Measurement of the stellar irradiance

Definitions

Specific Intensity : (monochromatic) $$I_\nu(x, y, z, \theta, \varphi, t)$$

- per unit area normal to the direction of radiation
- per unit solid angle • per unit wavelength unit (or frequency) • per unit time

Flux at the star surface : (monochromatic) $$\mathcal{F}_\nu^{\text{surface}} \equiv \mathcal{F}_\nu^+(r = R)$$

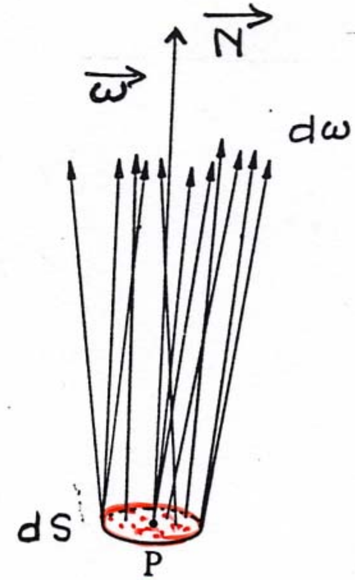
(non-irradiated spherical sphere)

Flux received at Earth : (stellar brightness) (monochromatic)

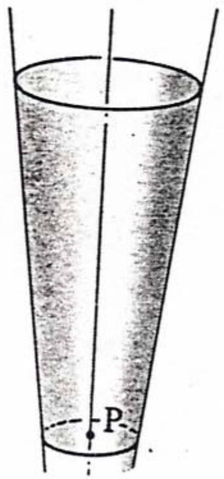
R : radius of the spherical star, *D* distance to the star

$$f_\circ = \frac{4\pi R^2}{4\pi D^2} \mathcal{F}_\nu^{\text{surface}}$$

Intensity of the radiation field



dω



$I_\nu(P, \vec{\omega})\, dS\, dt\, d\omega\, d\nu$

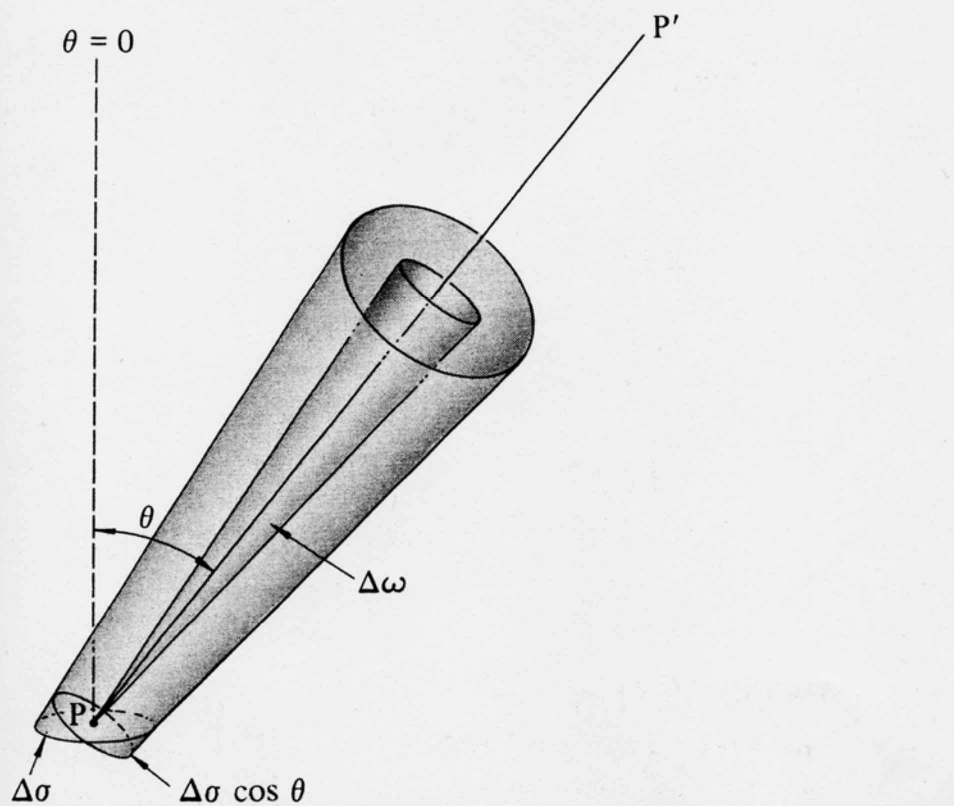
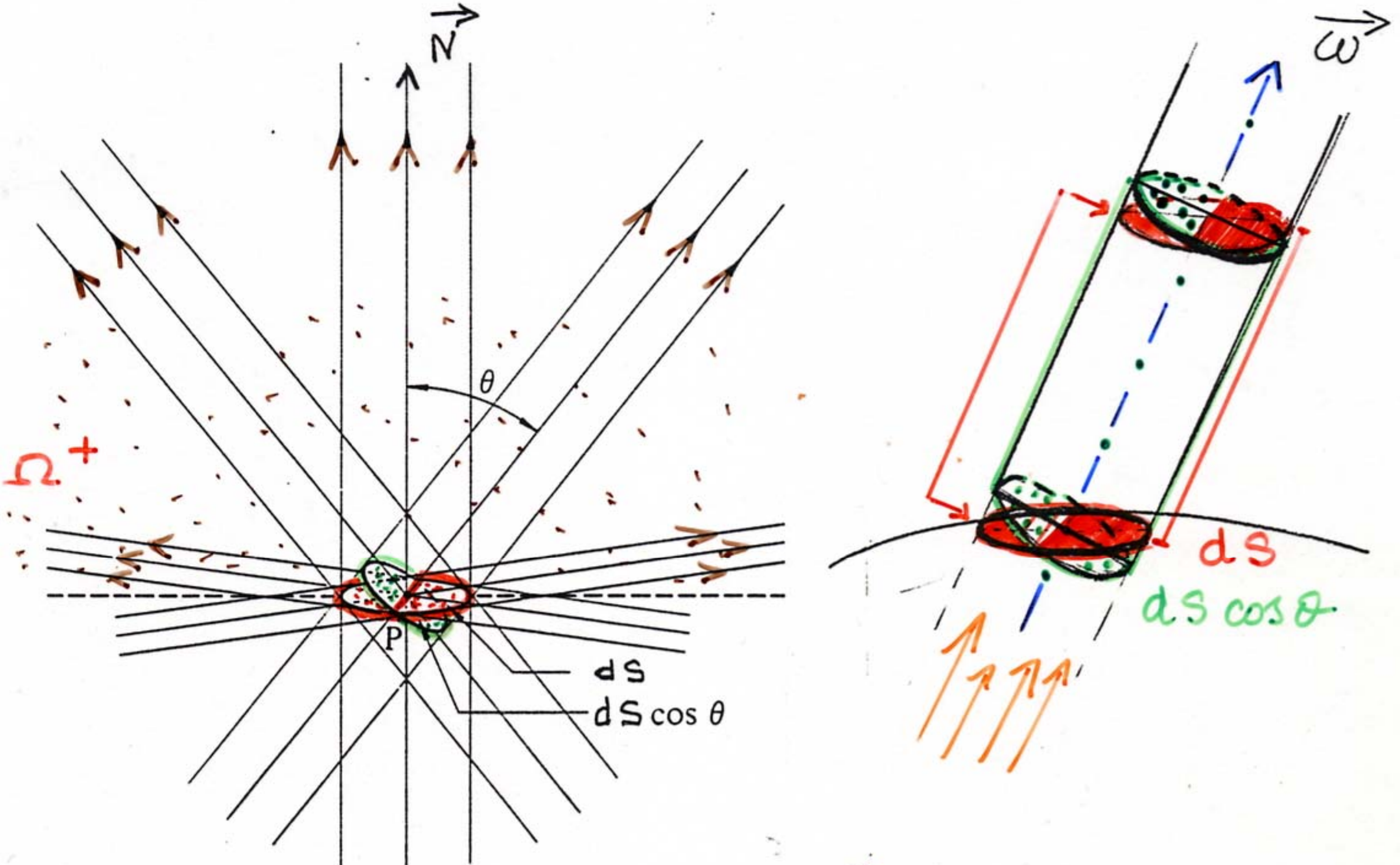


Fig. 2-3 Radiation passing into a solid angle $\Delta\omega$ about PP', at an angle θ to the normal to the circular element $\Delta\sigma$.

$dA = \Delta\sigma$

$\Delta\omega = d\Omega$

$$
\begin{aligned}
\mathrm{d}E_\nu &\equiv I_\nu(\vec{r},\vec{l},t)\,(\vec{l}\cdot\vec{n})\,\mathrm{d}A\,\mathrm{d}t\,\mathrm{d}\nu\,\mathrm{d}\Omega \\
&= I_\nu(x,y,z,\theta,\varphi,t)\ \cos\theta\,\mathrm{d}A\,\mathrm{d}t\,\mathrm{d}\nu\,\mathrm{d}\Omega.
\end{aligned}
$$



$$dE_\nu = I_\nu(P,\vec{\omega})\, dS \cos\theta \underbrace{d\nu}_{=1} d\omega \underbrace{dt}_{=1}$$

$$F_\nu^+ = \int_{\Omega^+} dE_\nu = \int_{\Omega^+} I_\nu(P,\vec{\omega})\, dS \cos\theta\, d\omega$$

Some basic notations :

(R = radius of the star, D = distance to the star)

► monochromatic stellar luminosity $L_o = 4\pi R^2 \mathcal{F}_o^{surface}$

► monochromatic stellar brightness $E_o = L_o / (4\pi D^2)$

in papers related to the calibration of the stellar brightness :

$$E_o = f_o$$

Objective :

→ to mesure the stellar brightness (ie the energy disribution) over the all spectral range

→ to determine the luminosity the distance being known)

→ to compute Teff from the luminosity (L = 4π R² ¾ T⁴)

for a set of "fundamental stars" (for which the radiis and the distance are known or angular diameter see after) these stars will then be used, in a second step, for the calibration of some selected parameters in Teff which in turn can be used to derive Teff for any star without determination of their distance, energy distribution or radiius.

basic recipe:

to determine $f_{\circ}$ over the all spectral range for Vega

(=**Spectral Energy distribution SED)**

⟶ convert monochromatic magnitude of Vega into energy through

absolute calibration given by black body radiation (platinum, copper)

► shape of the « stellar continum » determined
► plus flux intensity at some point : usually at λ = 5556 Å

→**cruxial role of the V-band magnitude**

⟶ convert monochromatic magnitude of any star into energy through

absolute calibration given by Vega

Energy received at Earth : (stellar brightness, stellar irradiance) (monochromatic)
R : radius of the spherical star, *D* distance to the star

f ° = $\frac{4\pi R^2}{4\pi D^2} \mathcal{F}_\nu^{\text{surface}}$

$f_\nu d\nu = f_\lambda d\lambda$ and $\nu = c/\lambda$,

units :

$[f_\nu] = \text{erg s}^{-1}\text{ cm}^{-2}\text{ Hz}^{-1}$
$[f_\lambda] = \text{erg s}^{-1}\text{ cm}^{-2}\text{ Å}^{-1}$

$1 \text{ Jy} = 10^{-26}\text{ w m}^{-2}\text{ Hz}^{-1}$
$= 10^{-23}\text{ erg s}^{-1}\text{ cm}^{-2}\text{ Hz}^{-1}$

monochromatic stellar irradiance not observed directly but from observations made with finite spectral bands : $< f_\lambda > = \int T(\lambda) f_\lambda d\lambda \,/ \int T(\lambda) d\lambda$,

...where T is the system response function.

monochromatic magnitude : $m_\nu(\lambda) \equiv -2.5 \log_{10} f_\nu(\lambda)$ + constant

$m_\lambda(\lambda) \equiv -2.5 \log_{10} f_\lambda(\lambda)$ + constant

In fact one measures $E_m{}^{i}(\lambda)$: an heterochromatic magnitude through the filter ***i***

$$m_i(\lambda) = m_0{}^{i} - 2.5 \log E_m{}^{i}(\lambda)$$

$m_0{}^{i}$ is an arbitrary constant (**zero point** of the magnitude scale through the filter ***i***).
For the UBV system the zero points were defined as such : for an A0V type star all the color indices equal 0 and V=0 for Vega.

Methods of the flux measurements

star and standard « source » observed with same telescope and equipment but not the same light path

Visible flux calibration

- standard sources are blackbodies (Cu, Pt etc.) and/or tungsten strip lamps, usually located on nearby mountain tops (many complications e.g horizontal extinction etc.and unaccuracies in the dta reduction)

  → define a primary standard

  → ***Vega is the primary standard star in the visible***

  (3300 – 10500 Å extended till 3.5 *μ*)

only selected regions observed over a finite Δλ domain (≈ 25 Å – 100 Å) no strong features

- then definition of ***secondary and tertiary standard stars :***

stars for which their flux is calibrated against Vega.

(fainter objects needed for large telescope, and southern hemisphere observatories)

Near infrared flux calibration - 3.5 *μm*

- blackbodies as in the visible → Vega primary standard and then definition of secondary standard stars.
- solar analog stars used: their energy distribution is supposed to be identical to that of the Sun (Neckel &Labs, 1981, Solar Physics, 74, 231).

monochromatic magnitude of Vega (Oke & Gunn, 1983, ApJ 266, 713)

$$m_\lambda(\lambda) \equiv -2.5 \log_{10} f_\lambda(\lambda)$$ - 48.6 (*AB mag*) erg s^{-1} cm^{-2} $Å^{-1}$.

$$m_\nu(\lambda) \equiv -2.5 \log_{10} f_\nu(\lambda)$$ - 21.1 (*ST mag*) erg s^{-1} cm^{-2} Hz^{-1}.

at λ = 5480 Å, V = 0.03

Survey and analysis of Vega absolute calibrations :

Hayes 1985 (Symp. 111, page 225)

Critical analysis on Vega calibrations in the visible and near-infrared :

Mégessier 1995, A&A 296, 771

⟶ flux at 5556 Å = 3.46 10^{-11} $Wm^{-2}nm^{-1}$ standard error 0.7%

internal consistency 0.4%

(value slight different compared to Oke&Gunn)

⟶ in the near IR flux measurement uncertainty : 2-3 %

standard deviation less than 2%.

primary standard → secondary standards → tertiary standards (fainter stars)

for example : Oke &Gunn 1983, ApJ, 266, 713 ; Taylor, 1984, ApJ, 54, 259 ; Massey et al 1988, ApJ, 328, 315 ; Hamuy et al, 1992, PASP, 104, 533 ; Stone, 1996, ApJS, 107, 423; etc.

Extention of the spectral domain covered: IR (1 – 35 μm)

no observations compared to blackbodies available (see discussion in Cohen et al.,1992, AJ, 104, 1650)

→ introduction of model athmospheres to calibrate

Models of Kurucz (1991) for Vega and Sirius are used for absolute calibration in the IR;

beyond 17μm Vega-model not used due to IR-excess of Vega

→ *absolutely calibrated spectrum of α Tau*

(Cohen et al, 1992, AJ, 104, 2030; see subsequent papers, .., 2003, AJ, 126, 1090)

If model atmosphere used for fainter stars, reddening has to be taken into account (discussion on reddening laws used : 2003, Cohen AJ 125, 2645)

(note: flux in the IR have been measured after the calibration of the space experiment before launch and/or using asteroides as « standards » those being considered as « black bodies » but such measurements are not as accurated as those described here, nevertheless, they are used for some studies)

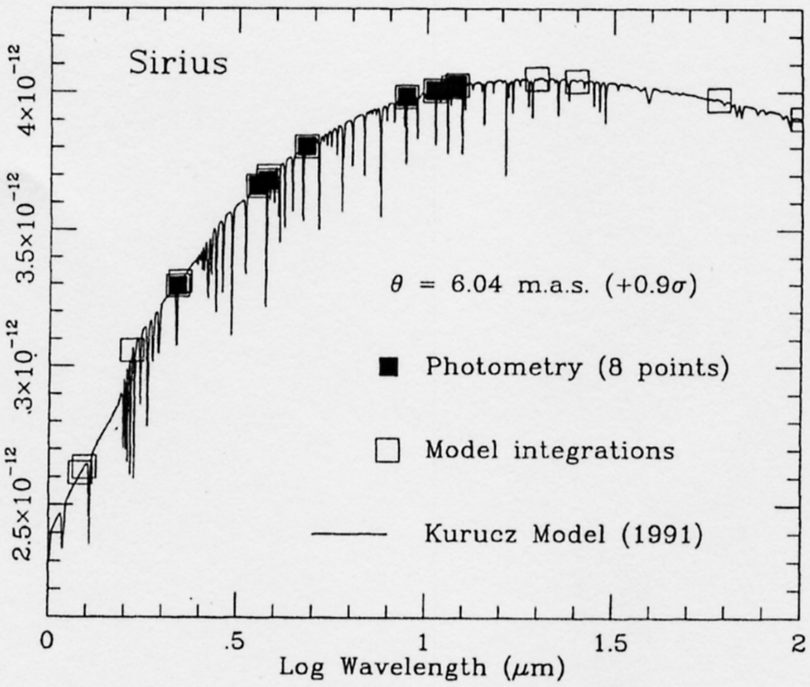


FIG. 3. Kurucz's (1991a) new Sirius model after final normalization. Open squares show actual monochromatic flux densities after integration over this model. Solid squares display the expected flux densities based on the eight magnitude differences between Vega and Sirius noted in the text, and the photometric calibration presented in Table 1(a). The implied angular diameter for Sirius is indicated on the plot along with its value relative to that measured by Hanbury Brown *et al.* (1974), in units of the σ of these authors' determination.

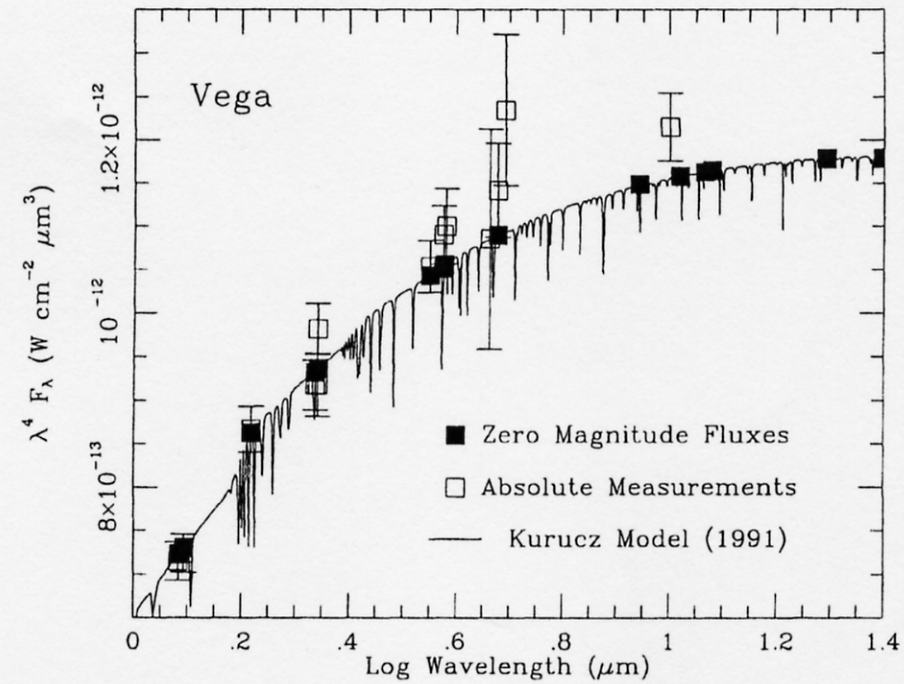


FIG. 2. The new Vega model displayed in the infrared after normalization to the Hayes (1985) average 5556 A monochromatic flux density. Solid squares represent the monochromatic flux densities obtained after integrating this model over the combined atmospheric and filter transmission profiles. Open squares with error bars denote the absolute mountaintop measurements of Vega cited in the text.

Cohen et al.1992, AJ, 104, 1650

Extention of the spectral domain covered : UV

no black body available on board

(note: flux in the UV have been measured after the calibration of the space experiment before launch and/or combining stellar model atmosphere for some stars : e.g. IUE)

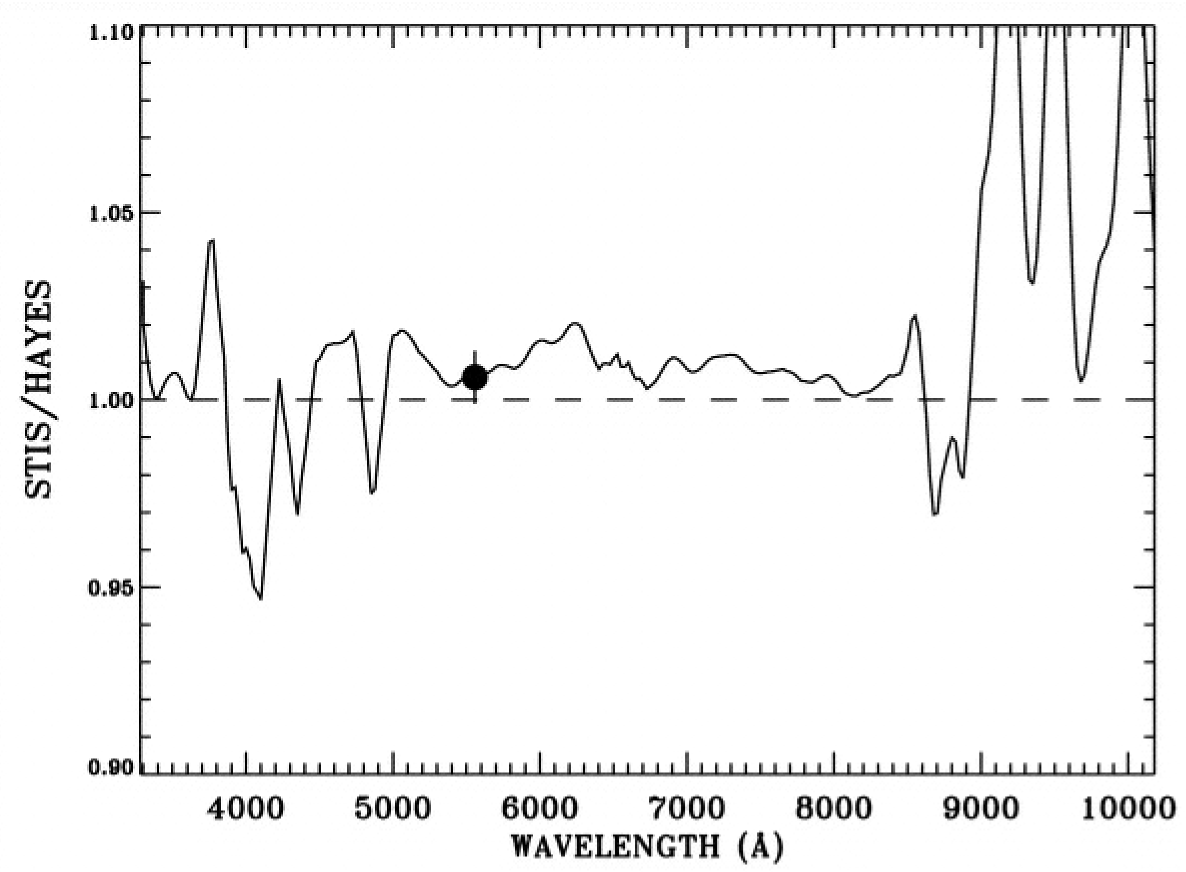
→ *based on model atmosphere of WD of nearly pure hydrogene atmosphere (featureless objects), tight on the Vega flux scale through the V-mag in the visible* (e.g. Bohlin, 2000, AJ, 120, 437)

HST absolute spectrophotometry of Vega from 0.17 to 1.01 *μm* .

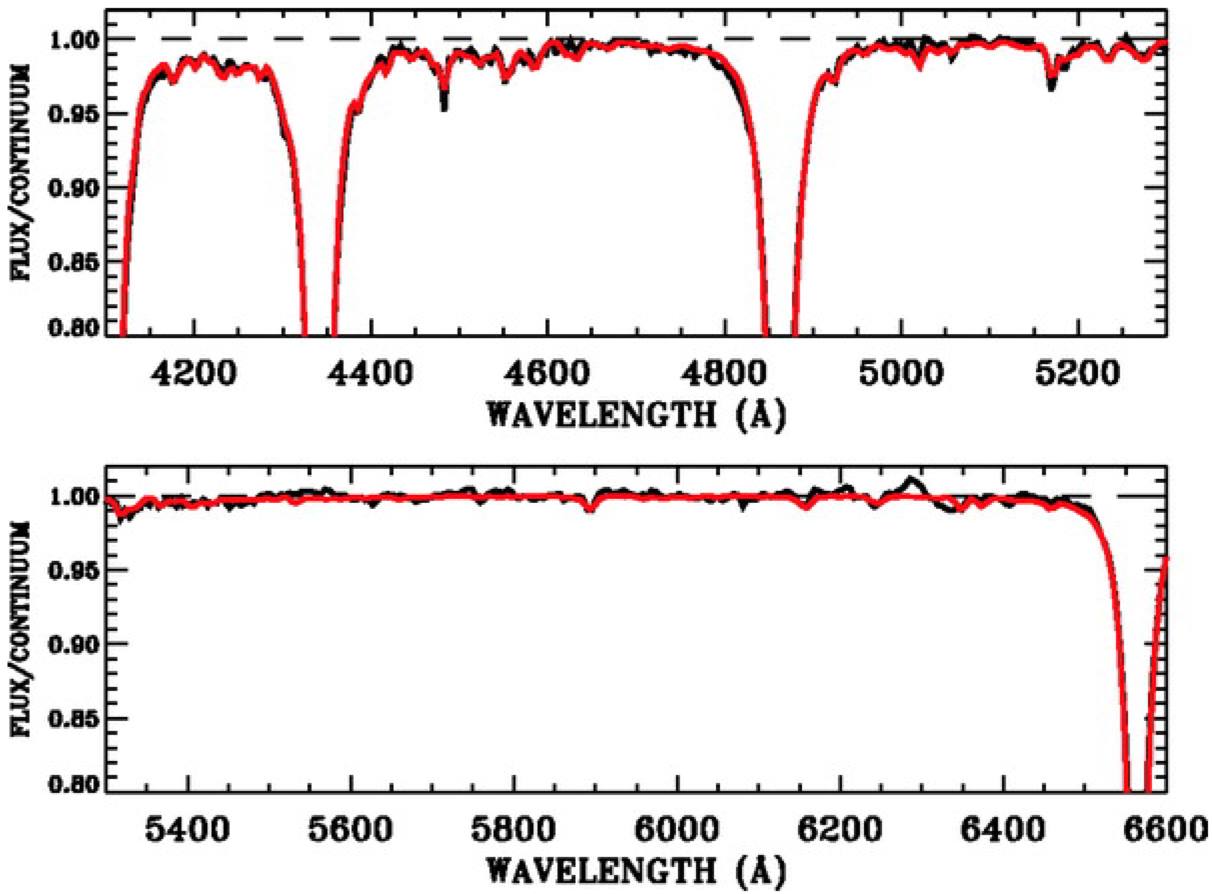
(Bohlin & Gilliland, 2004, AJ, 127, 3508)

Vega STIS observations calibrated with standard WD stars

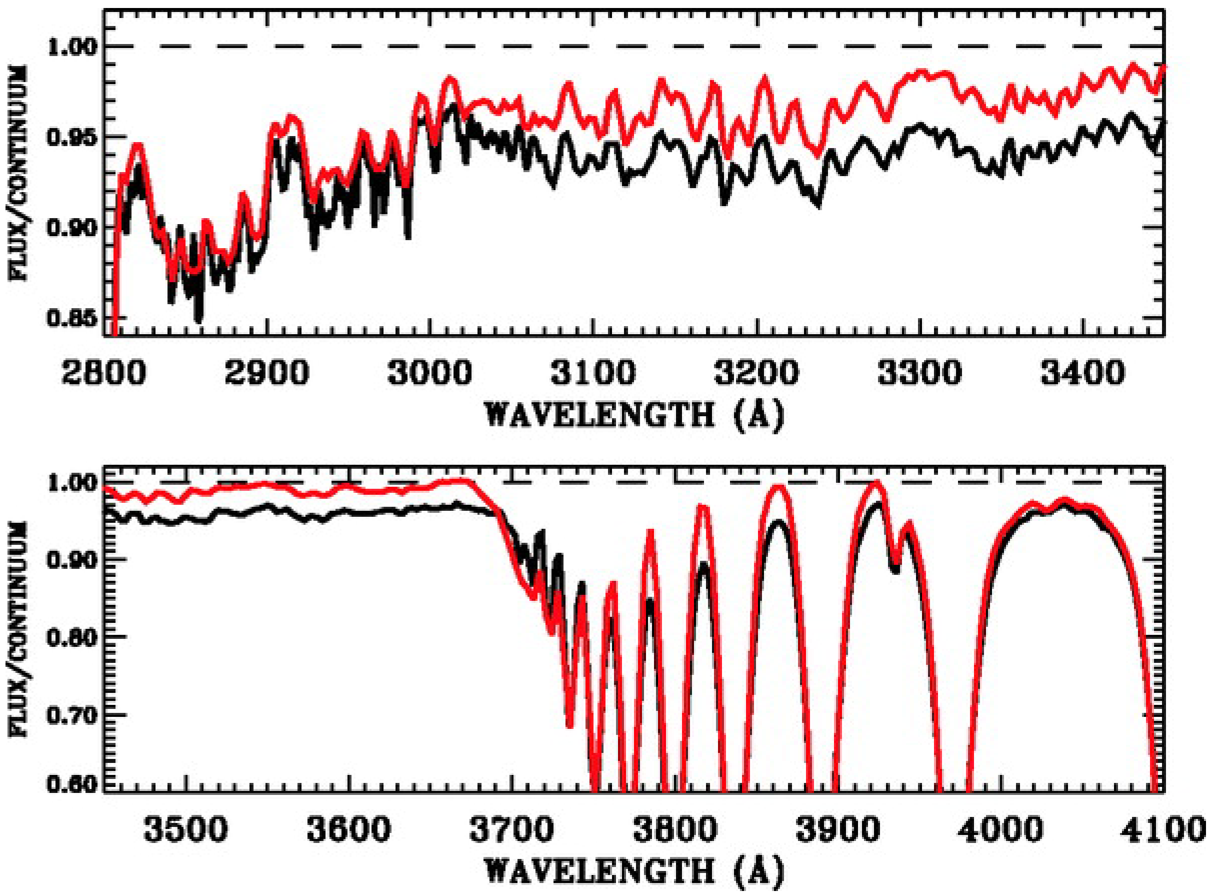
- ♦ good comparison with Hayes flux (standard lamps) in the visible
- ♦ excellent agreement with the Kurucz (2003) model in the visible, http://hurucz.haward.edu/stars/vega
- ♦ some discrepancies in the UV and in the Balmer lines region.



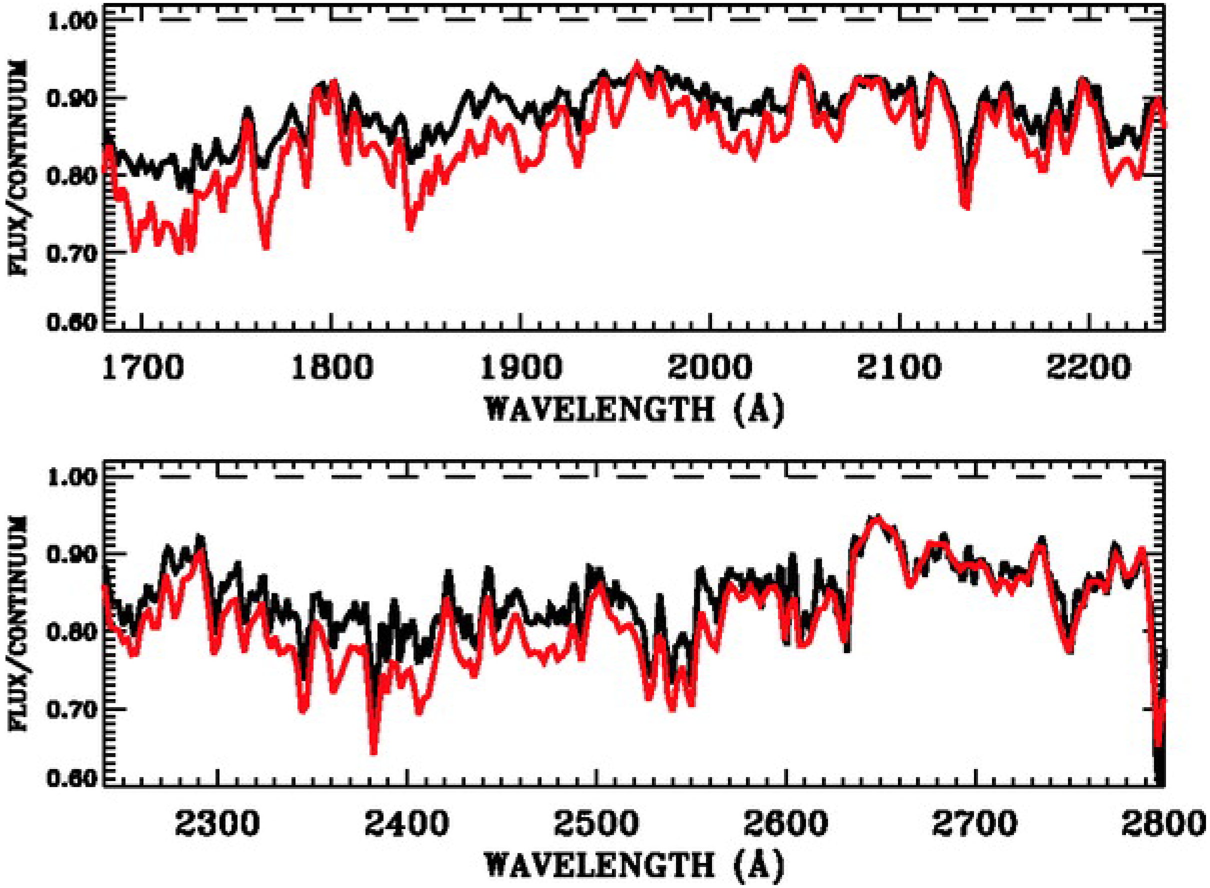
Ratio of the final STIS fluxes for Vega to those of Hayes (1985). The revised monochromatic flux of Megessier (1995) at 5556 Å is shown by the filled circle.



Comparison of the STIS model (*black*) with the Kurucz (2003) model (*red*) that has effective temperature 9550 K and log *g* = 3.95 from H to H . The observations and theory agree to 1%.



Comparison as in Fig. 6 for the Balmer continuum region. Systematic differences of up to 3% are prevalent. The top panel has an expanded vertical scale in comparison with the bottom panel.



Comparison in the UV below 2800 Å, where there is an excellent correlation in the wavelengths of the detailed spectral features. However, the model often shows an excess of metal-line blanketing by up to several percent.

Catalogues of SED

Jacoby et al, 1984 ApJS, 56, 257
Gunn & Stryker, 1983 ApJS. 52, 121
Glushneva et al. 1998, etc.
Kharitonov et al. 1998, etc.
Calibration of spectra (e.g.Prugniel & Soubiran, 2001, A&A, 369, 1048)
IUE spectra
http://www.ucm.es/info/Astrof./spectra.html
etc.

Discussion on methods for calibrating spectrophotometry :
Bessell, 1999, PASP, 111, 1426

Absolute flux calibration of photometry

Heterochromatic observations will give few points of the SED

A photometric system is defined by the magnitudes and color indices of « standard stars » (for that system)

For « standard stars » with a SED computed :

$$F'_\lambda = \frac{\int_0^\infty F^*(\lambda) S(\lambda) d\lambda}{\int_0^\infty S(\lambda) d\lambda}$$

F* = SED , S = response of the instrument for each pass-band of the system

the raw flux observed for that star is : $F = 10^{-0.4\, m}$

m is the magnitude mesured through a filter.

F' / F gives the conversion factor to obtain monochromatic flux for any other star

at a wavelength defined by:

$$\lambda_{\rm eff} = \frac{\int_0^\infty \lambda S(\lambda) d\lambda}{\int_0^\infty S(\lambda) d\lambda}$$

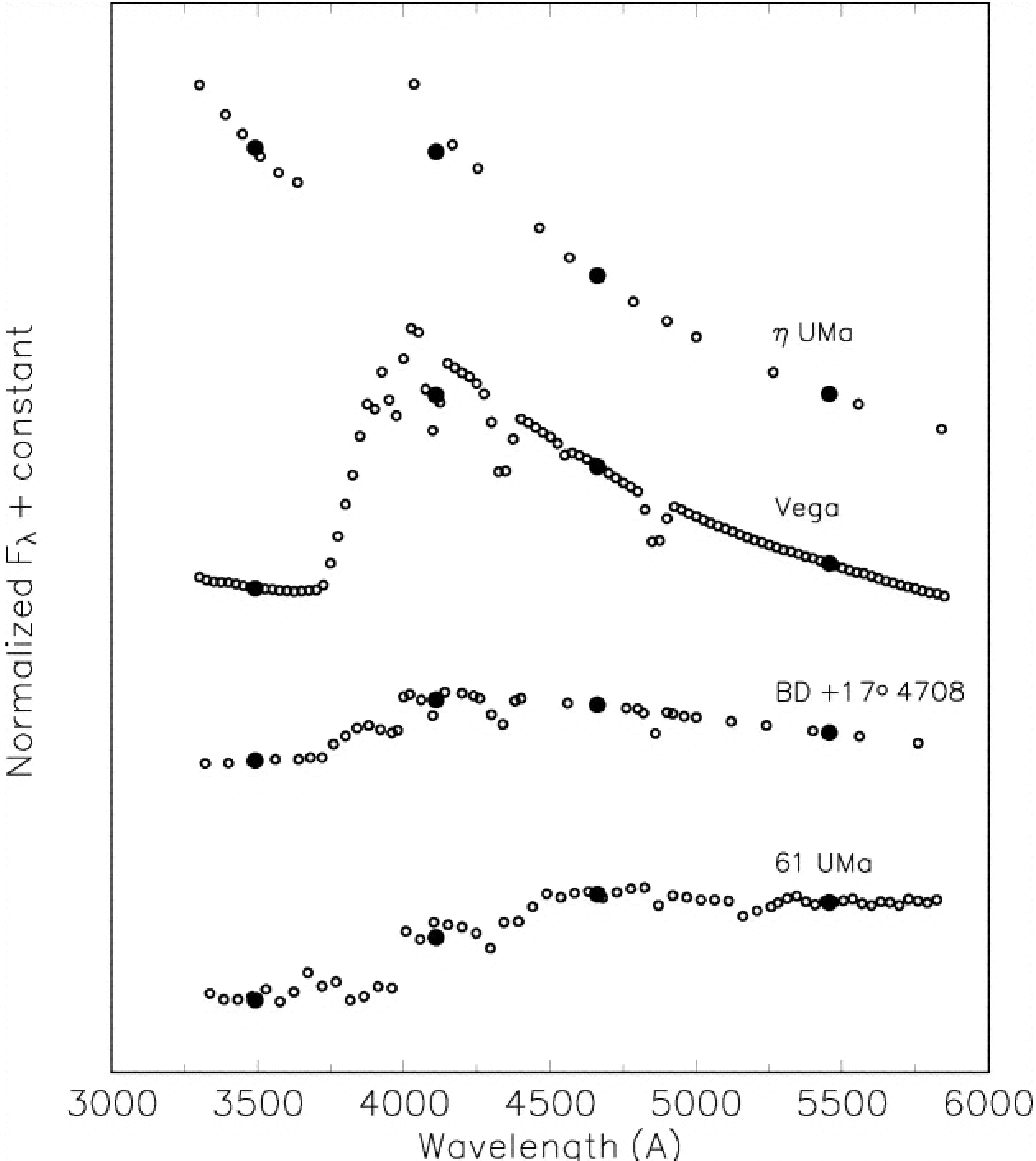
The « standard stars » can be reduced to one : Vega

(e.g. uvby Strömgren system : Gray, 1998, AJ, 116, 482)

Remark : the effective wavelength is also defined as : $\lambda_{eff} = (\int \lambda\ \mathrm{f}(\lambda)\ \mathrm{R}_V(\lambda)\ \mathrm{d}\lambda) / (\int \mathrm{f}(\lambda)\ \mathrm{R}_V(\lambda)\ \mathrm{d}\lambda)$

f = stellar flux, R_V = reponse of the system in the V-band;

for Vega λ_{eff} is 5448 Å; for the Sun it is 5502 Å



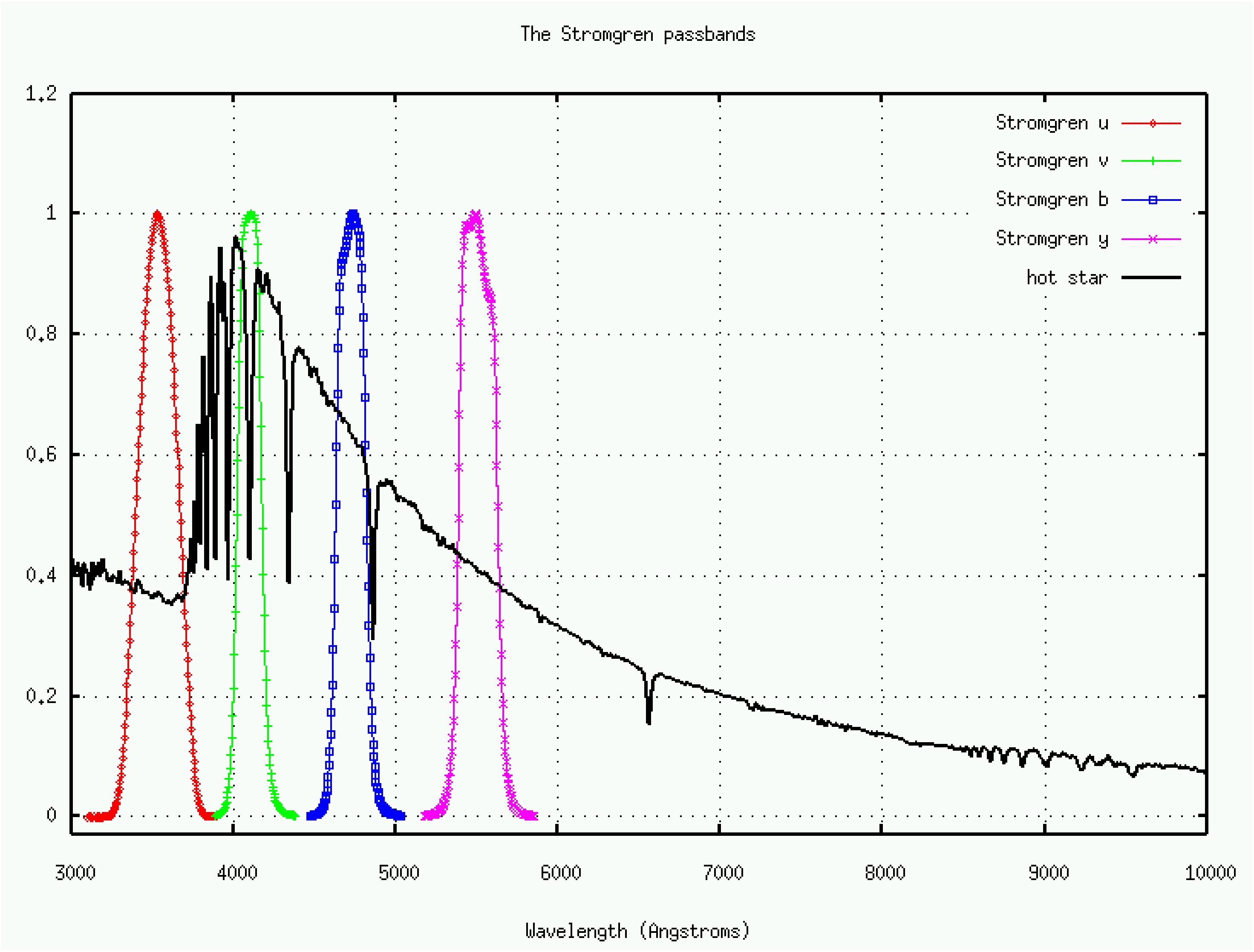
Some results

uvby photometry :

Comparison between spectrophotometry (*open circles*) for stars over a wide range of spectral types and the final calibration of Gray,1998 (*filled circles*).

The point for the *v* band falls below the continuum because of the presence of Hδ in the filter.

Strömgren photometric system



Zero-point of synthetic photometric systems

Principle : computed magnitude should be equal to the observed ones for « standard stars » (if atmosphere models correct) at least one star: Vega

→ zero-point has to be determined in order to compare observations to some finding out from models (e.g. *isochrones*)

(e.g. broadband UBVRIJHKL system: Bessell , 1998, A&A, 333, 231)

Zero-point for V-band defined with Vega model (Castelli & Kurucz, 1994)

$$V = -2.5 \log (\int f(\lambda) R_V(\lambda) d\lambda / (\int R_V(\lambda) d\lambda) - 21.100$$

$$V = -2.5 \log (\int f(\nu) R_V(\nu) d\nu / (\int R_V(\nu) d\nu) - 48.598$$

where $R_V(\lambda)$, $R_V(\nu)$ are the V response function (eg. normalised passbands from Bessell 1990) and $f(\lambda)$ and $f(\nu)$ are the computed flux at the earth in erg cm^{-2} s^{-1}Å^{-1} or in erg cm^{-2}s^{-1} hz^{-1} respectively. The above zeropoints realize a V magnitude of 0.03 mag for Vega.

We note that the absolute flux at 5556Å of the Vega model and the observed flux for Vega (Hayes 1985) are in good agreement and consistent within the 1 sigma error bars of the angular diameter measurements (Code et al. 1976). For Vega: $q_d = 3.24 \pm 0.07$ mas, the model implies 3.26 mas. For Sirius: $q_d = 5.89 \pm$

To derive the zero points for U-B, B-V, V-R, and V-I color indices we averaged the differences between the observed and computed colors for Vega and Sirius. The zero points for the V-J, V-H, V-K, and V-L colors were derived by fitting the observed indices of Sirius.

problems :

stability of R from one observatory to another.

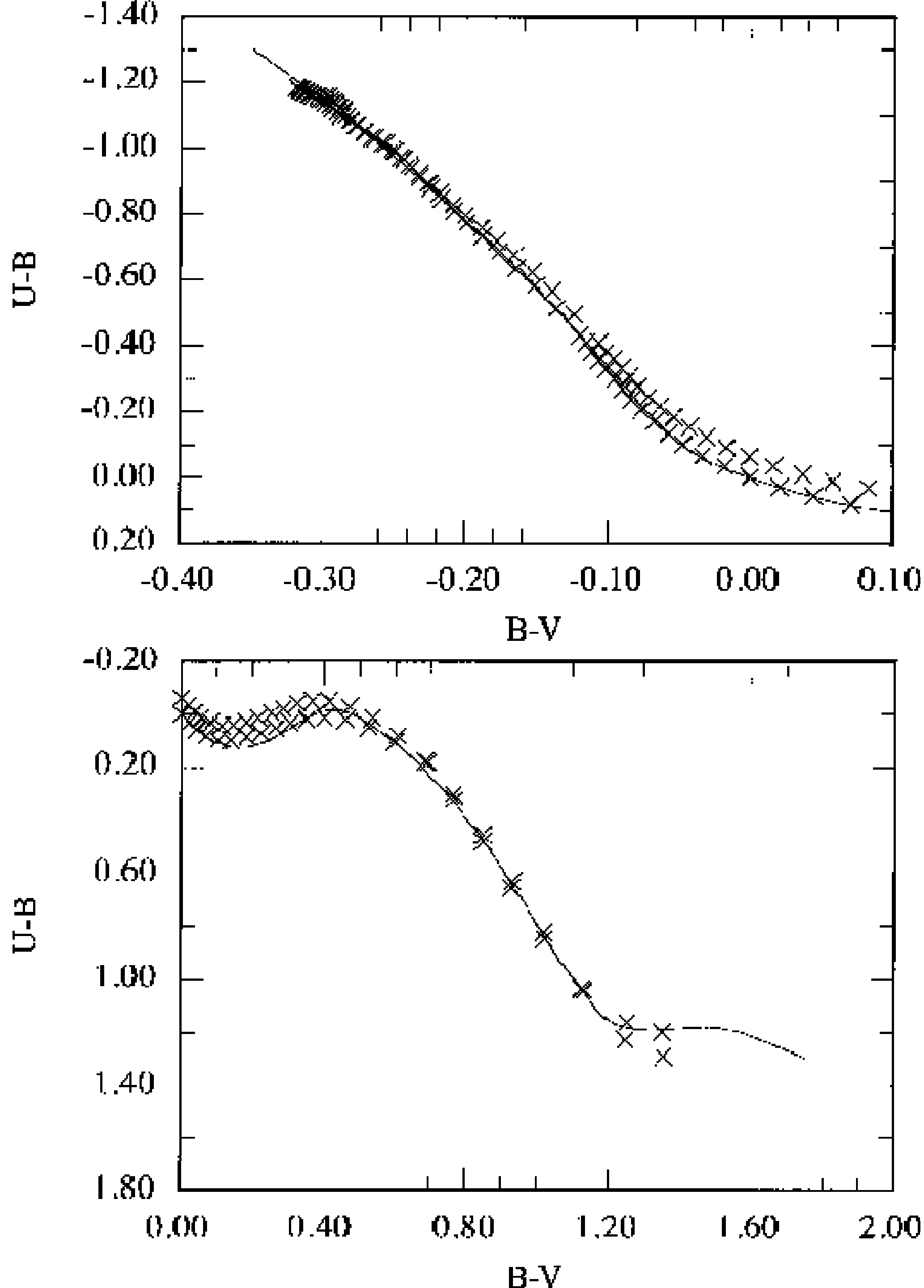
non-linear transformation over the all Teff range.

reddenning effect on energy distribution

luminosity effect.

etc.

→ **subject still in progess**



Some results

The theoretical U-B versus B-V diagram is plotted for log g=4.0 and 4.5 for and for log g=4.5 and 5.0 for (crosses). It is compared with the observed unreddened dwarf locus.

(*Bessell , 1998, A&A, 333, 231)*

What is measured ?

Photometry →

magnitude, color indices

are measurement (or a substitution) for the energy distribution

$m(\underbrace{\lambda_1, \lambda_2}_{\text{small}}) \rightarrow$ Spectrophotometry

Heterochromatic magnitude

$$E_m(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} E(\lambda) . S_i(\lambda) . S_e(\lambda) . S_t(\lambda) . S_s(\lambda) . S_r(\lambda) . d\lambda$$

$S(\lambda)$ = Spectral transmission of :

i : Interstellar medium
e : Earth atmosphere
t : Telescope
s : Photometric system
r : Receiver

$$E_m(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} E(\lambda)\, S_i(\lambda)\, S_e(\lambda)\, S(\lambda)\, d\lambda$$

$S_i(\lambda)$: interstellar absorption

$S(\lambda) = S_t(\lambda)\, S_s(\lambda)\, S_r(\lambda)$
observing system

$S_e(\lambda) =$ earth atmosphere transmission
extinction, to be corrected

$S(\lambda) =$ Spectral transmission of:

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$S_i(\lambda)$: interstellar absorption

$S(\lambda) = S_t(\lambda)\, S_s(\lambda)\, S_r(\lambda)$

observing system

$S_e(\lambda)$ = earth atmosphere transmission

extinction, to be corrected

$$E(\lambda) \cdot Se(\lambda) \equiv R(\lambda)$$

→ expand $R(\lambda)$ in Taylor series

(if continuous function and derivatives also continuous) $\lambda_0 \in [\lambda_1, \lambda_2]$

$$R(\lambda) = R(\lambda_0) + (\lambda - \lambda_0) R'(\lambda_0) + \frac{1}{2}(\lambda - \lambda_0)^2 R''(\lambda_0)$$

+ .....

λ_0 defined such as:

$$\int_{\lambda_1}^{\lambda_2} (\lambda - \lambda_0) S(\lambda)\, d\lambda = 0$$

$$\rightarrow \lambda_0 = \frac{\int_{\lambda_1}^{\lambda_2} \lambda S(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, d\lambda}$$ effective wavelength

$$\mu_2^2 = \frac{\int_{\lambda_1}^{\lambda_2} (\lambda - \lambda_0)^2 S(\lambda)\, d\lambda}{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, d\lambda}$$

(second moment)

and:

$$E_m(\lambda_1, \lambda_2) = \left[R(\lambda_0) + \frac{1}{2}\mu_2^2 R''(\lambda_0) \right] \int_{\lambda_1}^{\lambda_2} S(\lambda)\, d\lambda$$

if limited to the second order:

$$\approx \quad E_m(\lambda_1, \lambda_2) = R(\lambda_0) \int_{\lambda_1}^{\lambda_2} S(\lambda)\, d\lambda$$

$$E_m(\lambda_1, \lambda_2) = E(\lambda_0)\, S_e(\lambda_0) \int_{\lambda_1}^{\lambda_2} S(\lambda)\, d\lambda$$

observed

real "star"

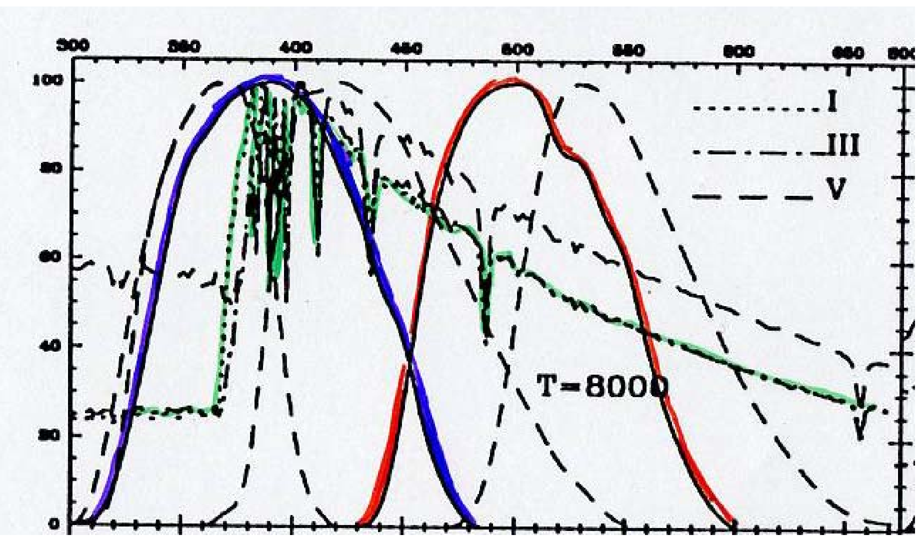
(valid if $R(\lambda) \approx$ linear)

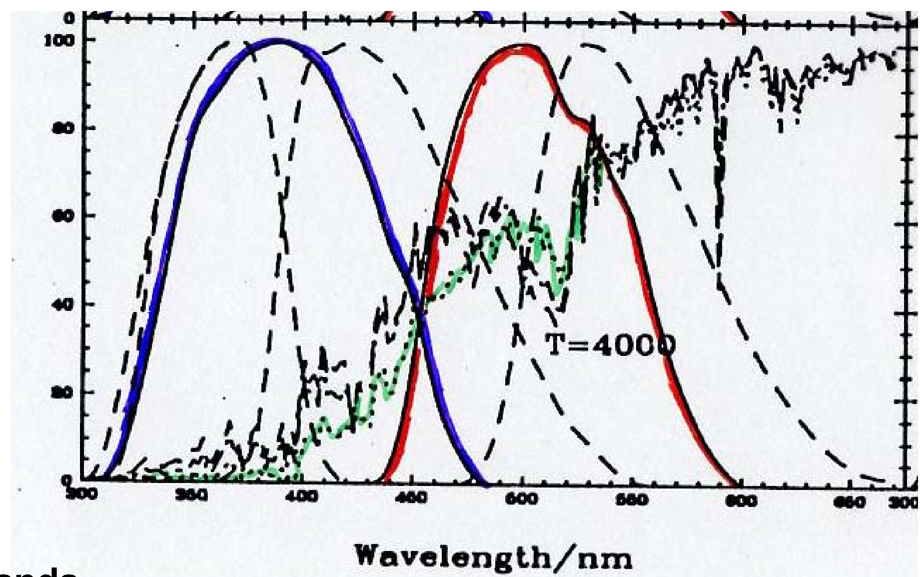
relation usefull to explore the properties of a photometric system

$$\underbrace{E_m(\lambda_1, \lambda_2)}_{\text{observed on Earth}} = E(\lambda_0)\, S_e(\lambda_0) \underbrace{\int_{\lambda_1}^{\lambda_2} S(\lambda)\, d\lambda}_{\text{observing device}}$$

received from the star

Earth atmosphere effect





Heterochromatic extinction : effect of the pass-bands.

Atmospheric extinction : Burki et al A&AS, 112, 383, 1995

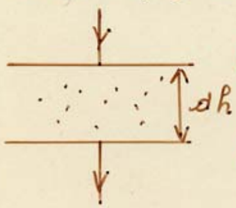
Warning !

Interstellar extinction

modify $E(\lambda)$ so $m(\lambda)$ and CI

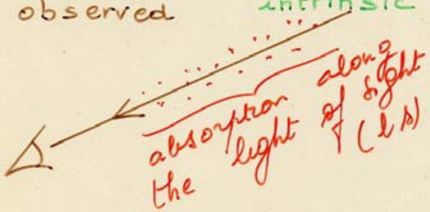
absorption due to the interstellar medium:

$$dE(\lambda,h) = \kappa(\lambda,h)\,\rho(h)\,E(\lambda,h)\,dh$$



(Similar to Earth atmospheric absorption)

$$\underbrace{E(\lambda,\text{Earth})}_{\text{observed}} = \underbrace{E(\lambda)}_{\text{intrinsic}}\, e^{-\int_{ls}\kappa(\lambda,h)\rho(h)\,dh}$$



(expressed in magnitude):

$$m_{obs}(\lambda) = m_{int}(\lambda) + \underbrace{2.5(\log e)\int_{ls}\kappa(\lambda,h)\,\rho(h)\,dh}_{A(\lambda,\,ls)\ \text{"absorption"}}$$

notation: $m(i)$: λ_i

$(i-j) = m(i) - m(j)$ Color Index

$$(i-j)_{observed} = (i-j)_{intrinsic} + \underbrace{A(i)-A(j)}_{E(i,j)}$$

$E(i,j)$ Color Excess

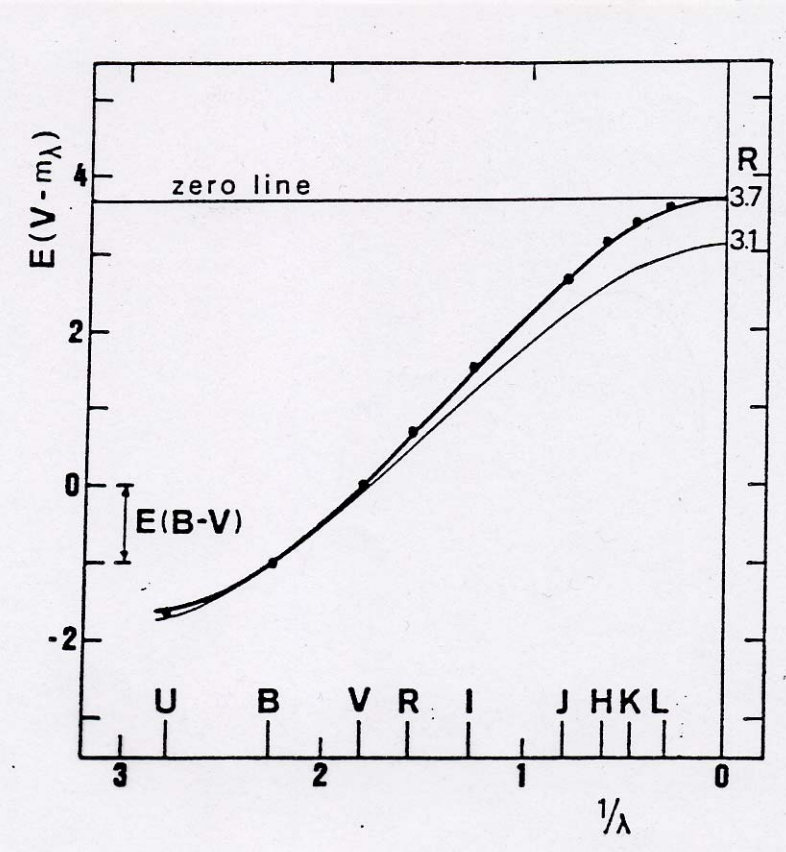
$$\longrightarrow\ m(\lambda) = M(\lambda) - 5 + 5\log d + A(\lambda)$$

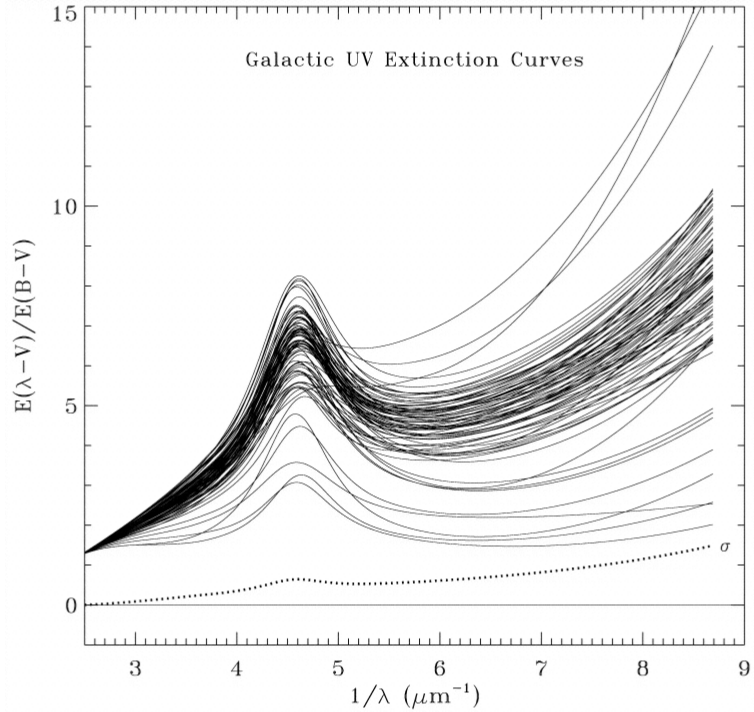
affects the distance determined.

if $(i-j)_{intrinsic}$ defined $\Rightarrow$ $E(i,j)$ computed

Interstellar reddening law:

$A(\lambda) \longrightarrow 0$ $\qquad \lambda \longrightarrow \infty$ (infra red)



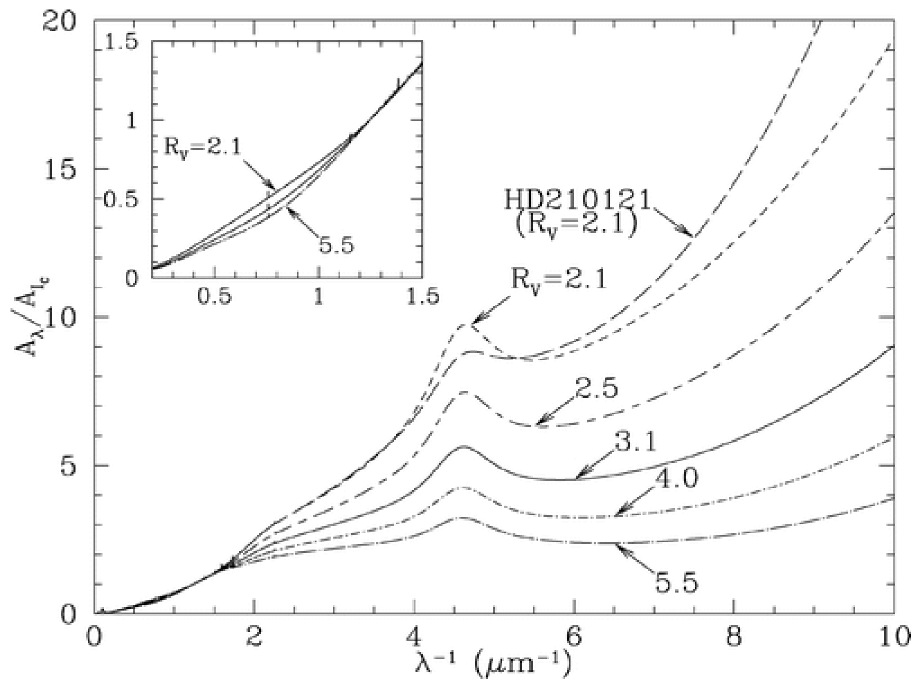


$$R = \frac{A(\lambda=V)}{E(B-V)}$$

Parametrization of the extinction curves :

Cardelli et al ApJ 345,245, 1989

Fitzpatrick PASP, 111, 63, 1999



DIB = Diffuse Interstellar Bands

Measure of E(B-V), A(V)

→ previous calibration needed

1 – Spectral type ~ color indices

2 – color indices ~ "intrinseque" colors

3 – open clusters ~ fit of the main sequence with ZAMS from evolutionary model (→ distance)

calibration means here values of color indices for "normal" non-reddened stars

1: Knude . Høg A.A 338, ,1998

2: Vergely . al. A.A 340, 543, 1998

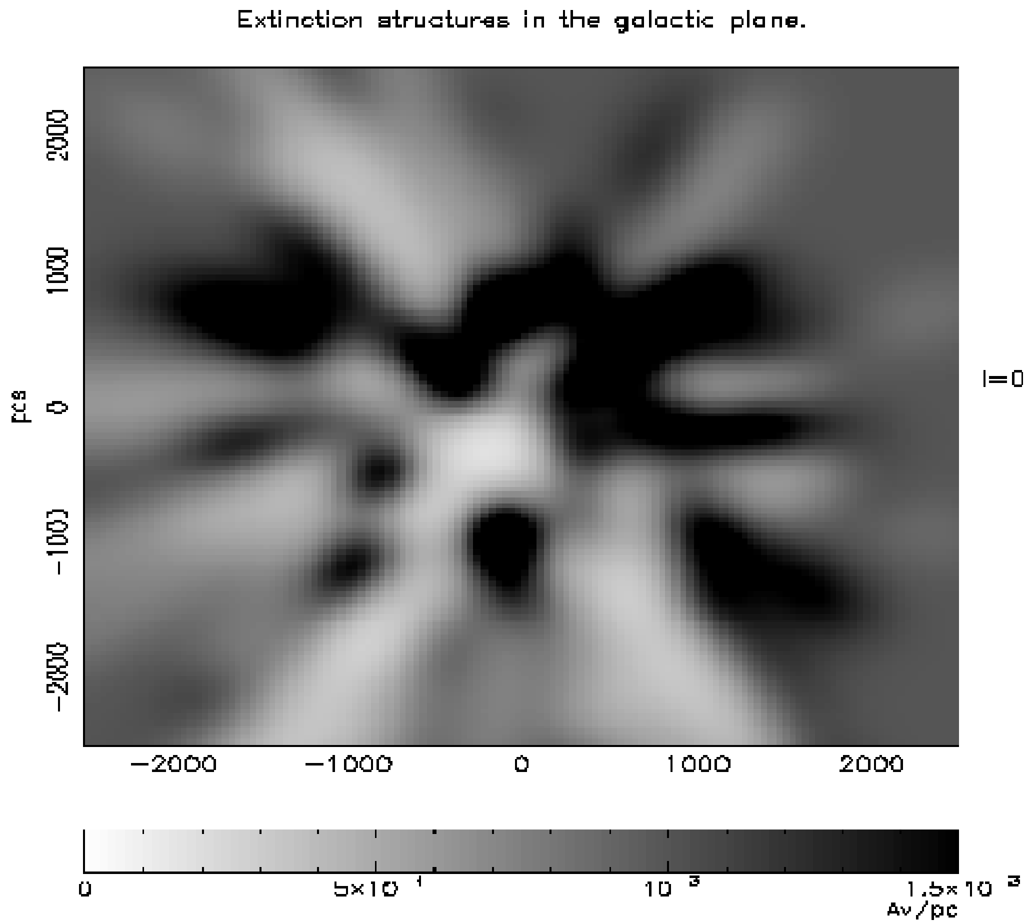
3: Chen . al A.A 336, 137, 1998

4: Fitzpatrick E. A.J. 111, 63, 1999

⚠ definition of an unbiaised sample of stars with no "peculiar objects", no "circumstellar dust".

→ Map of the interstellar absorption as a fonction of the distance to the Sun and position in the Galaxy (ℓ,b)

Maps used to determine the reddening of a star if its distance is estimated



(from: B. Chen at al A&A 336, 137, 1998)

Extinction computed from the reddening of open clusters as given in the data base (Mermilliod 1992 – Geneva Observatory)

The accuracy of such map will be improved with GAIA observations (Chen et al. 1999BaltA...8..195)

The resolution of extinction structures is 2–10 pc for *Gaia* and 20–40 pc for *Hipparcos*.

The interstellar extinction is of crucial importance on many fields of optical astronomy. However, the 3-dimensional distribution of the extinction is only known in the solar neighbourhood.

FitzGerald (1968) maps interstellar extinction using color excesses of 7835 O to M stars. Neckel & Klare (1980) derived extinctions and distances for more than 11000 stars and investigated the spatial distribution of the interstellar extinction at low galactic latitude . Using a larger sample (about 17000 stars) with MK spectral types and photoelectric photometry, Arenou et al. (1992) published an extinction model in which the sky was divided into 199 cells. Recently, Méndez & van Altena (1998) and Chen et al. (1998) have constructed interstellar extinction models of the solar neighbourhood.

All extinction models mentioned above are valid not far away from the Sun (r < 2 kpc).

Recently, Schlegel et al. (1998) published a full-sky map of the Galactic dust based upon its far-infrared emission (IRAS) The spatial resolution is about 6.1 arcmin . Chen et al (A&A, 352, 459, 1999) propose a new 3-dimensional extinction model based on the COBE/IRAS reddening map, extended to low galactic latitude regions.

Exemple of de-reddening :

Ramírez & Meléndez, 2005, ApJ, 626,446

We estimated $E(B-V)$ values from the maps of Schlegel et al. (1998) and Burstein & Heiles (1982), several extinction surveys included in the Hakkila et al. (1997) code, and empirical laws by Bond (1980) and Chen et al. (1998). For stars closer than 75 pc, $E(B-V)=0$ was adopted. The Arenou et al. (1992) extinction model included in the Hakkila et al. (1997) code seems to systematically overestimate the reddening of stars with $d < 0.5$ kpc, and so we have given a lower weight to the $E(B-V)$ values obtained from the Arenou et al. (1992) map for stars closer than 500 pc. A latitude-dependent weight was adopted for the reddening obtained from the Schlegel et al. (1998) and Burstein & Heiles (1982) maps, in such a way that the high-latitude objects ($|l| > 50$) had a larger weight and the low-latitude objects ($|l| < 30$) a weight that was close to zero.

There is evidence that the $E(B-V)$ values obtained from the Schlegel et al. (1998) map, which is based on dust maps by *COBE* DIRBE observations, overestimate the reddening, so we have multiplied the Schlegel et al. (1998) $E(B-V)$ values by 0.8 (Arce & Goodman 1999; Chen et al. 1999; Beers et al. 2002; Dutra et al. 2002, 2003).