自相邻电离态的谱线的强度比依赖于温度 T_{eff}

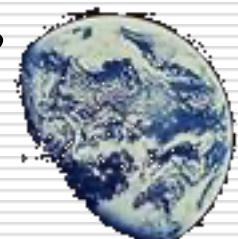


电离平衡作为温度或重力的标志

当温度高于5000 K 时 $\text{Fe II}/\text{Fe I}$ 的电离平衡(数密度形式) 不像温度低于5000 K时那么依赖于温度.

当温度高于8000 K时 Fe 又变得敏感于温度T, 这是因为很快出现的 Fe II 电离.

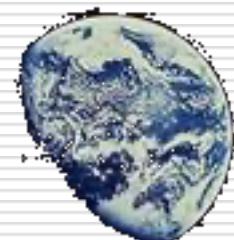
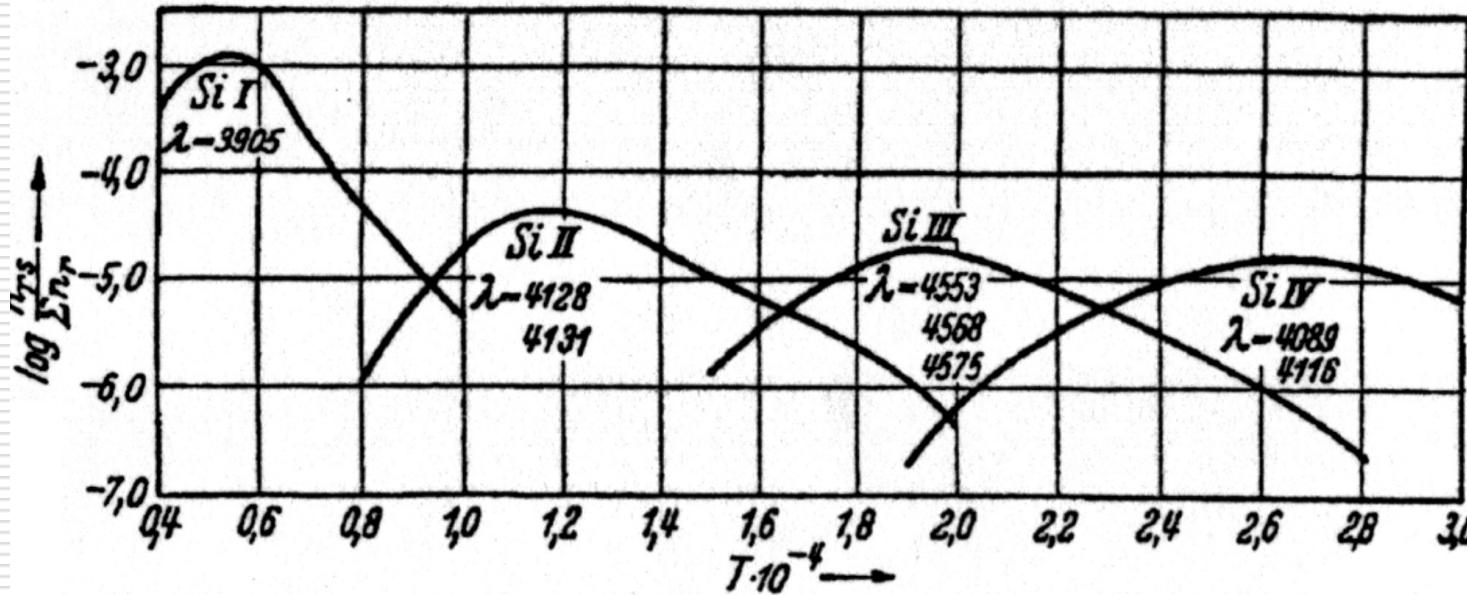
在这两个温度之间 $\text{Fe II}/\text{Fe I}$ 依赖于表面重力, 这是因为改变了表面压力, 会改变电子密度.



电离平衡作为温度或重力的标志

在高温时(>8000 K)一些电离平衡被用来作为温度的标志,

一种非常实用的元素是Si.对光谱型为早B型的恒星(



在这里有Si II, III和IV离子，所有都有足够多的数目在光学波段形成足够强的谱线。

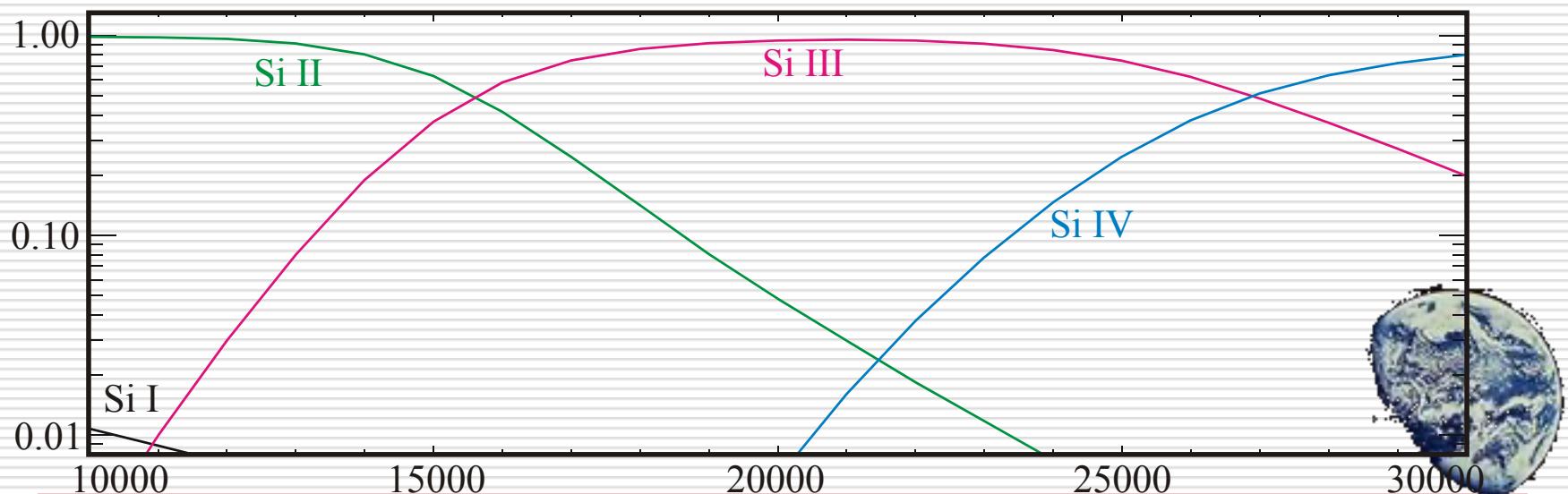
电离平衡作为温度或重力的标志

举例：

B型星： Si III / Si II 谱线强度比是很好的温度示踪，

B和O型星 Si IV / Si III 谱线强度比。

粒子数布居比 Si I 到 Si IV



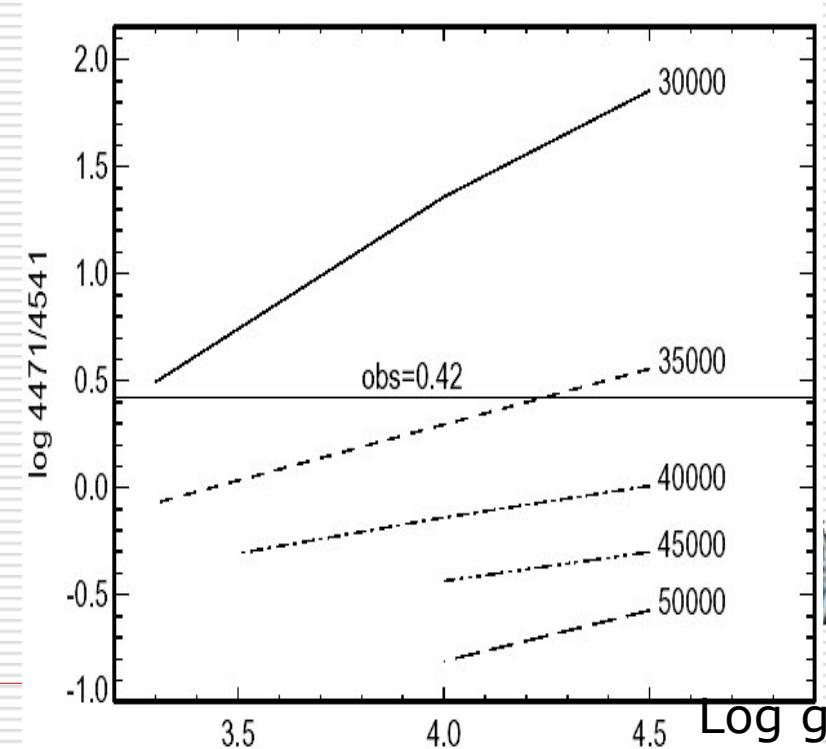
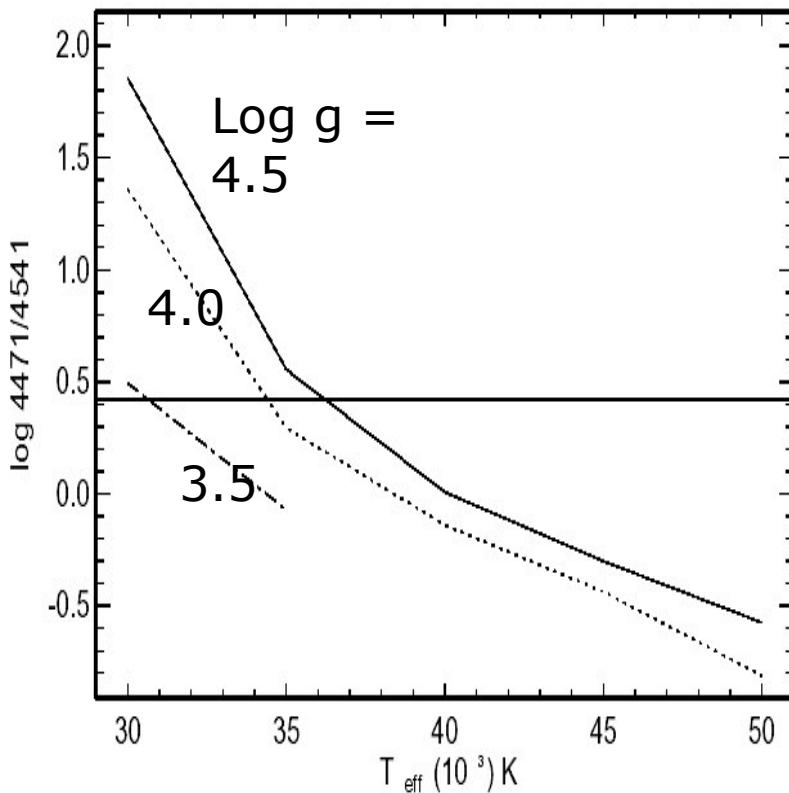
电离平衡作为温度或重力的标志

在很热的星中甚至helium有时被用来作为 T_{eff} 标志.

在非常热的O型星这一情形变得更加复杂，因为这时候由于星风，He II 谱线变成发射线了。

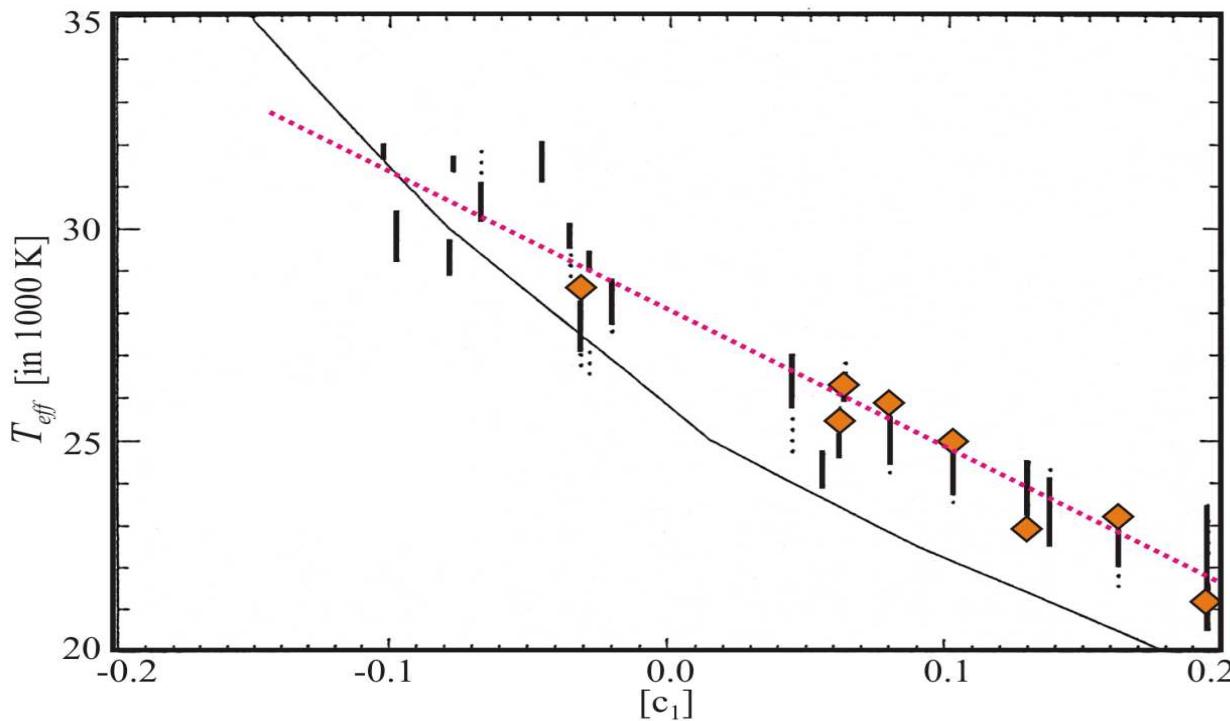
来自邻近电离态的离子的谱线强度比依赖于 T_{eff}

例子： 理论计算的邻近O型星参数恒星的 $W(\text{He I } 4471)/ W(\text{He II } 4541)$ 线强比

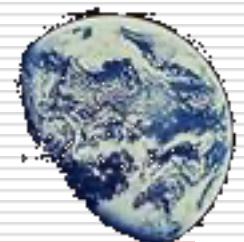


电离平衡作为温度或重力的标志

热星：理论的 $[c_1]$ 相对有效温度 T_{eff} 图（实线），与利用He II/He I（垂直线）和Si IV/ Si III/ Si II（长方形）电离平衡得到的温度比较



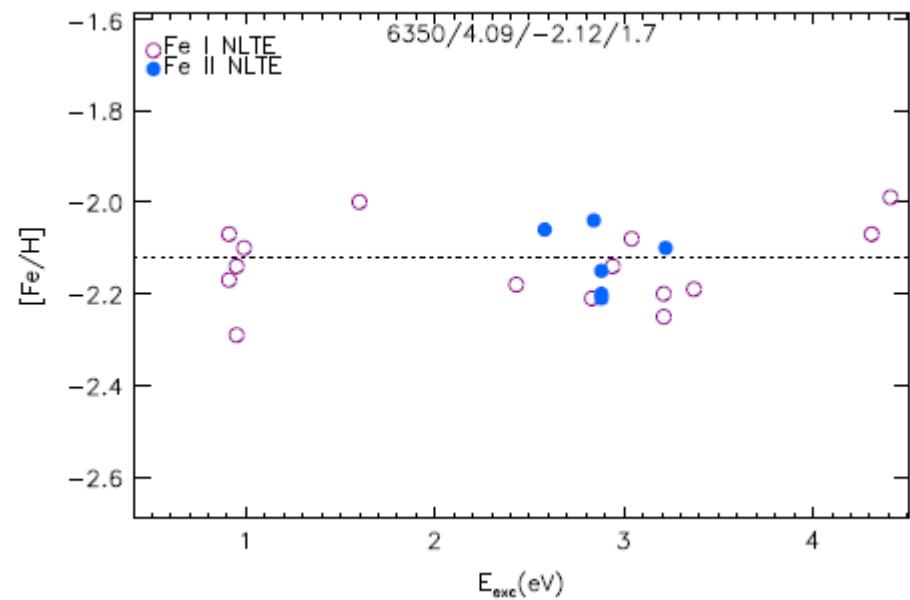
测光与光谱温度
之间存在系统
差，最大可达
2500 K



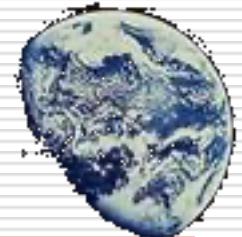
T_{eff} 利用激发电势不同的谱线

利用低能级激发电势不同的谱线形成于不同温度处的性质确定温度：

丰度与激发电势无关



Sitnova et al. 2015



T_{eff} 利用激发电势不同的谱线

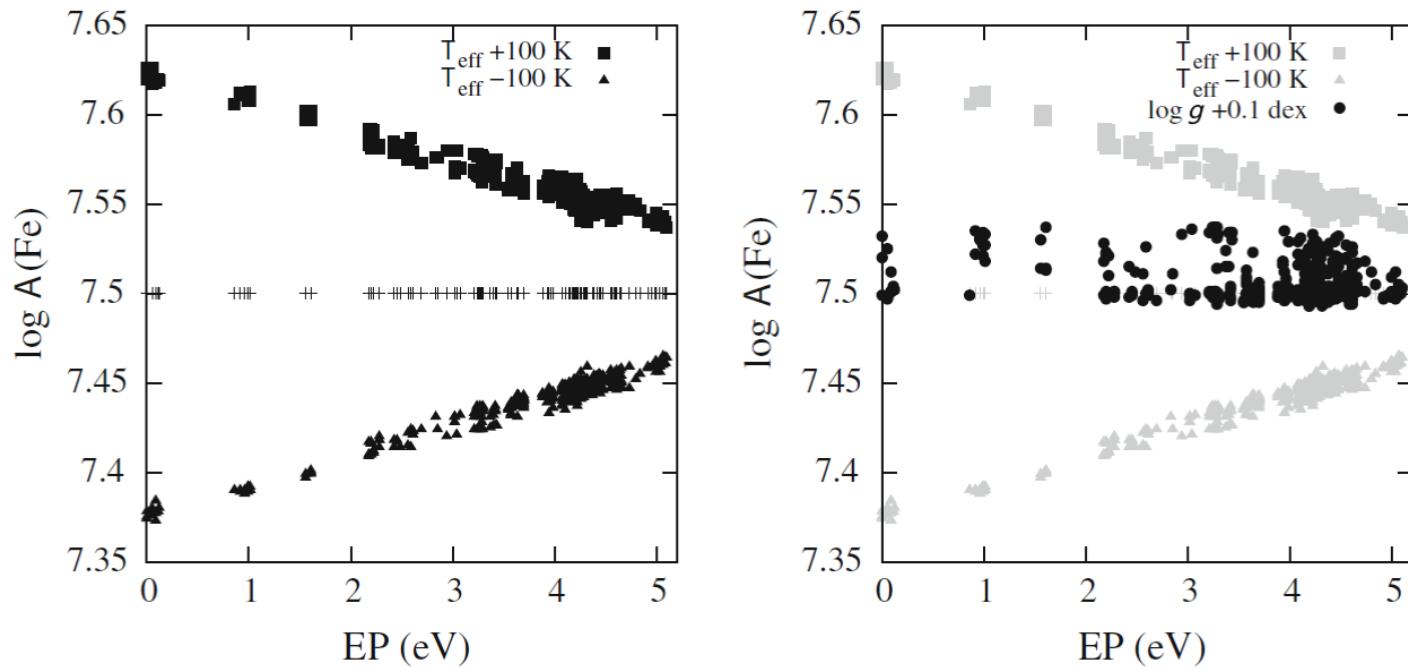


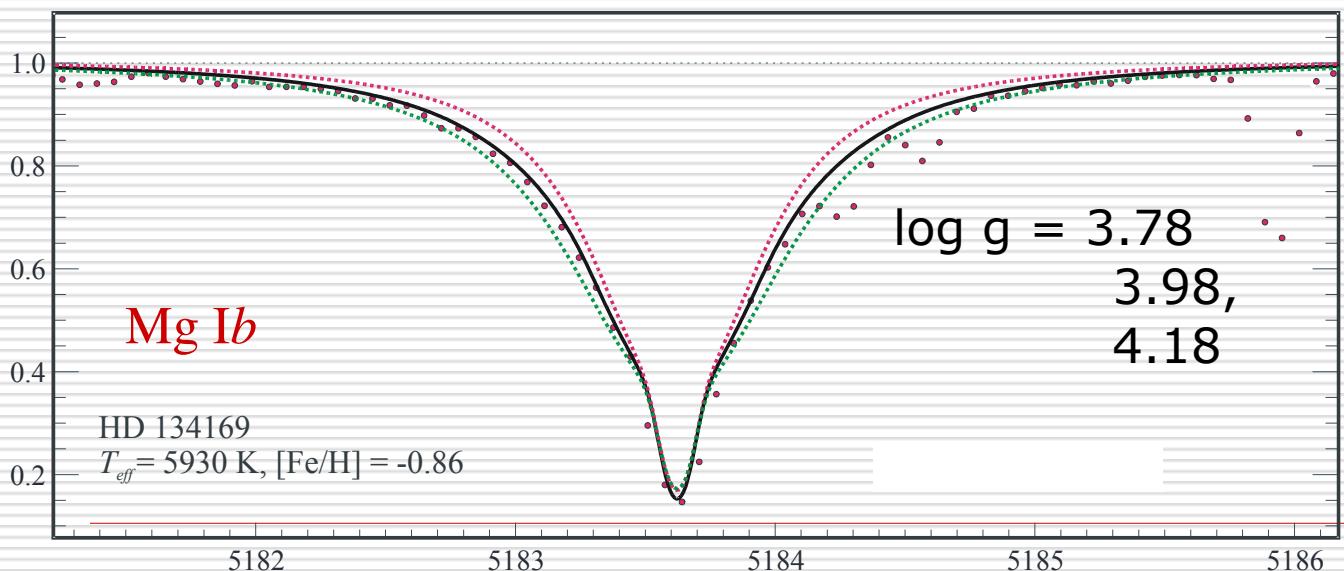
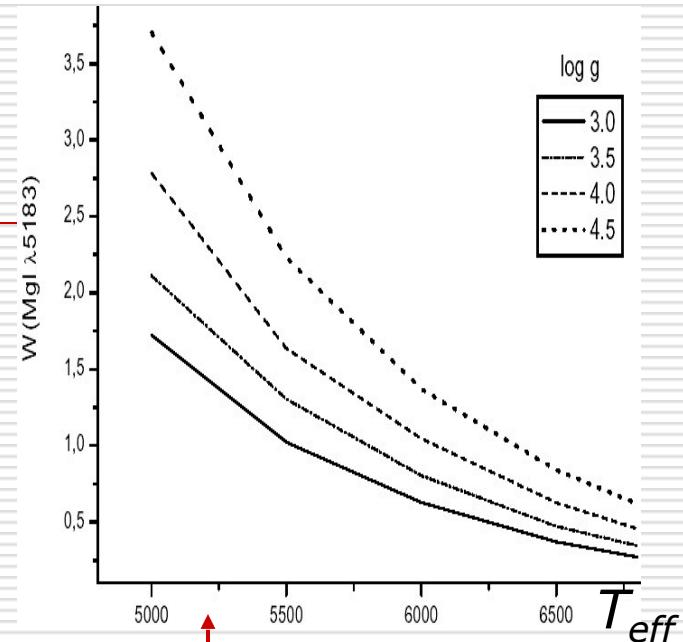
Fig. 6 The effect of changing T_{eff} (left) and changing $\log g$ (right) on the correlation between $\log A(\text{Fe})$ and EP



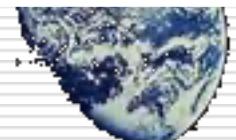
$\log g$ 利用冷星中的强金属谱线

恒星大气中少数元素的强线的范德瓦尔

斯阻尼致宽线翼依赖于 $\log g$. 一旦这个
阻尼参数被确定 (如利用太阳光谱),
观测到的谱线轮廓通过改变表面重力拟合.
这一方法只对 $[Fe/H] > -2$ 的恒星适
合.



Mg Ib等值宽度W
对有效温度 T_{eff}
和表面重力 $\log g$ 的
依赖性



电离平衡作为温度或重力的标志

类似的现象可以在晚型恒星大气中的金属出现,假如它们的电离度低到中性谱线可以观测到。

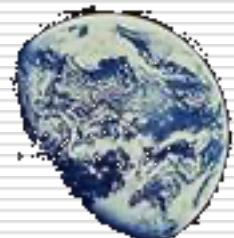
晚型恒星中最重要的电离平衡的元素有

Fe II/Fe I Cr II/Cr I Ti II/Ti I

Ca II/Ca I Mg II/Mg I Si II/Si I

$\log g$ 可以从那些两个电离态都有很多谱线的元素确定。

如: Fe 和 Ti.



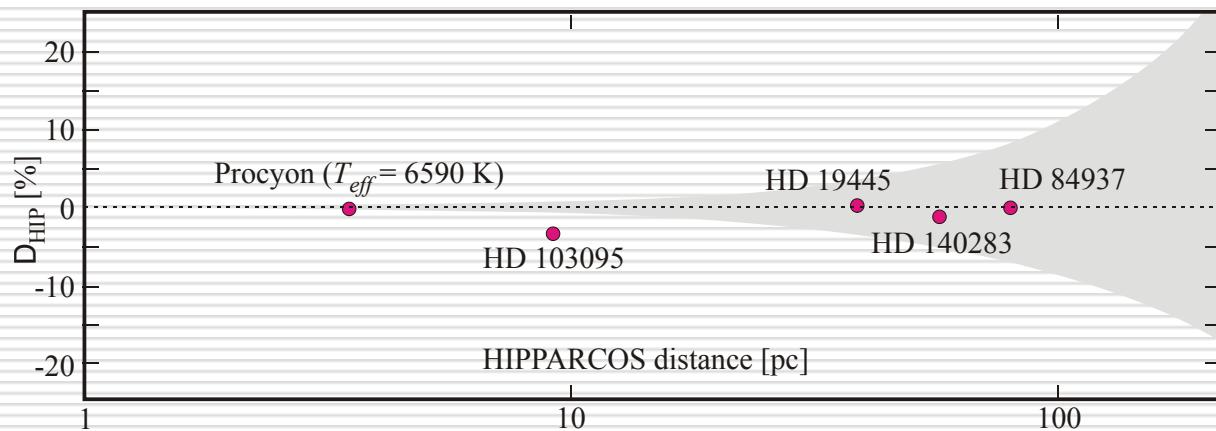
$\log g$ 利用电离平衡性确定 (冷星)

在冷星中, 相邻两个电离态的金属谱线的强度依赖于 $1/P_e$:

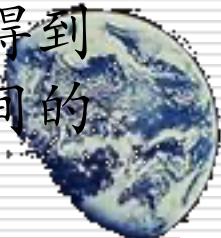
表面重力越大, 谱线强度比越小:

Fe II/Fe I, Cr II/Cr I, Ti II/Ti I, Ca II/Ca I

$\Delta \log g(\%)$



利用Fe I/Fe II
电离平衡的光
谱方法与用HIP
距离方法得到
的重力之间的
差别

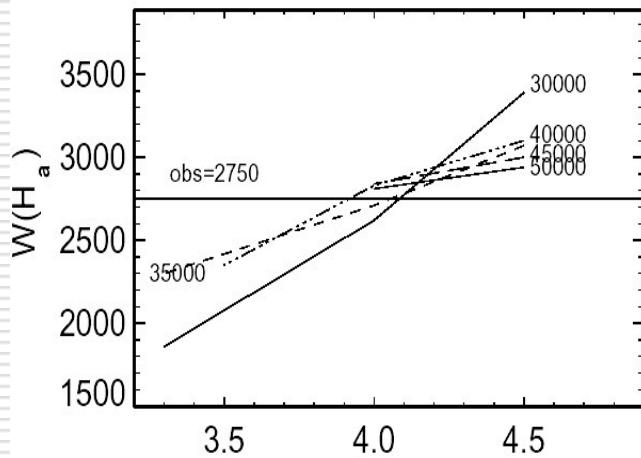


Korn 2003 基于NLTE结果

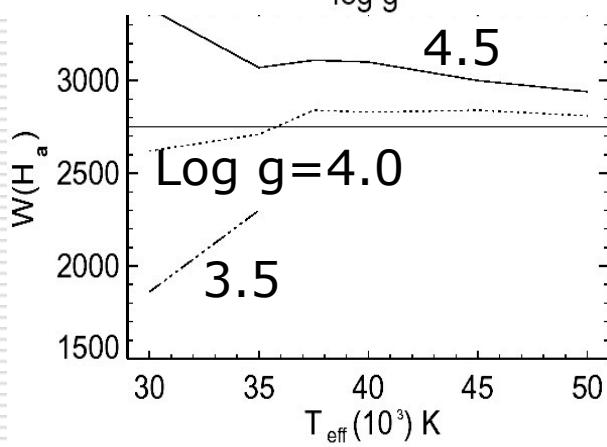
T_{eff} – $\log g$ 图

很多被用来作为 T_{eff} 和 $\log g$ 标志的光谱特征常常同时敏感于这两个参数。

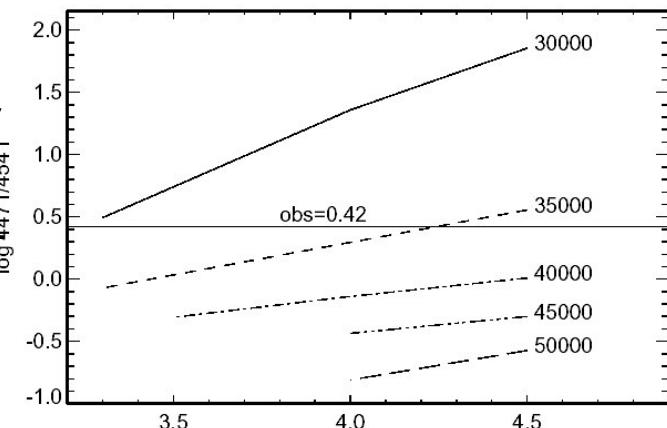
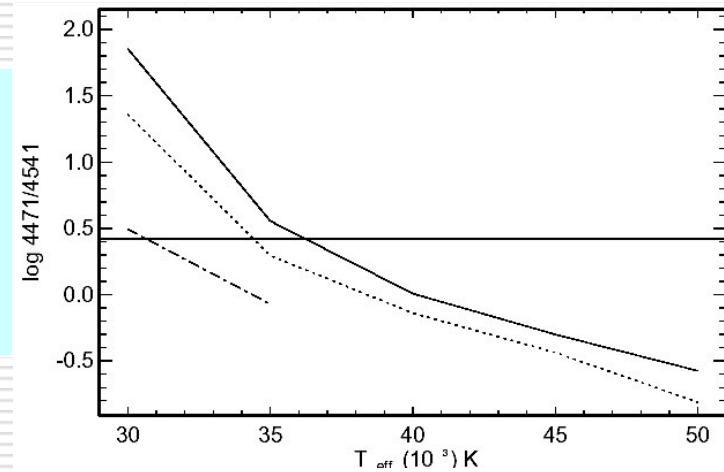
例如: 10 Lac, O9V; 在O星中的Balmer谱线是表面重力的标志和 $W(\text{He I } 4471)/W(\text{He II } 4541)$ 比值是 T_{eff} 指示.



3对 $\log g, T_{\text{eff}}$ 值
对应观测到的
 $W(\text{H}_\alpha)$



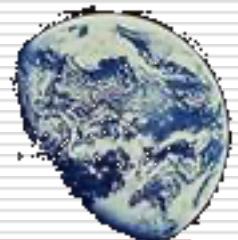
4对 $\log g, T_{\text{eff}}$ 值对应,
观测到的
 $\text{He I } 4471/\text{He II } 4541$
比值



电离平衡作为温度或重力的标志

很重要的一点：大多数恒星的 T_{eff} 和 $\log g$ 通过分析 Balmer 谱线和金属的电离平衡确定

总的来说：测光得到的恒星参数不可能比用光谱方法得到的要好，而且测光方法常常会导致严重的误差。



微观湍流速度 ξ_t 的确定

ξ_t 的确定是利用一种离子的不同强度的谱线得到的丰度一致

等值宽度范围 10 到 100 mÅ

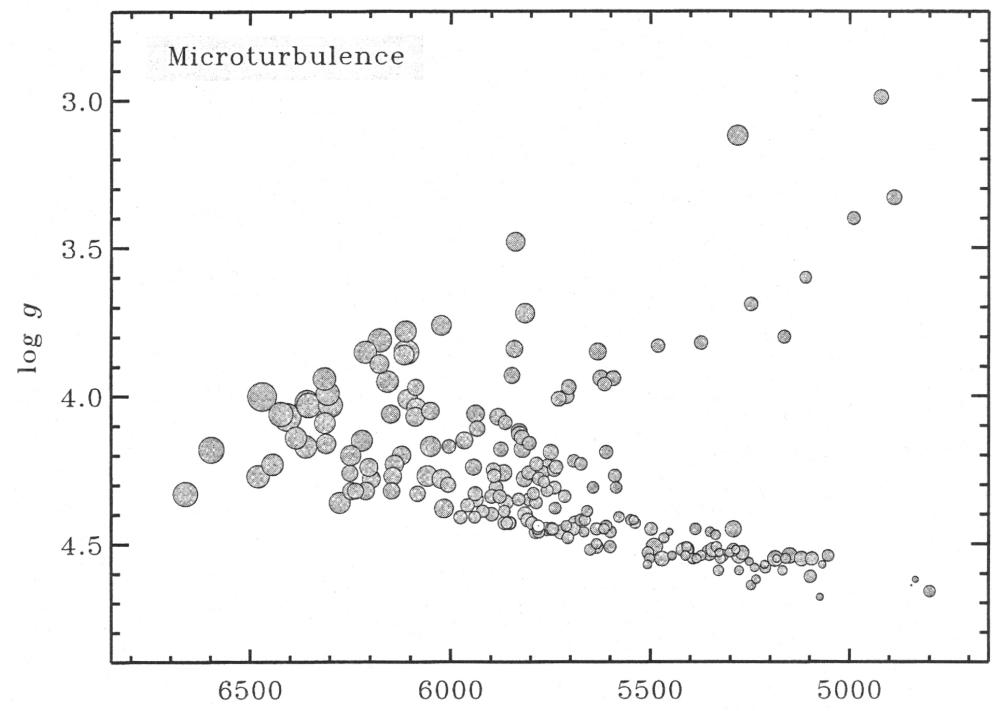
利用弱线我们可以得到丰度，而这些丰度被用来利用强线确定 ξ_t ，这些强线位于生长曲线饱和部分。

薄盘和厚盘恒星的微观湍流速度与有效温度和表面重力相关性的统计结果。

图中圆的半径正比于 ξ_t ：

$\xi_t = 0.6 \text{ km/s}$ 冷矮星,

2 km/s 热星



Fuhrmann 2004

强线确定微观湍流速度

得到的丰度值与谱线强度无关.

最好的选择是Fe II 谱线.

因为 ξ_t 会影响得到的丰度值.

举例：确定b Vir (一颗G0V星)

的Fe丰度.

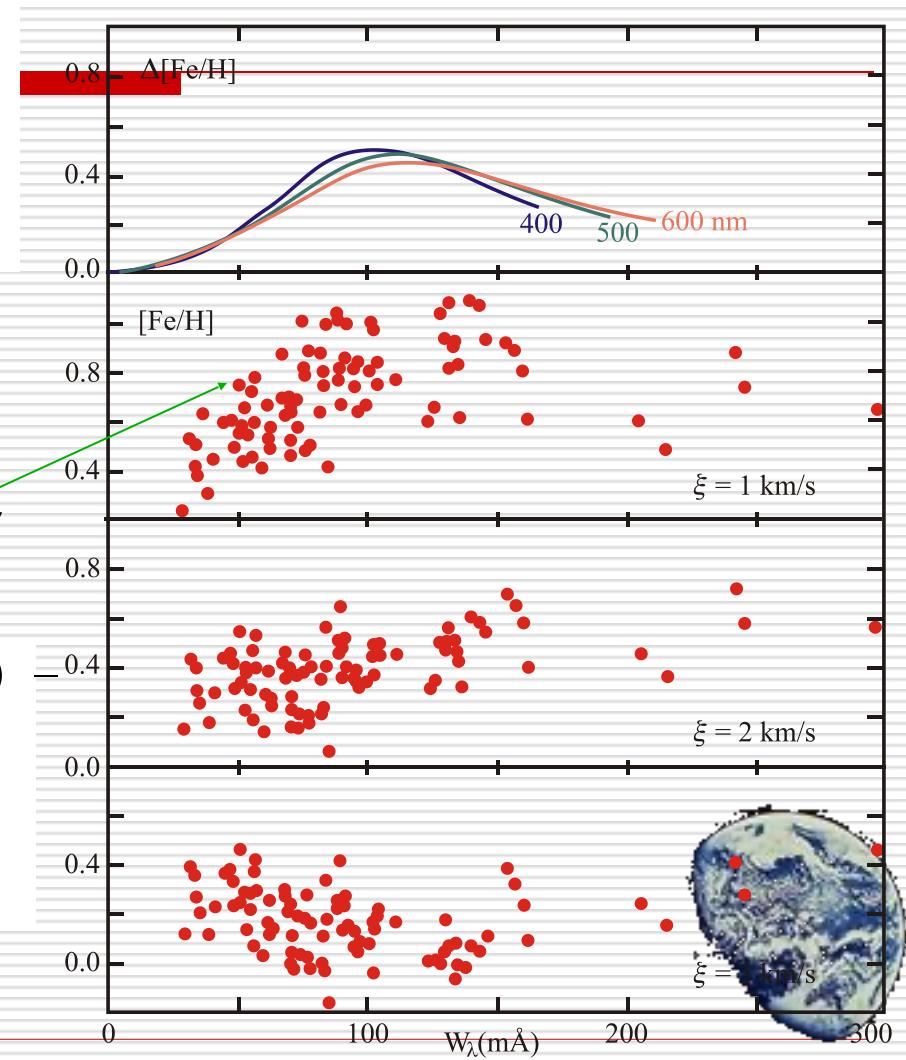
注意，这里 $[Fe/H]$ 从0.2变化到0.7

上图： $\Delta[Fe/H] = [Fe/H] (\xi_t = 1 \text{ km/s})$

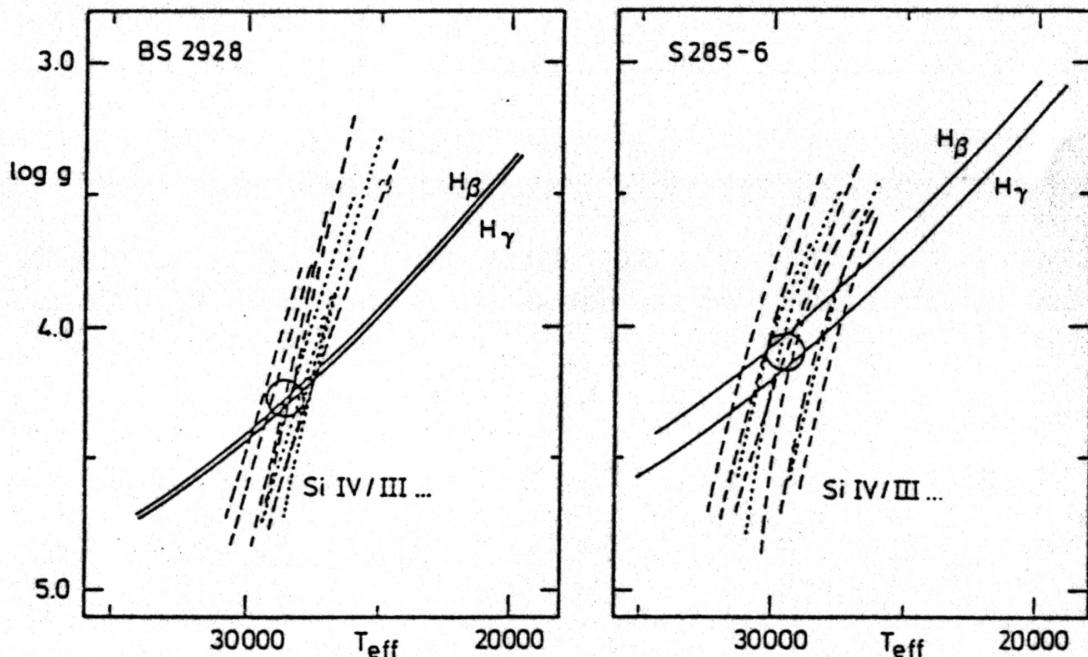
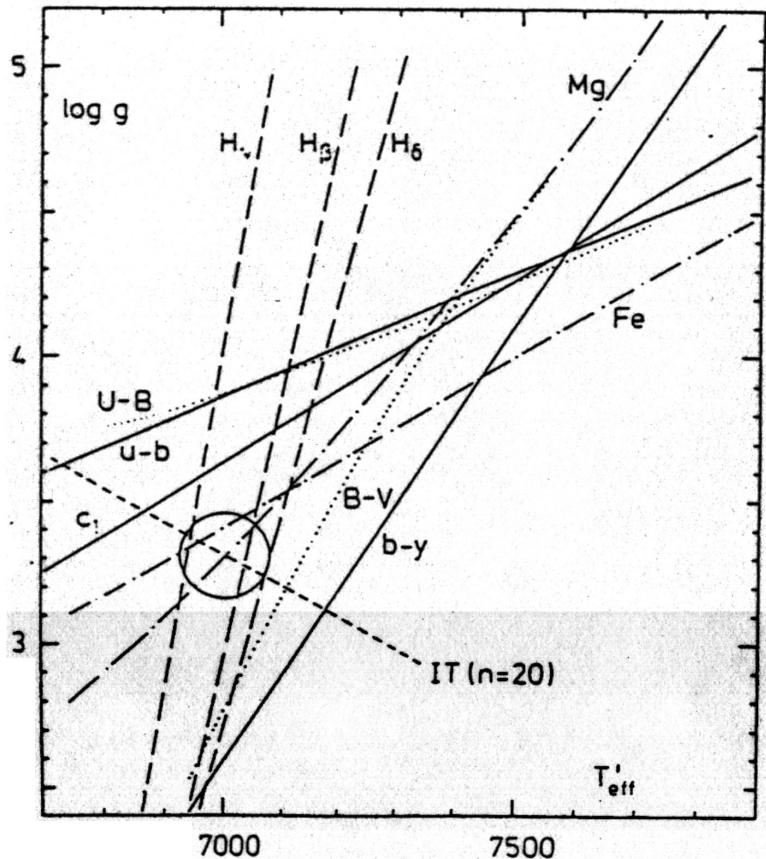
$[Fe/H] (\xi_t = 3 \text{ km/s})$

依赖于 W_λ

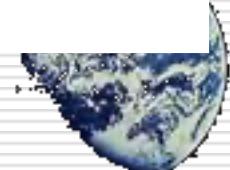
$\xi_t = 3 \text{ km/s}$ 是最后确定的值



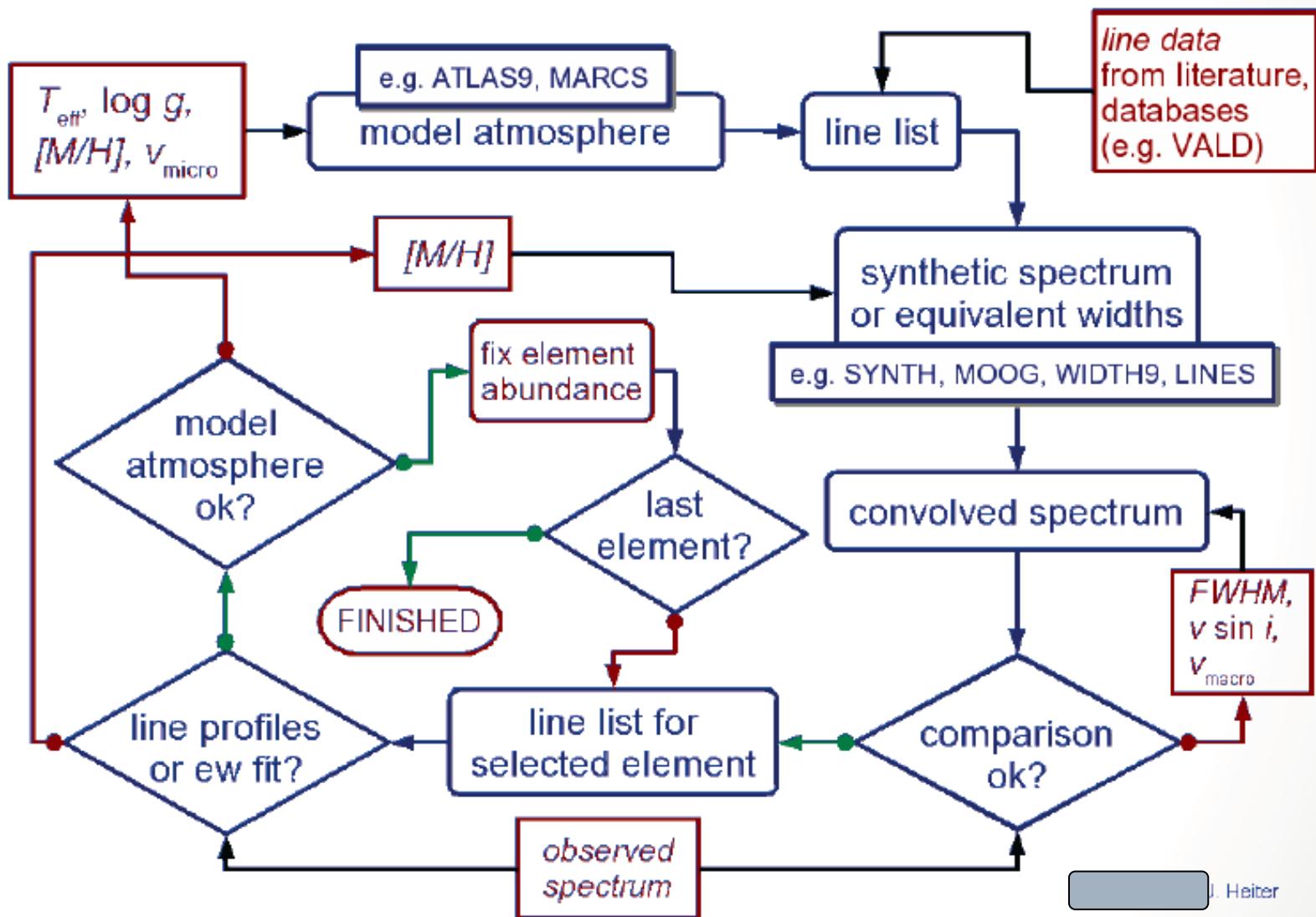
Examples



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.



高分辨率恒星光谱定量分析





如何获取元素丰度信息

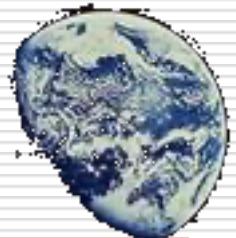
➤ 计算恒星大气模型

方法：

- 1、生长曲线
- 2、光谱综合

生长曲线：等值宽度---元素丰度

光谱综合：利用的丰度计算理论光谱并与观测光谱比较后确定元素丰度

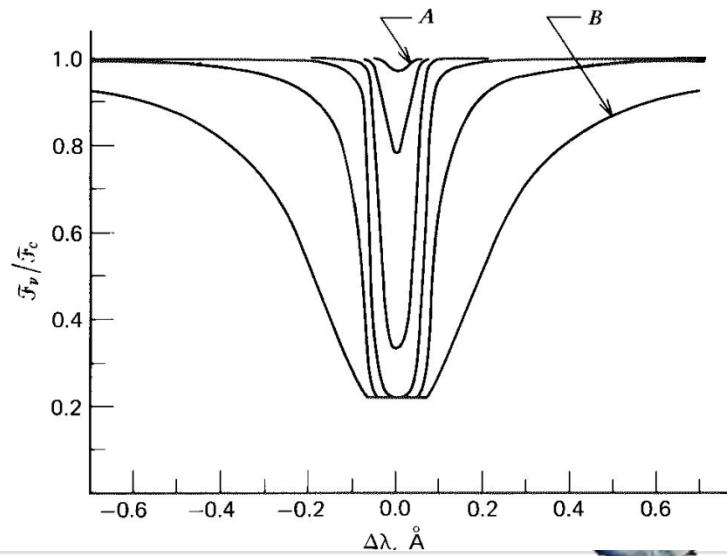
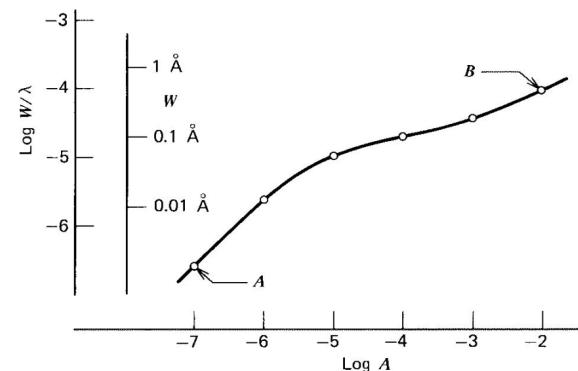


从谱线到丰度

等值宽度方法：利用谱线的等值宽度与元素丰度的相关性（生长曲线）

- 弱线： $W \propto A$
- 强线： $W \propto \sqrt{\log A}$
- 很强的谱线：阻尼致宽主导
 $W \propto \sqrt{A}$

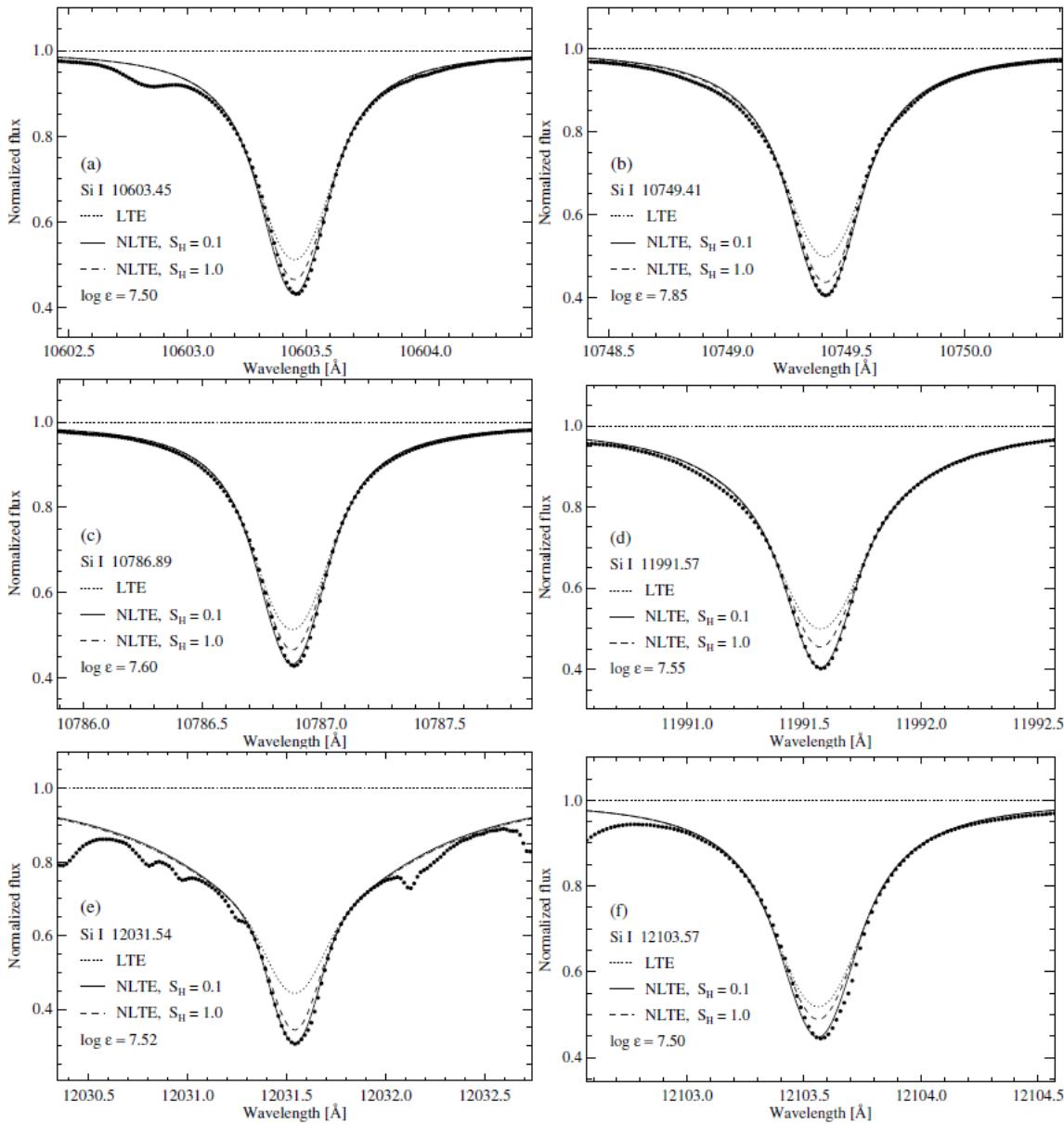
因此弱线是元素丰度最好的标志
中等强度的谱线最差！



从谱线到丰度

光谱综合：

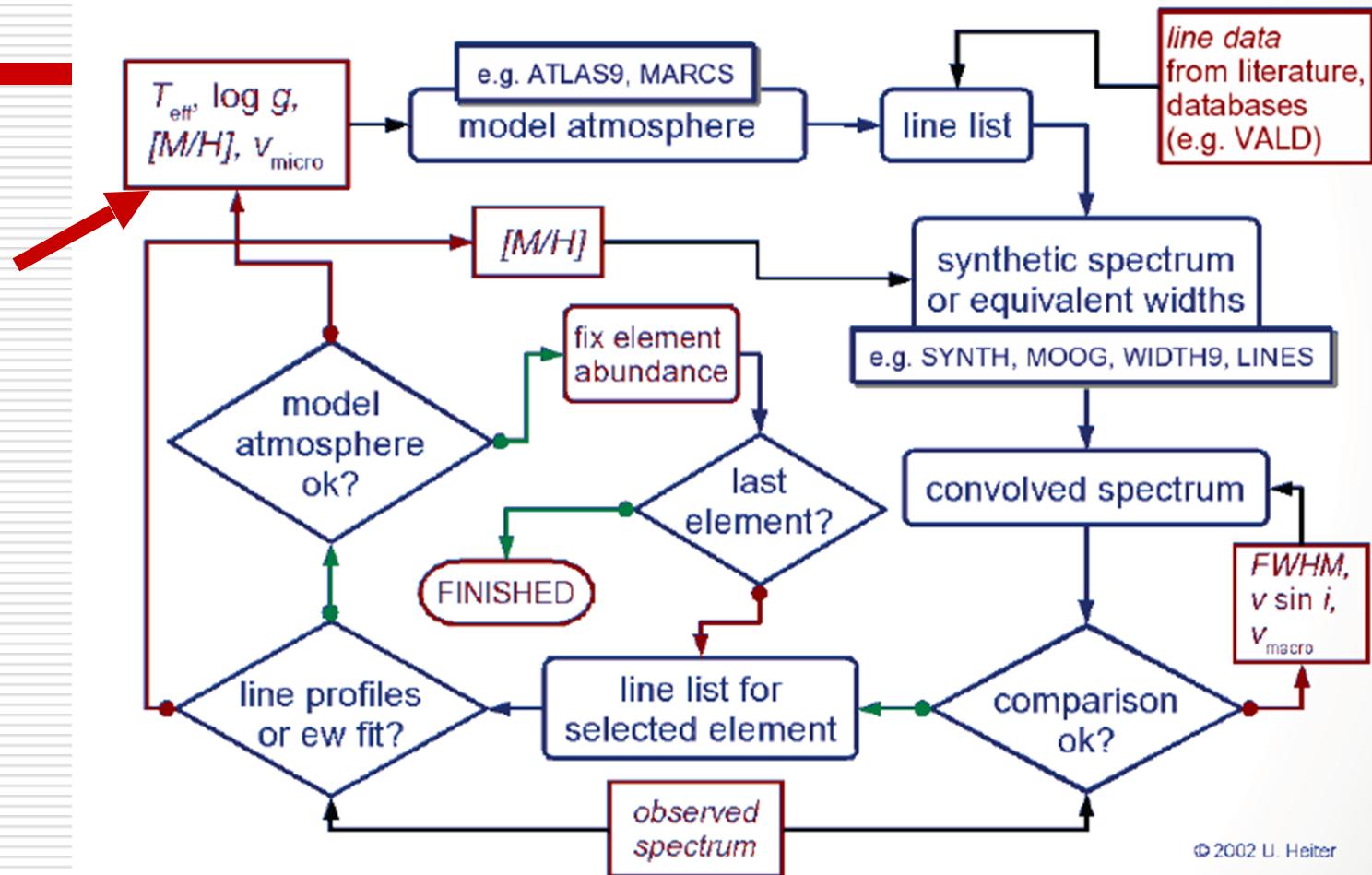
目前更多的科学家开始
用光谱综合方法确定元
素丰度



高分辨率恒星光谱定量分析

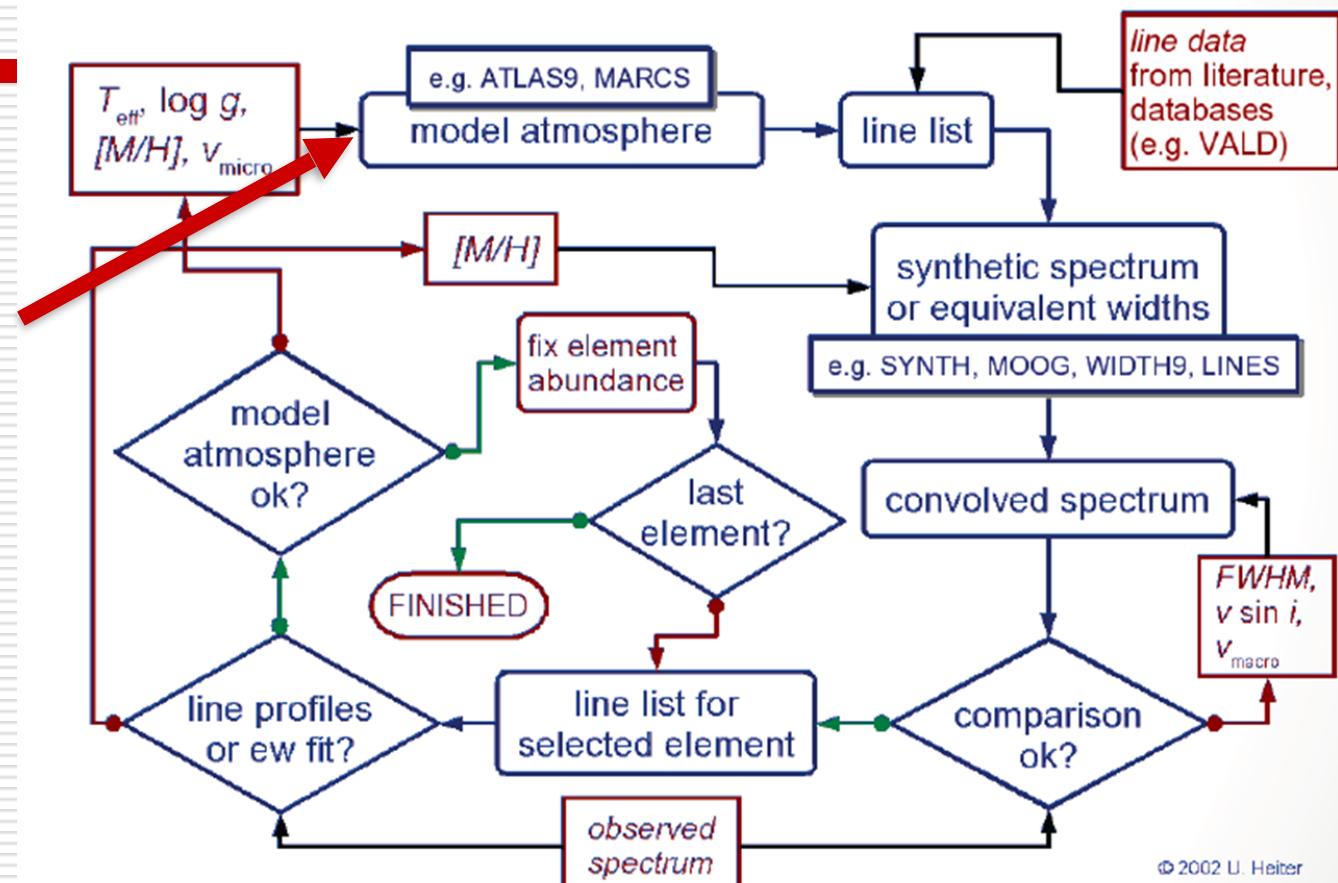
T_{eff}
 $\log g$
[Fe/H]
 ξ_t

初始值如何得到?



高分辨率恒星光谱定量分析

- ## ● 恒星大气模型

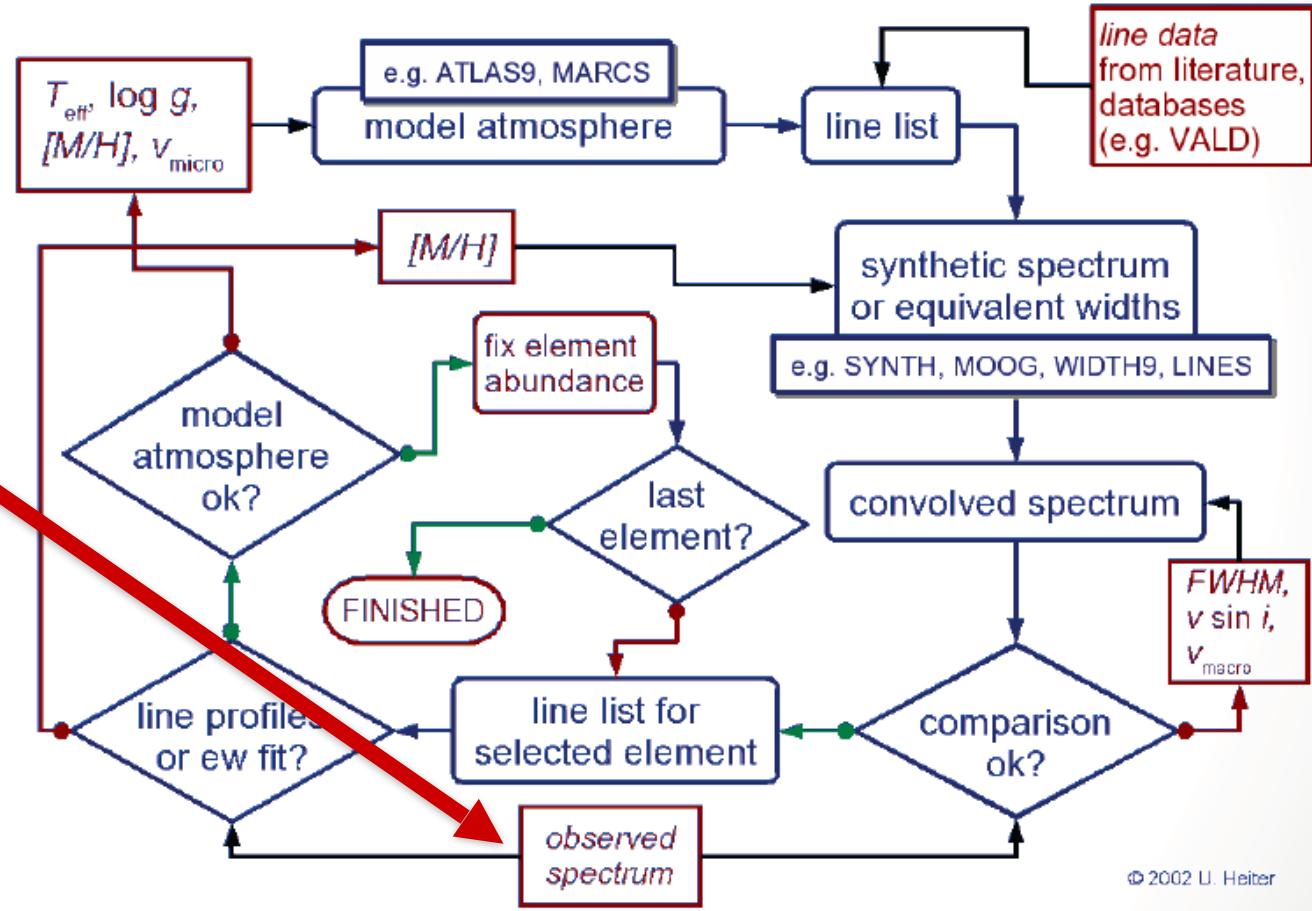


恒星大气模型的建立



高分辨率恒星光谱定量分析

- 现代光谱仪
- 光谱处理
 - > 等值宽度
 - > 谱线轮廓



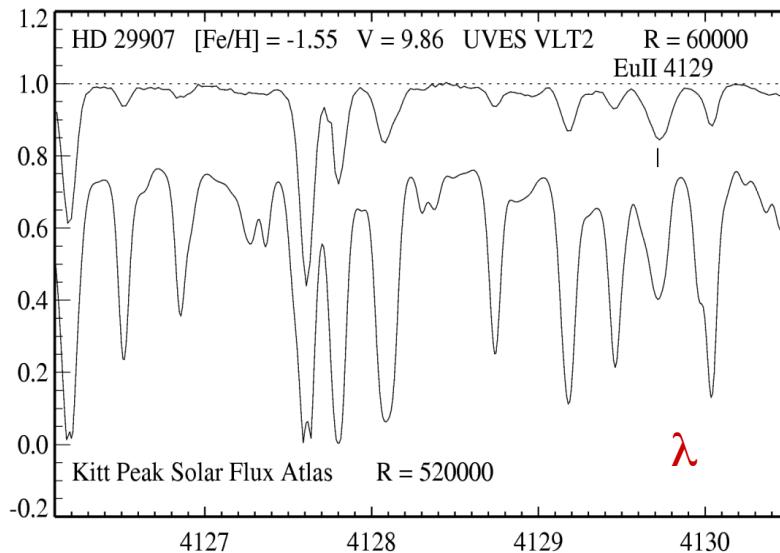
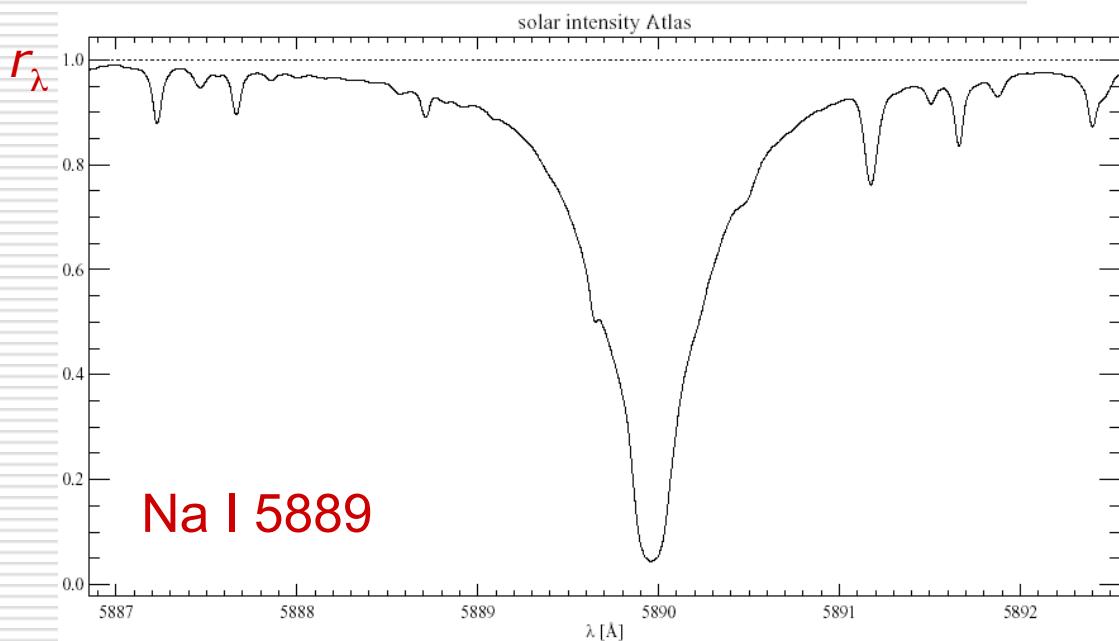
© 2002 U. Heiter

观 测 量

谱线轮廓:

$$R_\lambda = F_\lambda / F_c \text{ 随 } \lambda \text{ 的变化}$$

剩余或相对流量

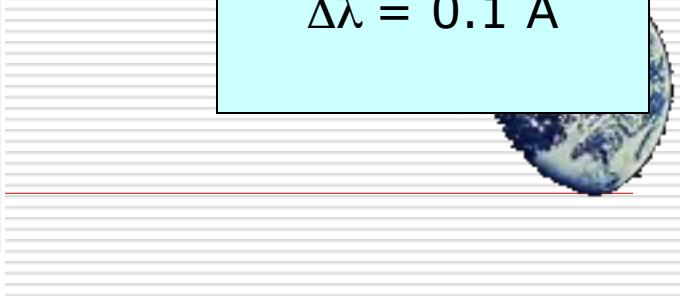


$$R = \lambda / \Delta\lambda$$

$$\lambda = 6000 \text{ \AA}$$

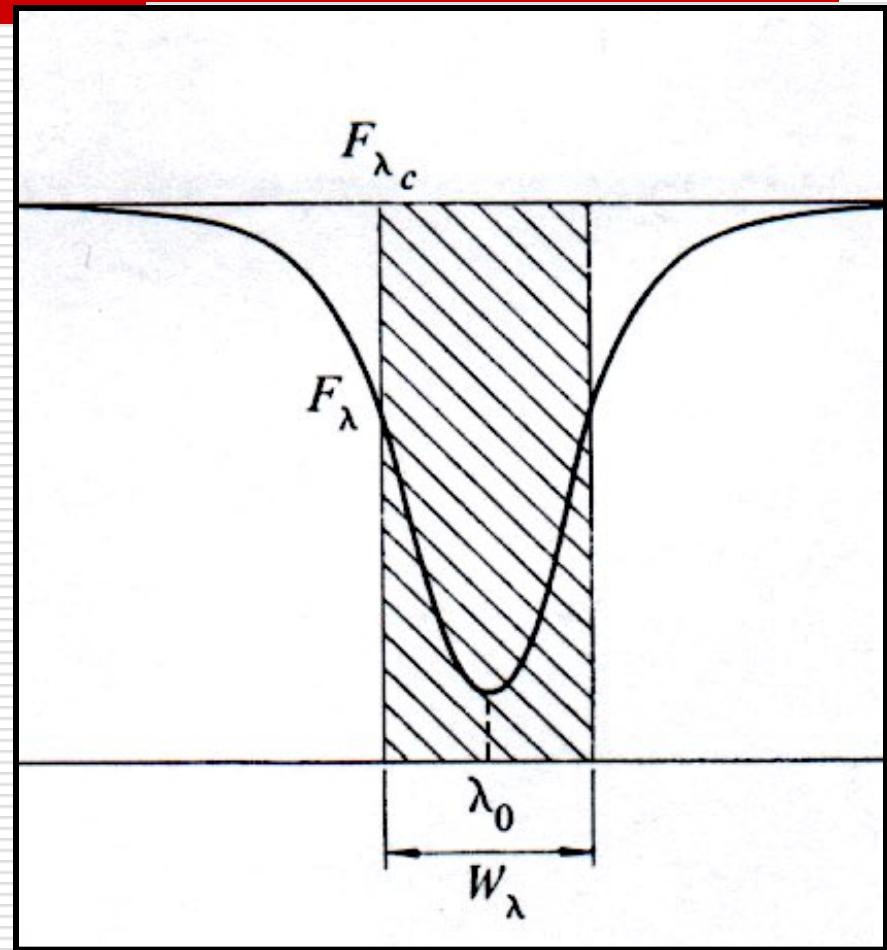
$$R = 60000$$

$$\Delta\lambda = 0.1 \text{ \AA}$$



等值宽度是什么?

- 等值宽度衡量一条谱线的强度
- 大小等于100%深度的矩形面积
- 三角形近似: 一半高度乘以宽度
- 对拟合的谱线轮廓积分(Gaussian, Voigt.)
- 单位是 \AA 或 mA



高分辨率恒星光谱定量分析

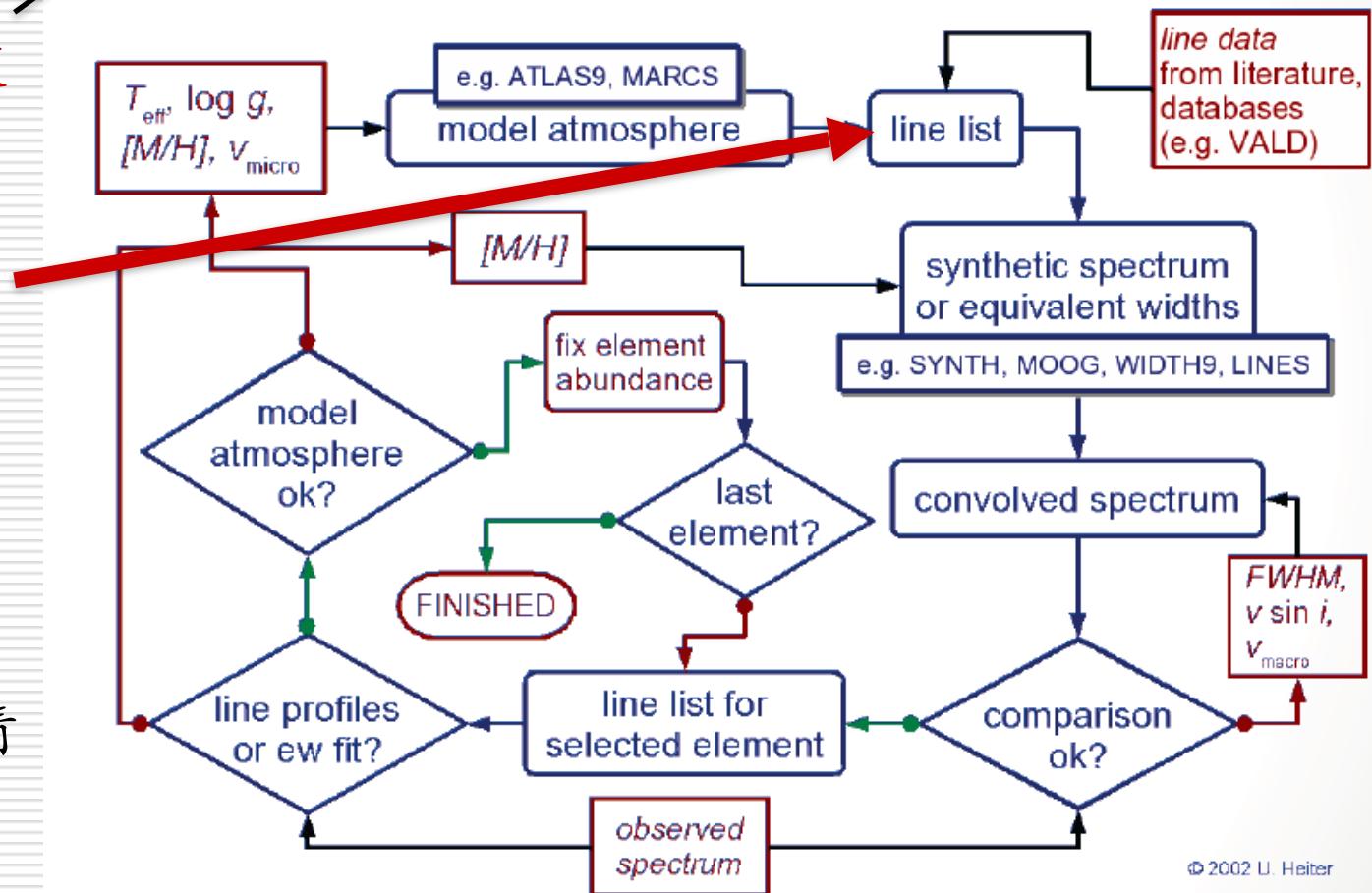
$$\kappa_L(\Delta\lambda) = \kappa_0 \phi(\Delta\lambda) = \frac{\pi e^2}{mc^2} \lambda_0^2 f N \phi(\Delta\lambda)$$

线吸收系数

- 振子强度 (gf)
 - 内部致宽机制

C_4 、 C_6 和 ξ_t

同位素合超精细结构

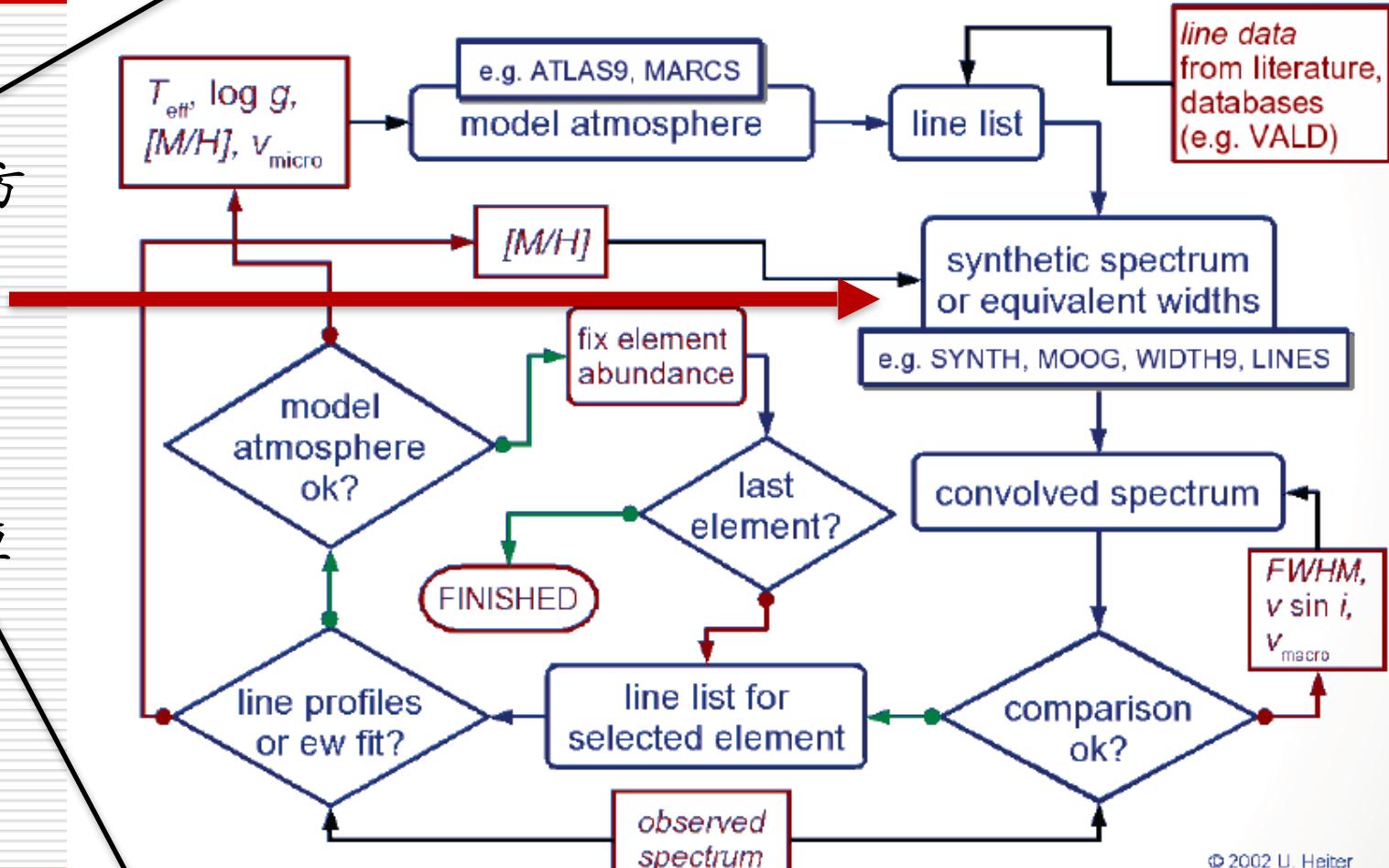


高分辨率恒星光谱定量分析

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - \frac{k_\nu}{\chi_\nu} B_\nu - \frac{\sigma}{\chi_\nu} J_\nu - \frac{\chi_\nu^l}{\chi_\nu} S_\nu^l$$

- 含谱线的辐射转移方程

- NLTE 效应



2024-7-7

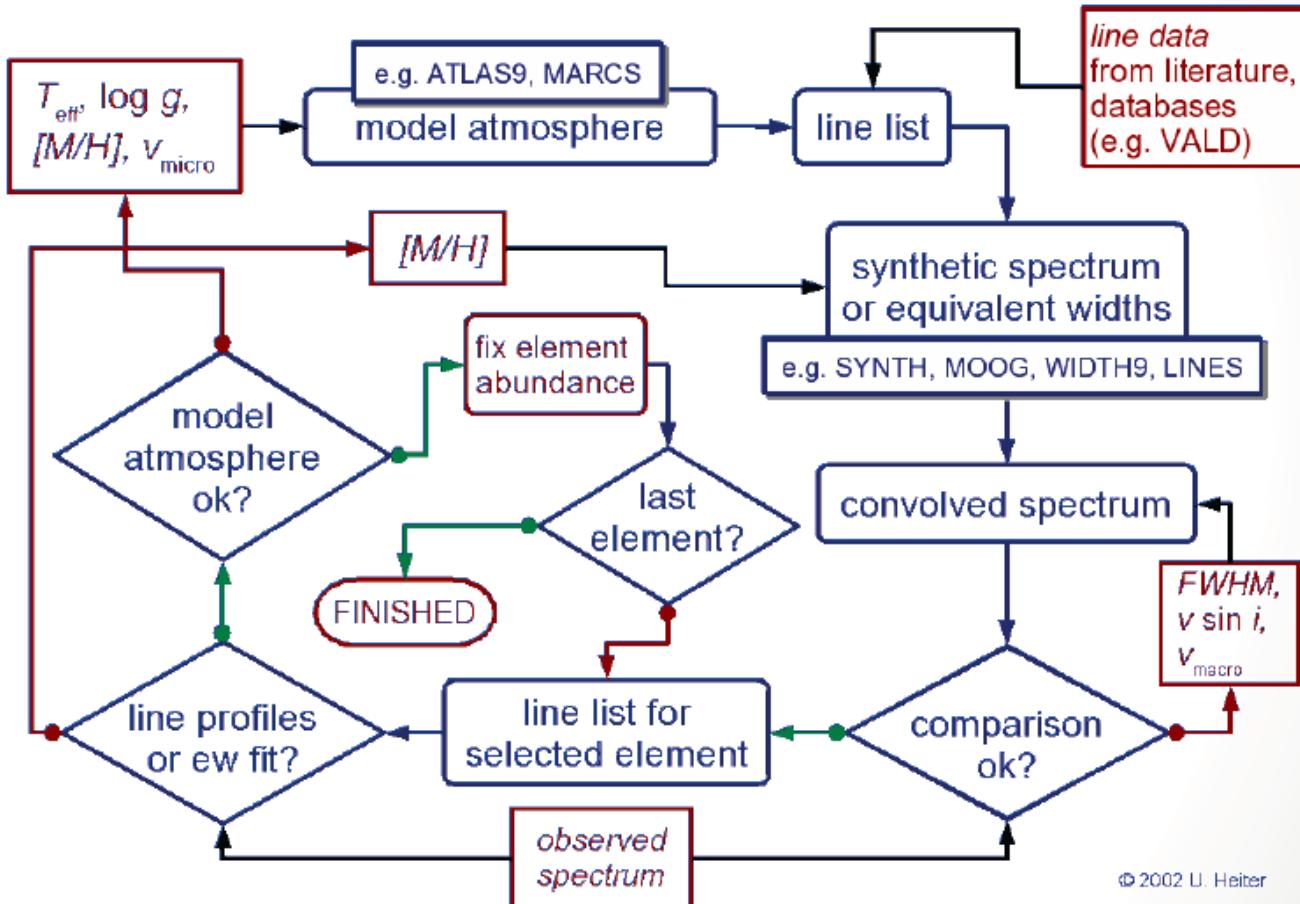
$$\chi_\nu^l \sim n_i \left(1 - \frac{n_j g_i}{n_i g_j}\right) \sim b_i \left(1 - \frac{b_j}{b_i} e^{-hv/kT}\right)$$

© 2002 U. Heiter

高分辨率恒星光谱定量分析

丰度确定

是个循环
过程，最
后得到基
本参数和
元素丰度



© 2002 U. Heiter



Kurucz恒星大气模型

Current versions of ATLAS are much more sophisticated. The report is on my website <http://kurucz.harvard.edu/papers> as are the previous series of talks I gave in Trieste in 2005:

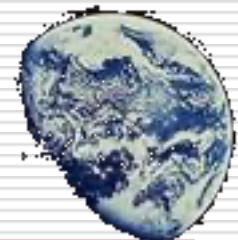
- /SAO309 ATLAS: A computer program for calculating model stellar atmospheres (Kurucz 1970).
- /triesteatlas12 ATLAS12, SYNTHE, ATLAS9, WIDTH9, etc. (Kurucz 2005a).
- /triestelimits Physical, numerical, and computational limits for Kurucz codes (Kurucz 2005b).
- /triesterapid Rapid computation of line opacity in SYNTHE and DFSYNTH (Kurucz 2005c).
- /triestelines Including all the lines (Kurucz 2005d).
- /triestesolar New atlases for solar flux, irradiance, central intensity, and limb (Kurucz 2005e).



Kurucz恒星大气模型

- Kurucz RL (2005a) Mem Soc Astron Ital Suppl 8:10
Kurucz RL (2005b) Mem Soc Astron Ital Suppl 8:69
Kurucz RL (2005c) Mem Soc Astron Ital Suppl 8:72
Kurucz RL (2005d) Mem Soc Astron Ital Suppl 8:83
Kurucz RL (2005e) Mem Soc Astron Ital Suppl 8:158
Kurucz RL (2005f) Kitt Peak Solar Flux Atlas (2005f). <http://kurucz.harvard.edu/sun/fluxatlas2005>
Kurucz RL (2005g) Kitt peak solar irradiance Atlas. <http://kurucz.harvard.edu/sun/irradiance2005>

<https://research.iac.es/proyecto/ATLAS-APOGEE/>



Kurucz恒星大气模型

Observational Pipeline

Rotating star

Circumstellar material

ISM reddening

ISM lines

ISM diffuse bands

Telluric airglow

Anthropogenic light

Telluric broad features

Telluric lines

Aerosols

Telescope transmission

Instrumental transmission

Scattered light

Detector sensitivity

Cosmic rays+radioactivity

Instrumental profile

Observed spectrum

Compare to observed spectrum

Iterate

Computational Pipeline

Grid of models and
intensity spectra

Interp. rotated flux spectrum

Circumstellar transmission

ISM reddening

ISM lines

ISM diffuse bands

Telluric airglow

Anthropogenic light

Telluric broad features

Telluric lines

Aerosols

From reduction procedure

From reduction procedure

From reduction procedure

From reduction procedure

Removed by red. procedure

From reduction procedure

Computed spectrum

Programs

ATLAS9/12+

SYNTHE

ROTATE

not yet

REDDEN

not yet

not yet

not yet

not yet

TRANSYNTH

TRANSYNTH

not yet

BROADEN

PLOTSYN



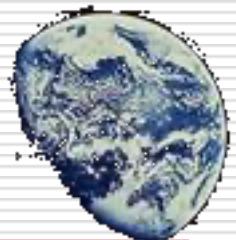
MARCS 恒星大气模型

MARCS is the acronym for Model Atmospheres with a Radiative and Convective Scheme.

This is a grid of one-dimensional, hydrostatic, plane-parallel and spherical LTE model atmospheres. These may be used together with atomic and molecular spectral line data and software for radiative transfer to generate synthetic stellar spectra.

The MARCS site contains about 52,000 stellar atmospheric models of spectral types F, G, K, and M in 3 different formats and also flux sample files indicating rough surface fluxes. The data files are downloadable in limited amounts in the form of tar archives after registration. We ask users to cite the basic reference containing a description of the models: Gustafsson+ 2008, A&A 486, 951.

<https://marcs.astro.uu.se/>



MARCS 恒星大气模型

Model parameters:

The stellar atmospheric model parameters range in effective temperature from 2500 to 8000K in steps of 100 K from 2500 to 4000K and 250K between 4000 and 8000K. The logarithmic surface gravities between -1.0 and 5.5 in steps of 0.5. Overall logarithmic metallicities relative to the Sun are between -5.0 and $+1.0$ in variable steps. The reference solar abundance mixture is that of Grevesse+ (2007). The atmospheres of more luminous stars with low surface gravities (-1.0 to $+3.5$) are calculated in spherical geometry and with different stellar masses: the standard mass is 1.0 solar mass with sparse grids at 0.5, 2.0, and $5.0 M_{\odot}$. The spectral differences of using spherical rather than plane-parallel models and/or radiative transfer for luminous stars were explored by Heiter & Eriksson (2006). Plane parallel models are computed for gravities between 3.0 and 5.0 or 5.5 for the cooler models. Models with different choices of "microturbulence parameters" are also available.



<https://marcs.astro.uu.se/>

Stellar abundances in practice

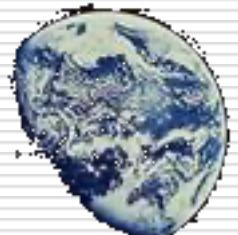
data and tools needed

Model atmospheres for various T_{eff} , $\log g$ and chemical compositions

- Kurucz models (LTE, plane parallel): very extended grid,
<http://kurucz.harvard.edu/grids.html>
- MARCS models (LTE, plane parallel): for cool stars (4000 to 8000 K)
<http://marcs.astro.uu.se/>
- TLUSTY models (NLTE, plane parallel): for hot stars (27500 to 55000 K)
<http://nova.astro.umd.edu/Tlusty2002/tlusty-grids.html>

Line data: wavelengths, excitation potentials, oscillator strengths, broadening parameters <http://ams.astro.univie.ac.at/vald/>

Observed spectrum normalized to the continuum, and equivalent widths



Stellar abundances in practice

Tools needed

Data reduction software :Iraf, MIDAS and/or instrument specific pipelines

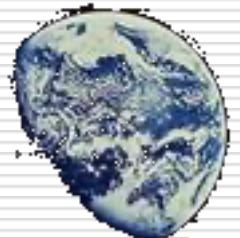
Good procedure for continuum normalization (not so easy!)

Code of spectral synthesis, e.g.: Synspec (Hubeny & Lanz) for hot stars <http://nova.astro.umd.edu/Synspec43/synspec.html> Moog (Sneden) for average and cool stars <http://verdi.as.utexas.edu/moog.html>

Expected precision: Differential abundances: $\approx 0.04\text{-}0.05$ dex

Absolute abundances: $> 0.1\text{-}0.2$ dex!

Problems: NLTE effects Uncertain or wrong $\log(gf)$ values
3D hydrodynamic models $\rightarrow Z=0.014$ instead of 0.018!



NLTE 恒星大气模型

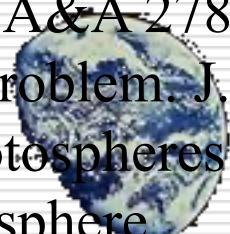
TLUSTY Hubeny and Lanz 1995

<http://nova.astro.umd.edu/index.html> (Hubeny. A computer program for calculating non-LTE model stellar atmospheres. Comp. Phys. Commun., 52, 103, 1988, Hubeny & Lanz. Non-LTE line-blanketed model atmospheres of hot stars. I. Hybrid complete linearization/accelerated lambda iteration method. ApJ 439 875, 1995,)

NLTE line-blanketed model atmospheres

PRO Werner et al. 2003 Tübingen Model Atmosphere Package

<http://astro.uni-tuebingen.de/~TMAP/> (Dreizler & Werner. Line blanketing by Fe group elements in non-LTE model atmospheres for hot stars. A&A 278 199, 1993. Werner & Dreizler. The classical stellar atmosphere problem. J. of Comp. and Appl. Math 109, 65, 1999, Werner et al. Model photospheres with accelerated lambda iteration. In Hubeny et al. Stellar Atmosphere Modeling, page 31, 2003)



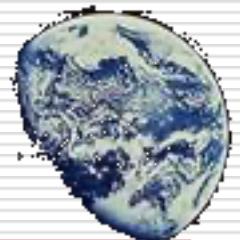
NLTE 恒星大气模型

PHOENIX

For cool stars (Hauschildt et al.. Parallel implementation of the PHOENIX generalized stellar atmosphere program. ApJ 483,390, 1997, Hauschildt et al. Convergence properties of the accelerated iteration method for the solution of radiative transfer problems. J. Quantit. Spectrosc. Radiat. Transf.,51,875,1994)

ATA uses the accelerated lambda iteration method and combines it with the linearization method to calculate static NLTE model atmospheres of spherically-symmetric stellar atmospheres (Kubát 2003)

<http://www.asu.cas.cz/~kubat/ATA/>



NLTE 恒星大气模型

NLTE Wind Model Codes:

CMFGEN Busche and Hillier 2005

<http://kookaburra.phyast.pitt.edu/hillier/web/CMFGEN.htm>

A radiative transfer code designed to solve the radiative transfer and statistical equilibrium equations in spherical geometry. It has been designed for application to W-R stars, O stars, and Luminous Blue-Variables.

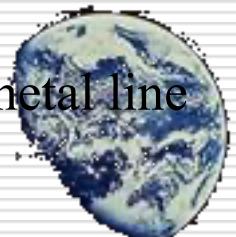
PoWR Hamann and Gräfener 2004

<http://www.astro.physik.uni-potsdam.de/~wrh/PoWR/>

This WEB interface allows to inspect and download synthetic spectra for Wolf-Rayet and OB stars. The spectra are calculated from PoWR model atmospheres which account for Non-LTE, spherical expansion and metal line blanketing.

FASTWIND Puls et al. 2005

<http://kookaburra.phyast.pitt.edu/hillier/web/CMFGEN.htm>



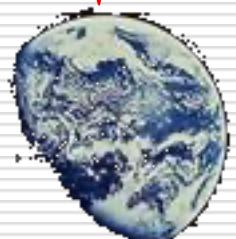
其他模型

Hydrodynamical Radiation code (HYDRA)

HYDRA Höflich (2003) 超新星模型

HDUST Carciofi & Bjorkman (2008) 星周盘NLTE

尽管NLTE恒星大气模型和NLTE谱线形成能给出比LTE近似更真实的结果，概括地说，它们不是最后一步。还有很多事情需要做，包括合适处理辐射与物质的相互作用。

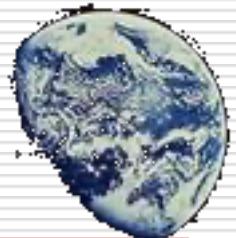


原子数据的获取

Kurucz' collection of the atomic and molecular line parameters can be found on the website <http://kurucz.harvard.edu/>. It consists of three different parts: **Line lists, Atoms, and Molecules**.

NIST database <http://www.nist.gov/pml/data/asd.cfm>

VALD : <http://vald.astro.univie.ac.at/~vald3/php/vald.php>

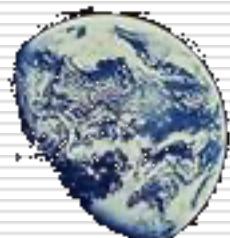


光谱分析软件

MOOG: An LTE Stellar Line Analysis Program

MOOG is a Fortran code designed by Sneden (1973) for LTE line analysis in plane-parallel 1-D stellar atmosphere. It calculates disk-integrated flux or specific intensity from the star's centre either integrated over the line profile (equivalent width) or in the format of synthetic spectrum. Typical usage is the determination of the chemical composition of a star. In many ways MOOG follows the formalism developed in WIDTH and SYNTHE codes by R. L. Kurucz. MOOG has two main options:

<http://www.as.utexas.edu/~chris/moog.html>



光谱分析软件

Spectrum Investigation Utility

Spectrum Investigation Utility SIU is a Fortran code built into IDL (Interactive Data Language) environment (Reetz 1991). Unlike MOOG and other codes that will be discussed later, it does not work without IDL. SIU calculates the emergent specific intensity or disk-integrated flux from plane-parallel 1-D stellar atmosphere both in LTE and NLTE approximations. The code includes continuous opacity due to bound-free transitions of H I, H $_2^+$, H $^-$, He I, He II, metals up to Fe, Rayleigh and Thompson scattering.

SIU works with a grid of MAFAGS- OS atmospheric models (Grupp 2004) built into an IDL shell, as well as with individual models from other codes converted into special binary format which includes partial pressures for all elements in first three ionization stages.



光谱分析软件

Synth3

SYNTH3 (Kochukhov 2007) is designed to calculate spectra emerging from the static, 1-D model atmosphere, under the assumption of LTE. These approximations are adequate for a wide range of main-sequence stars. In practice, the code is successfully used to model stars of spectral classes from early-B to late-M.

The SYNTH3 program is written in Fortran 77, which ensures portability to all major computer platforms and straightforward interfacing with alternative software modules. The code does the following set of operations:

The codes (executables for Linux and Intel Mac computers) are available on [http://
www.astro.uu.se/~oleg/download.html](http://www.astro.uu.se/~oleg/download.html).

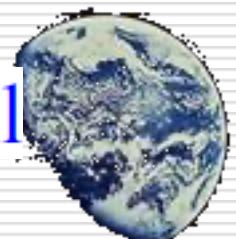


光谱分析软件

BinMag3

For Abundance Fit operation, BINMAG3 requires a Unix-like environment and SYNTH3 or SYNTHV_NLTE executables in the default search path. As a result the user automatically gets the abundance from the individual spectral line/blend of lines for pre-calculated model atmosphere. It is possible to extract the average abundance from several spectral lines. With pre-calculated *b*-factors the user automatically gets NLTE abundance.

<http://www.astro.uu.se/~oleg/download.html>

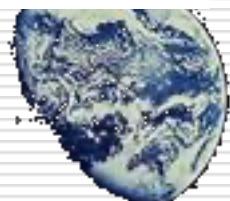


光谱分析软件

synthV_NLTE

SYNTHV_NLTE was written by Tsymbal (1996). Similar to SYNTH3, SYNTHV_NLTE calculates spectrum emerging from the static, 1-D model atmosphere under both LTE and NLTE assumptions, and can be used for modelling stars of spectral classes from early B to late M. The format of the input line list is the same as in SYNTH3. SYNTHV_NLTE is also able to compute spectra for chemically stratified stellar atmospheres.

SYNTHV_NLTE codes and executable are available at <http://vald.inasan.ru/~vadim/downloads/>.

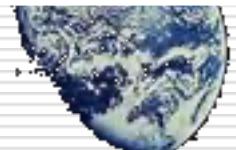


光谱分析软件

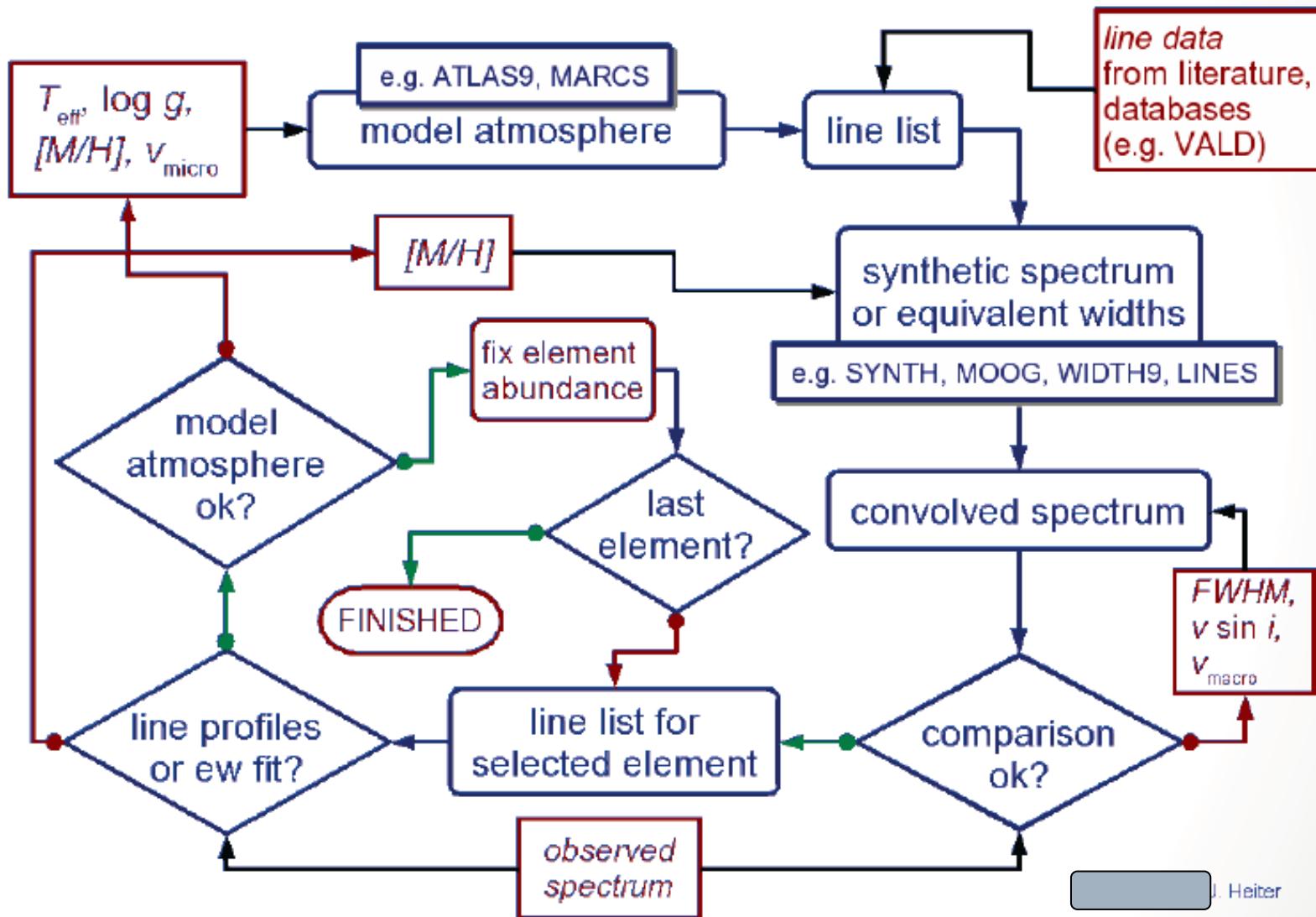
Spectroscopy Made Easy

Spectroscopy Made Easy (SME) (Valenti and Piskunov 1996) is a tool for fitting the theoretical spectra to the observations. Fitting parameters include global stellar parameters (T_{eff} , $\log g$, metallicity, ξ_t , ζ_{RT}) plus line parameters, radial velocity, instrumental broadening and continuum level. It can also be used for simple synthetic spectrum calculations. SME consists of two parts: Graphical User Interface (GUI) `sme` and solver `sme_main`.

A detailed description of SME is given in [SME_Manual](#) and [SME_Tutorial](#) included in SME package which can be downloaded from www.stsci.edu/~valenti/sme.htm.



Abundances analysis





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