Photometric Studies in Astronomy

Books:

» **M. Golay: Introduction to astronomical photometry**

» **E. Budding: Astronomical photometry**

» **Howell: CCD photometry**

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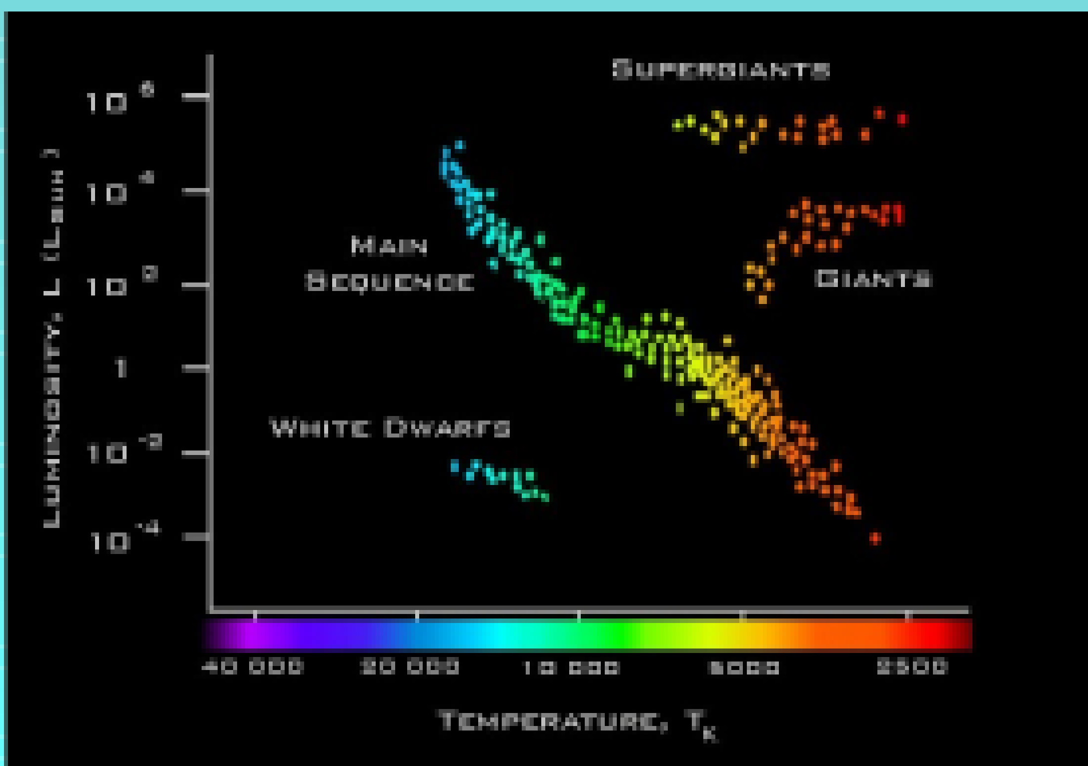
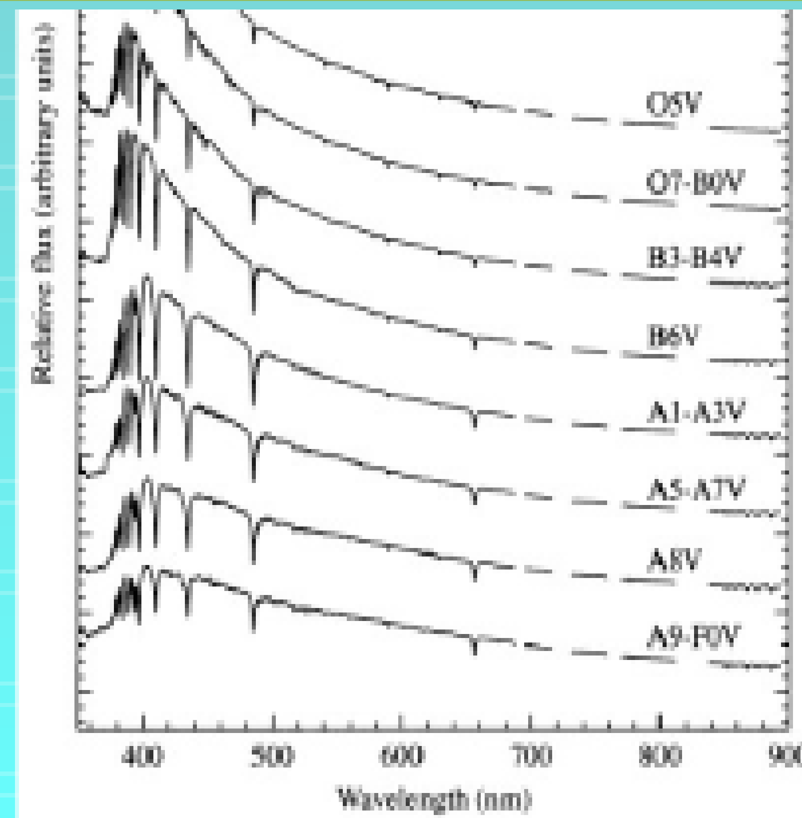
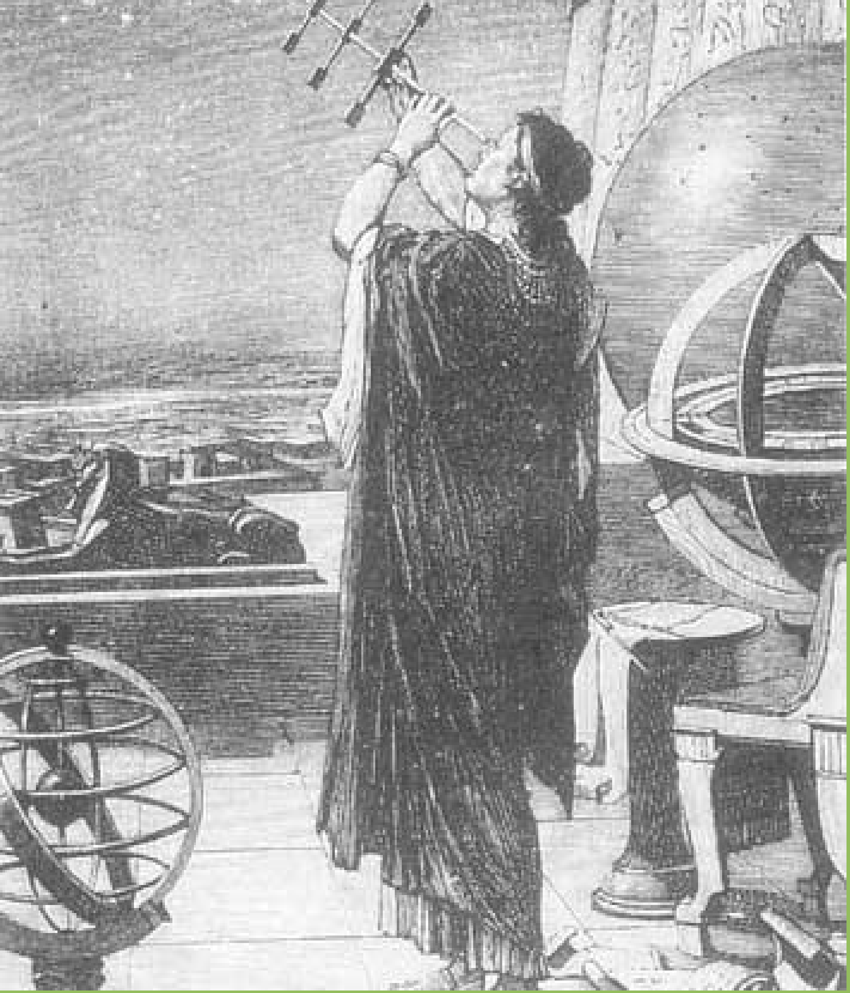
Photometry

Measurement of flux or intensity, combined with distance information, provide total power output or luminosity (Unit: ergs s-1) of object (over specified wavelength range).

Energy information is used to infer or model the object’s physical properties, such as temperature, size, pressure, mass, etc.







Photometry:

Measurement of the brightness of a star

Hipparchus compared the relative brightness of stars (as seen from earth)

Brightest star – magnitude 1

Faintest star – magnitude 6

Each grade of magnitude was considered twice the brightness of the following grade (a logarithmic scale)

Norman Robert Pogson (1856)

Formalized the system by defining a first magnitude star as a star that is 100 times as bright as a sixth-magnitude star, thereby establishing the logarithmic scale still in use today.

This implies that a star of magnitude m is about 2.512 times as bright as a star of magnitude m + 1.

This figure, the fifth root of 100, became known as Pogson's Ratio.

The zero point of Pogson's scale was originally defined by assigning Polaris a magnitude of exactly 2.

Astronomers later discovered that Polaris is slightly variable, so they switched to Vega as the standard reference star, assigning the brightness of Vega as the definition of zero magnitude at any specified wavelength.

Magnitude 1

Magnitude 2

Magnitude 3

Magnitude 4

Magnitude 5

Magnitude 6

Difference in brightness

$(2.512)^{(m2-m1)}$

for (m2-m1)=10, Brightness differ by

10,000 times

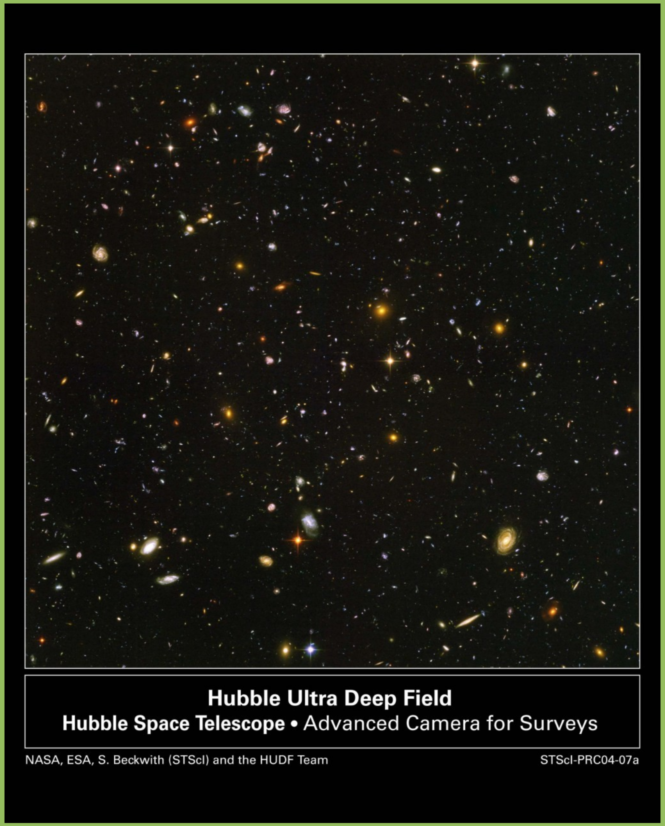
Apparent magnitudes

$$m_X - m_{ref} = -2.5\log\left(\frac{f}{f_{ref}}\right)$$

Object	Apparent mag
Sun	-26.5
Full moon	-12.5
Venus	-4.0
Jupiter	-3.0
Sirius	-1.4
Polaris	2.0
Eye limit	6.0
Pluto	15.0
Reasonable telescope limit (8-m telescope, 4 hour integration)	28
Deepest image ever taken (Hubble UDF)	29

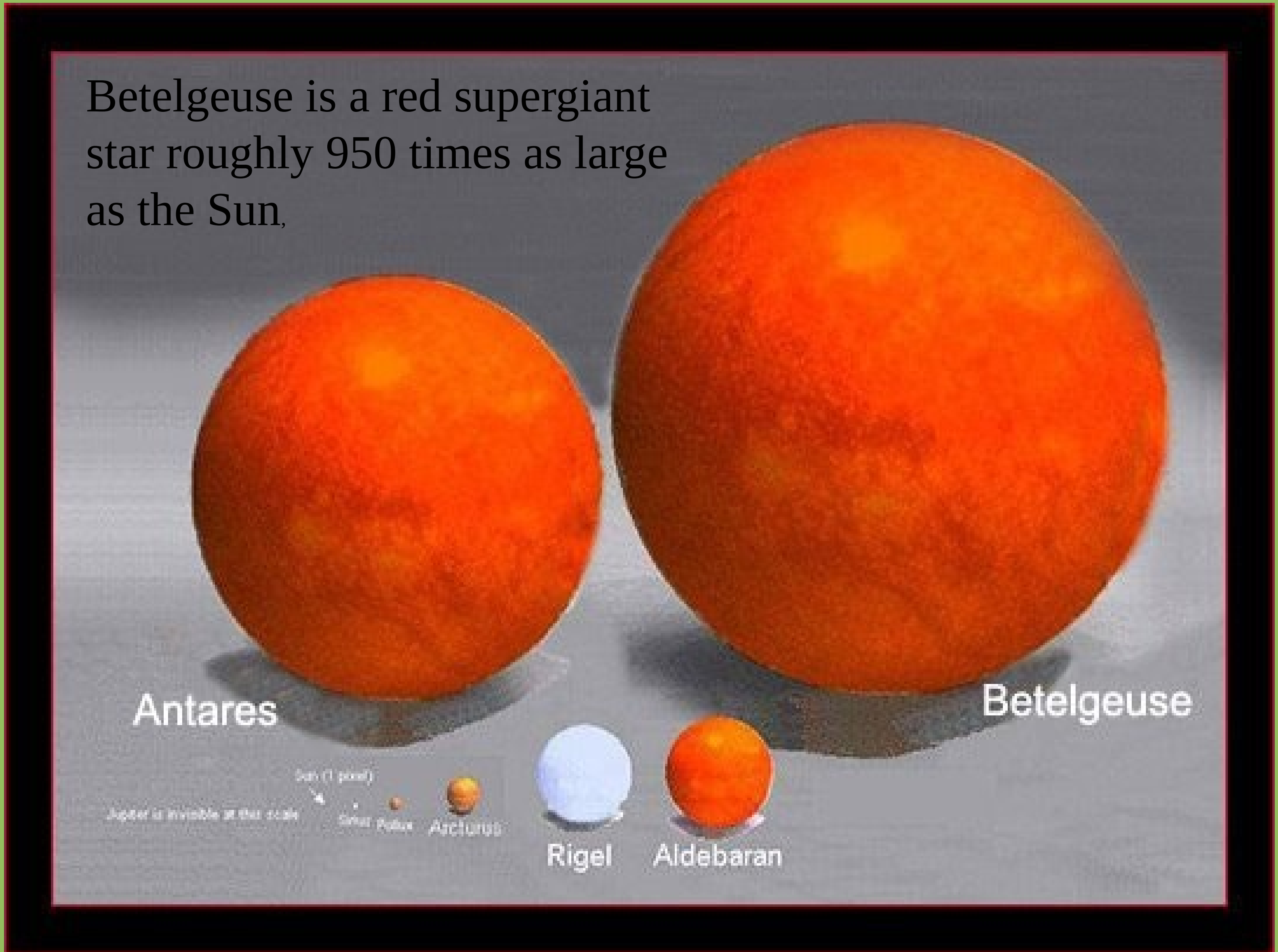
The faintest (deepest) telescope image taken so far is the Hubble Ultra-Deep Field. At m=29, this reaches more than 1 billion times fainter than what we can see with the naked eye.

$$10^{(29-6)/2.5} = 10^{46/5} \approx 10^9$$



Apparent magnitude of Sun is -26.7 and that of Betelgeuse is 0.5. Sun is 76 billion times brighter than Betelgeuse

Betelgeuse is a red supergiant star roughly 950 times as large as the Sun,



Absolute magnitudes

It is also useful to have a measurement of *intrinsic* brightness that is independent of distance

$$F = \frac{L}{4\pi r^2}$$

Absolute Magnitude (M) is therefore defined to be the magnitude a star would have if it were at an arbitrary distance D_0=10pc:

$$m - M = -5\log\left(\frac{10\text{ pc}}{D_{star}}\right)$$

(note the zeropoints have cancelled)

$$5\log\left[\frac{D_{star}}{\text{pc}}\right] - 5$$

The value of m-M is known as the *distance modulus.*

This means at a standard distance of 10 parsecs

the sun would appear to be a dim star of M = 4.85, Betelgeuse M= -5.85

Not All Stars Created Equal

Visible differences in stars not just due to different distances.

Stars have intrinsic differences!

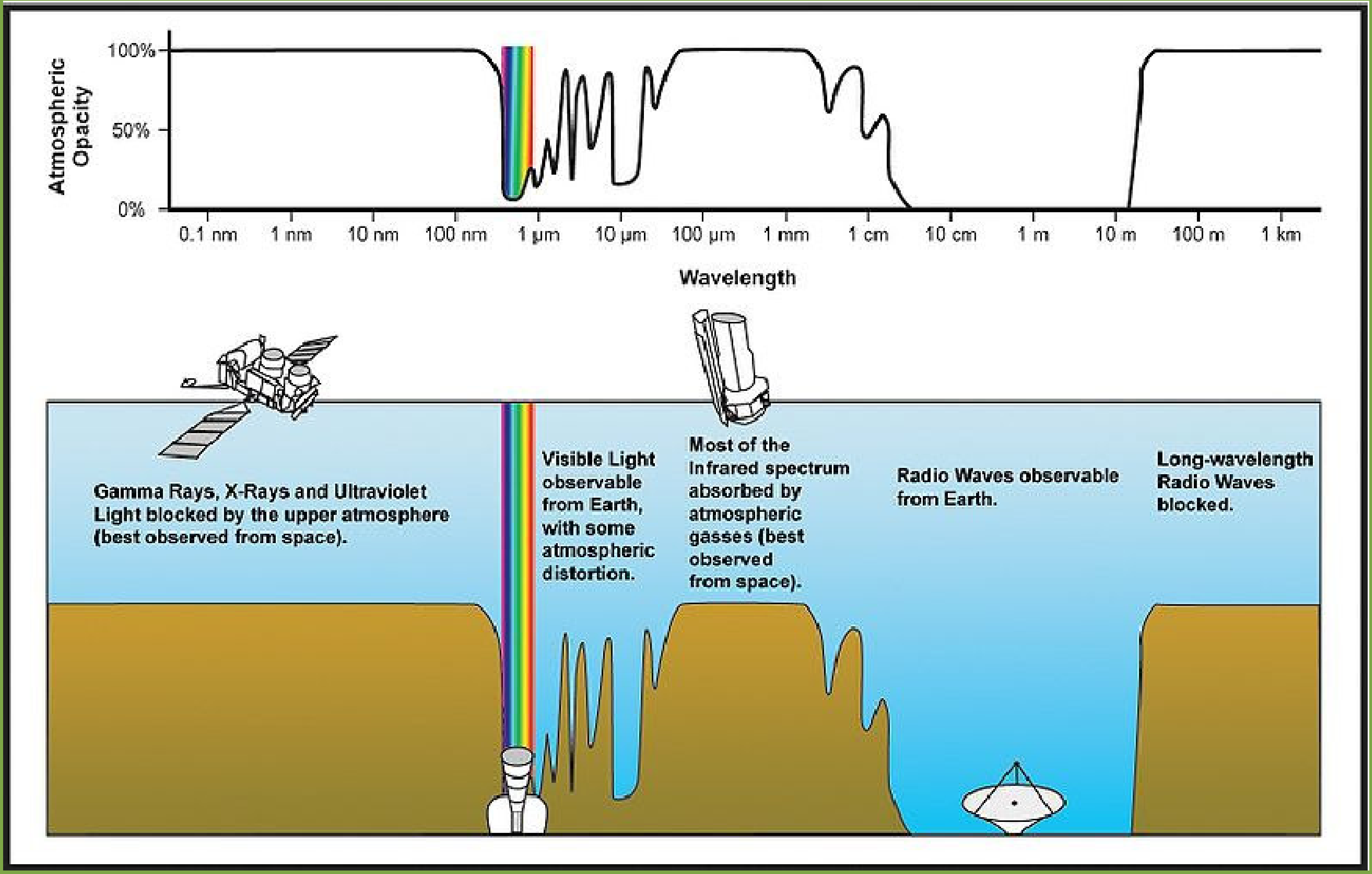
Different colours – which indicate different temperatures

Different sizes

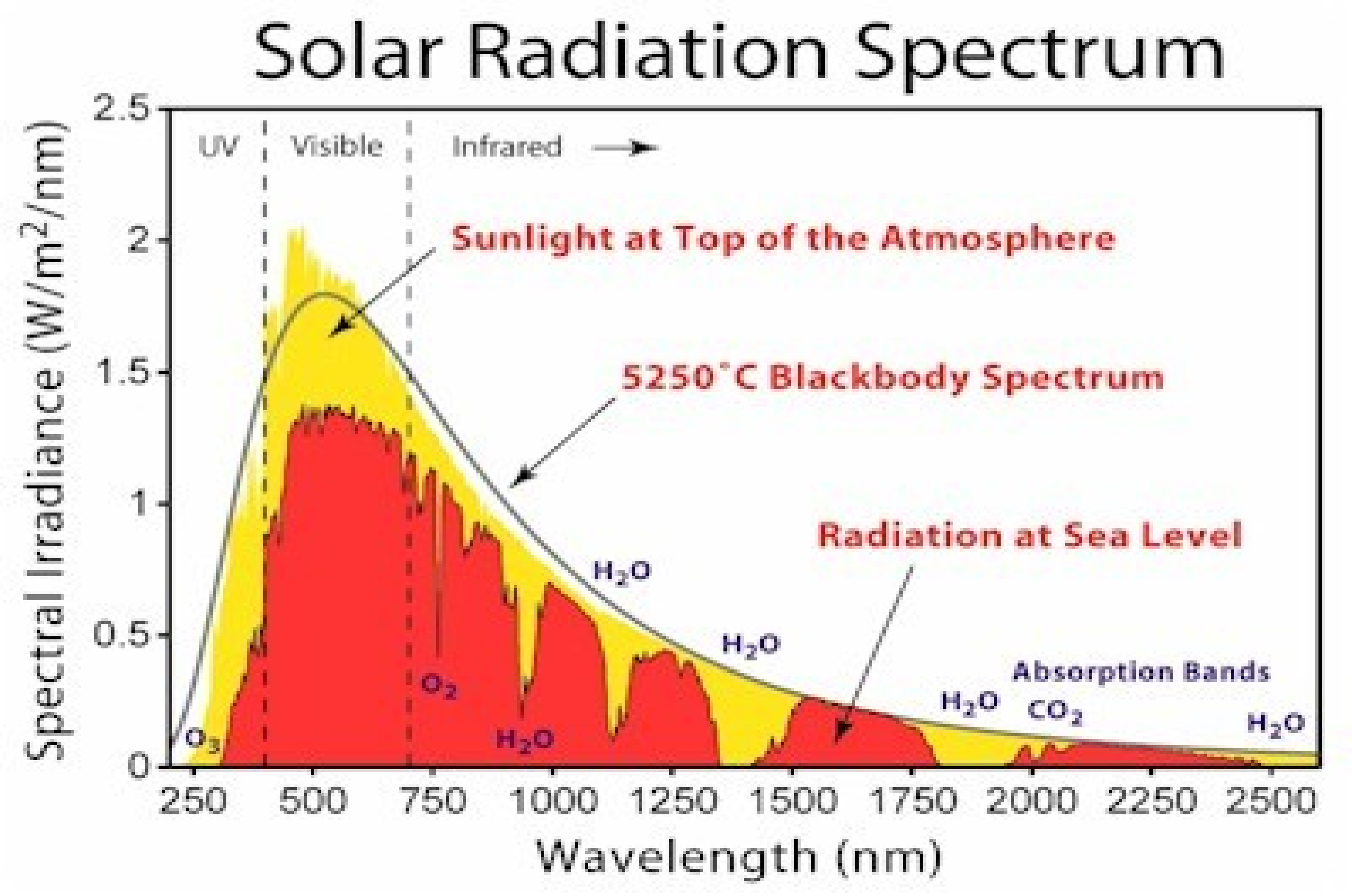
Different masses

The bigger it is, the hotter it is & thus the faster it burns out. Life fast, die young.

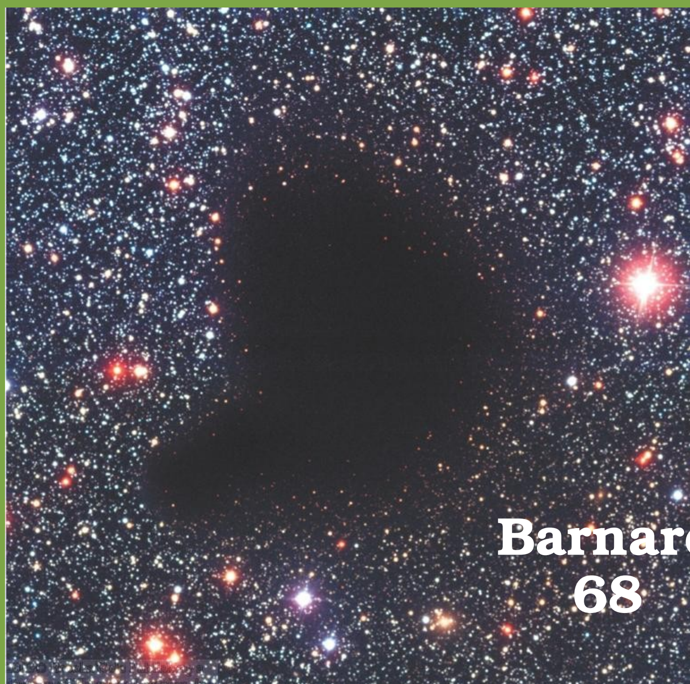
Atmospheric Extinction



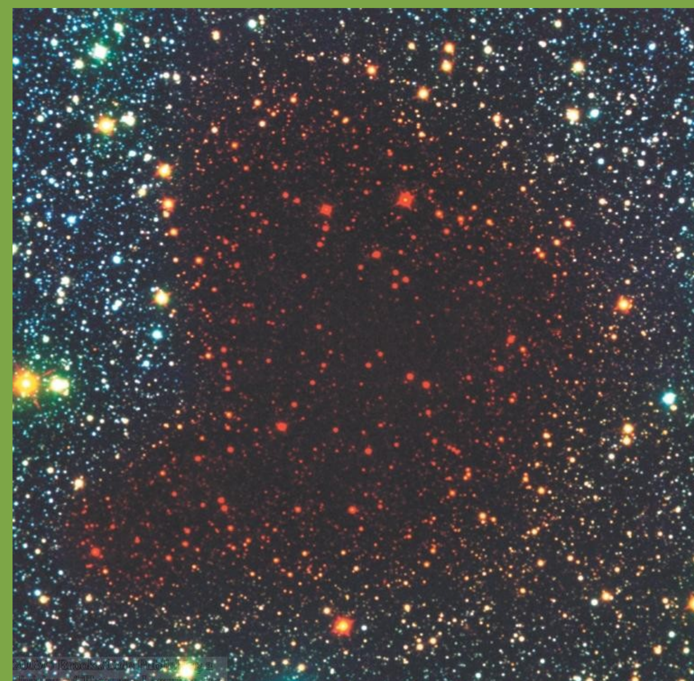
Atmospheric Extinction



Interstellar Reddening



Visible



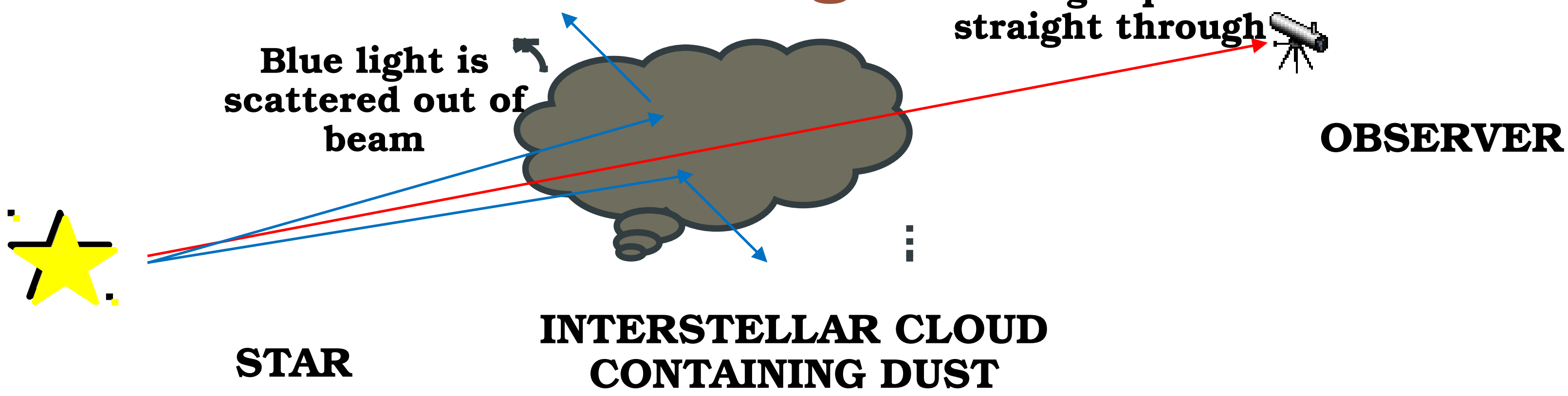
Infrared

Infrared radiation is hardly absorbed at all

Interstellar clouds make background stars appear redder

Interstellar Extinction

(Blue Sky Effect viewed from different angle)



Here the scattering is caused by interstellar dust grains

The more interstellar gas along the sight line, the more reddening occurs

Distant stars appear redder than nearby ones

Astronomers have to correct (de-redden) a stellar spectrum to account for this and to derive the star's true color.

1.1. Definition of Photometric Measurement, a Special Case of Astronomical Measurement

Let:

$I_1(\lambda)$	be the radiance of star 1 per unit interval of wavelength.
$I_2(\lambda)$	be the same for star 2.
α_1 and α_2	be the apparent diameters of stars 1 and 2, which are assumed to be spherical and emit isotropic radiation.
$T_i(\lambda, d_1)$	be the fraction of the radiation of star 1 transmitted by interstellar space in the direction d_1 of star 1.
$T_i(\lambda, d_2)$	be the same for star 2.
$T_a(\lambda, d_1)$	be the fraction of stellar radiation transmitted by the Earth's atmosphere when star 1 is in direction d_1.
$T_a(\lambda, d_2)$	be the same for star 2 when it is in direction d_2.
$T_t(\lambda)$	be the fraction of stellar radiation transmitted by the optical system of the telescope t, whose entry pupil is perpendicular to the star's direction.
$T_f(\lambda)$	be the fraction of stellar radiation transmitted by a filter f placed in front of the receiver.
$r(\lambda)$	be the response of the receiver r which, for simplicity, we assume to depend only upon λ.

The following expression defines the apparent magnitude difference on Earth, $m_1 - m_2$, of stars 1 and 2. The difference is measured with receiver r, filter f, and telescope t for star 1 in direction d_1, and for star 2 in direction d_2.

$$m_1 - m_2 = -2.5 \log \frac{\int_{\lambda_a}^{\lambda_b} \alpha_1^2 I_1(\lambda)\, T_i(\lambda, d_1)\, T_a(\lambda, d_1)\, T_t(\lambda)\, T_f(\lambda)\, r(\lambda)\, \mathrm{d}\lambda}{\int_{\lambda_a}^{\lambda_b} \alpha_2^2 I_2(\lambda)\, T_i(\lambda, d_2)\, T_a(\lambda, d_2)\, T_t(\lambda)\, T_f(\lambda)\, r(\lambda)\, \mathrm{d}\lambda} \tag{1}$$

$m_1 - m_2$ is the observed value, which is given at the exit of the receiver, and represents the receiver's reaction to stellar radiation. The limits of integration, λ_a and λ_b where

Let us suppose

$$S(\lambda)=T_t(\lambda)\ T_f(\lambda)\ r(\lambda)$$

$S(\lambda)$ is the response curve of a photometric system incorporating a filter f.

$$E(\lambda)=\frac{\alpha^2}{4}\ I(\lambda)\ T_i(\lambda, d)$$

Finally we obtain, outside the atmosphere:

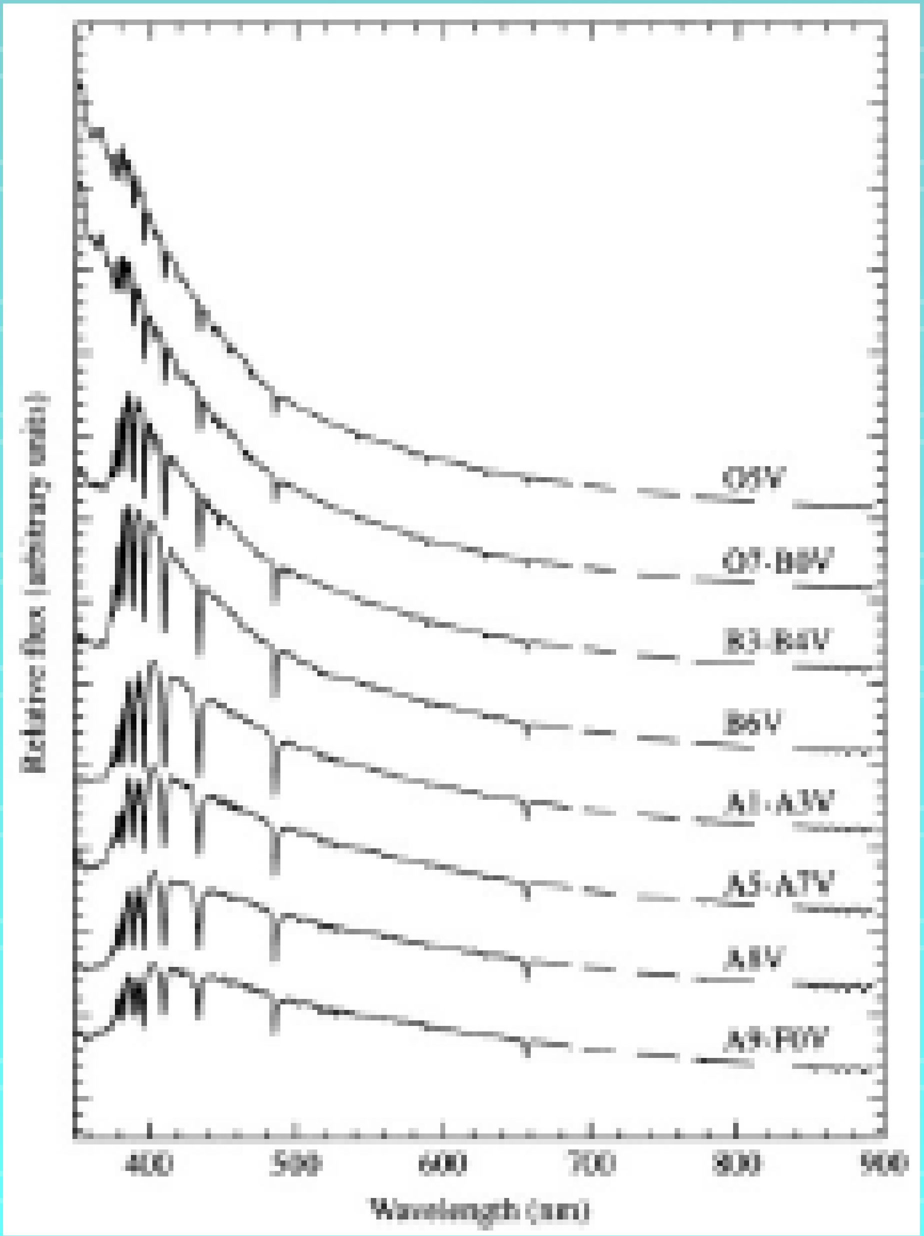
$$(m_1-m_2)_0=-2.5\log\frac{\int_{\lambda_a}^{\lambda_b} E_1(\lambda)\cdot S(\lambda)\,\mathrm{d}\lambda}{\int_{\lambda_a}^{\lambda_b} E_2(\lambda)\cdot S(\lambda)\,\mathrm{d}\lambda}.$$

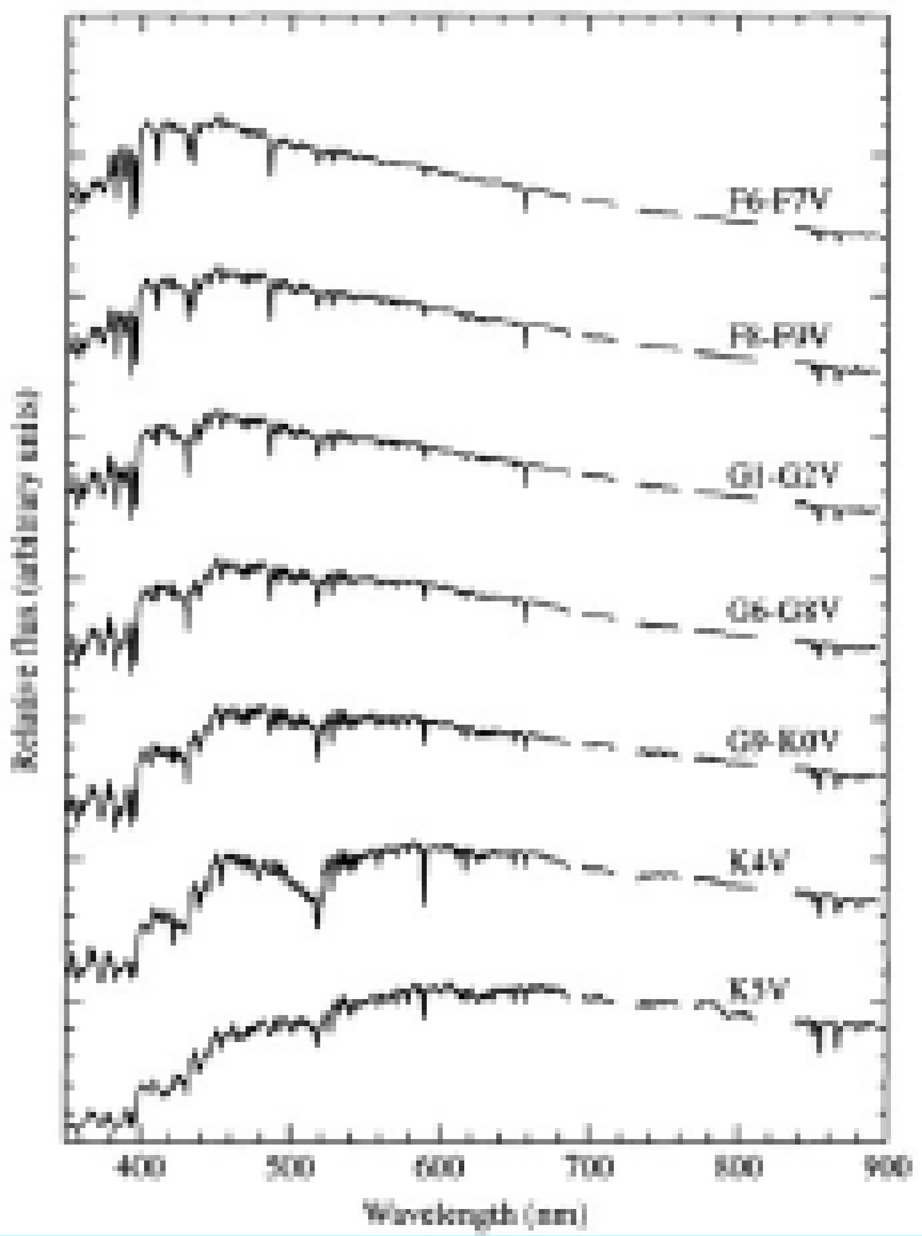
$$C_{AB}=m_A-m_B=-2.5\log\frac{\int_A E(\lambda)\ S_A(\lambda)\,\mathrm{d}\lambda}{\int_B E(\lambda)\ S_B(\lambda)\,\mathrm{d}\lambda}$$

B. Strömgren, [4, 5], distinguishes between 3 types of photometry, depending upon the spectral interval covered by the response curves $S(\lambda)$. If λ_a and λ_b are the lower and upper limits of the spectral interval for which $S(\lambda)$ is defined:

$\lambda_b-\lambda_a<90$ Å	narrow band photometry
90 Å $<\lambda_b-\lambda_a<300$ Å	intermediate band photometry
300 Å $<\lambda_b-\lambda_a$	wide band photometry

The energy emitted by all objects vary with wavelengths. To measure it, we would need to observe from all wavelengths, from gamma-ray to radio waves.





The perfect astronomical observing system:

Would tell us the amount of radiation, as a function of wavelength, from the entire sky in arbitrarily small angular slices.

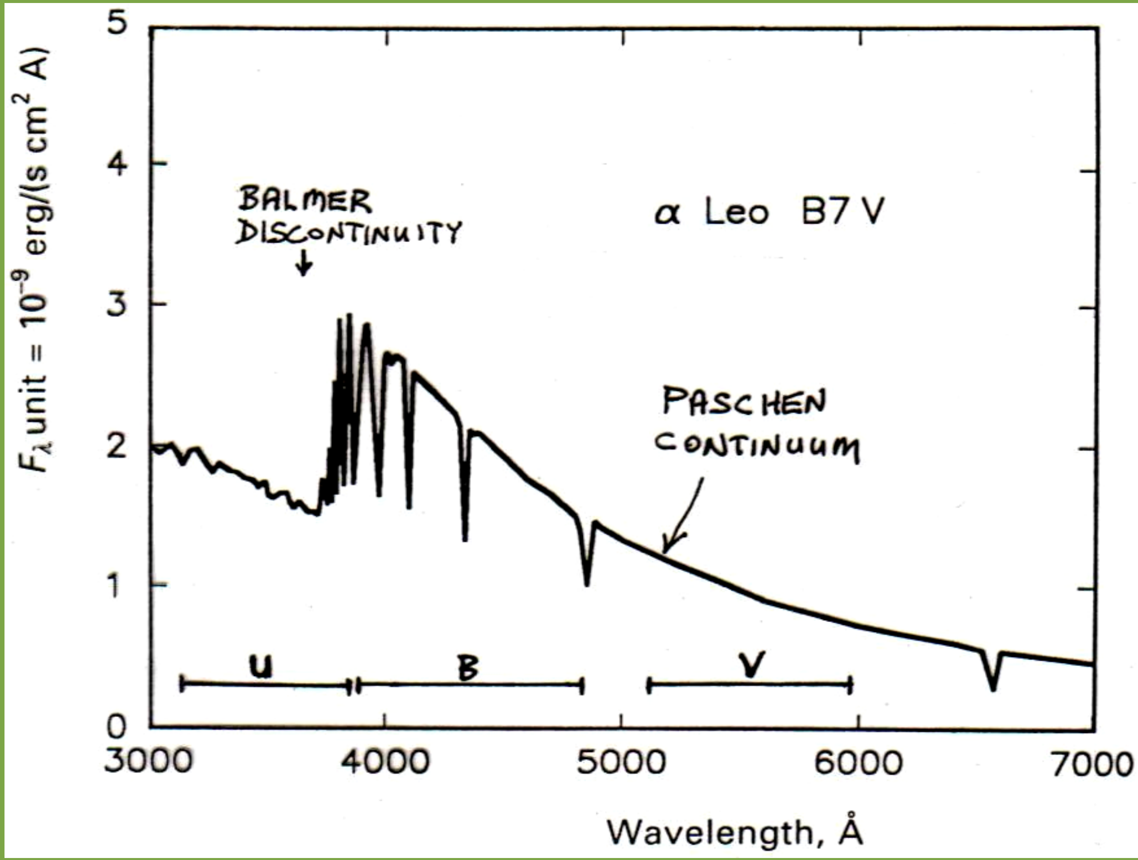
Such a system does not exist!

We are always limited in angular and wavelength coverage, and limited in resolution in angle and wavelength.

A given telescope can measure the brightness of an object through a filter to far fainter limits than the same telescope could do spectrophotometry, at the trade off, of course, of less information on the distribution of flux with wavelength.

Photometric Systems:

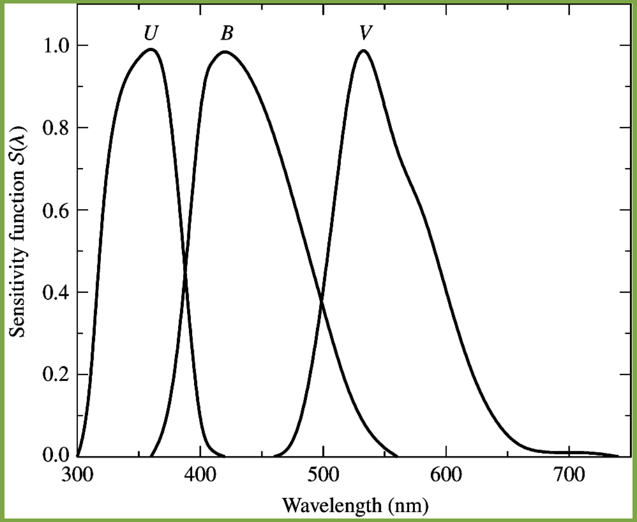
For early-type stars, the Balmer discontinuity (λ3647) and Paschen jump (λ8206) result from the opacity of H, and are modified by electron scattering in hot O-type stars and H^- (negative H ion) opacity in cool GK stars. The Balmer discontinuity is very sensitive to both T_{eff} and log *g*, so many systems use filter sets to isolate stellar continua on either side of it.



The discontinuity at the end of the Balmer series of hydrogen absorption lines is a conspicuous feature in the near ultraviolet of stellar spectra.

Johnson's *UBV Broad band* System.

Filter	λ_{eff}(nm)	$\Delta\lambda$(nm)
U	365	68
B	440	98
V	550	89



The *UBV* system:

(i) an RCA 1P21 photomultiplier with *U* (Corning no. 9863 filter), *B* (Corning no. 5030 filter + 2 mm Schott GG13 filter), and *V* (Corning no. 3384 filter) standard filter sets.

(ii) a reflecting telescope with aluminized mirrors,

(iii) standard reduction procedures (later), and

(iv) an altitude for observations of ~7000 feet. The standard colour indices in the system were defined to be *U*–*B* = *B*–*V* = 0.00 for unreddened AO V stars in the North Polar Sequence.

Results for the *UBV* System:

The system was calibrated and the colours normalized relative to stars in the North Polar Sequence, so that $U–B = B–V \equiv 0.00$ for A0 V stars.

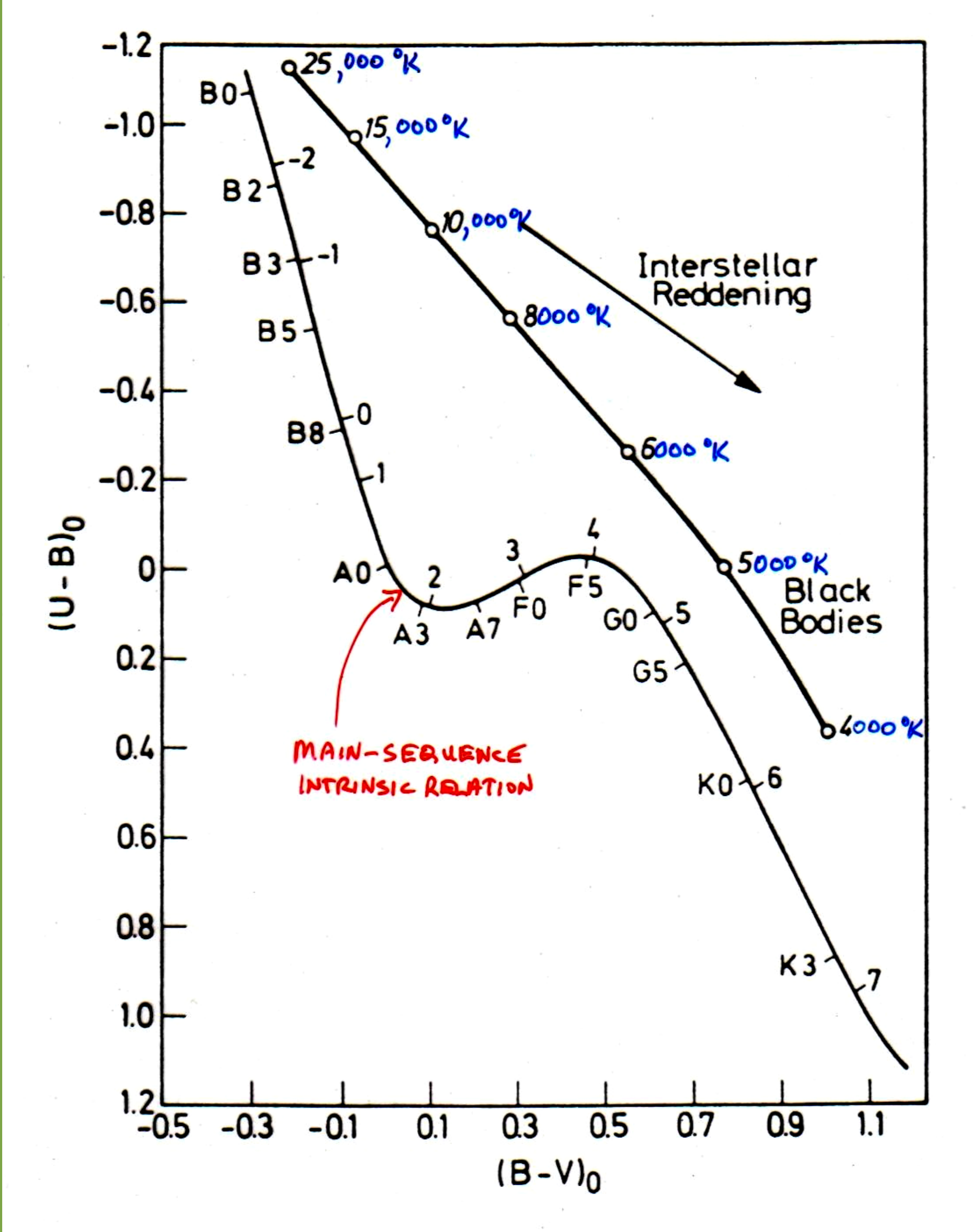
The nature of the system is such that the *B* and *V* filters are located on the Paschen continua of stellar spectra, while the *U* filter straddles the Balmer discontinuity at λ3647Å. The slope of the Paschen continuum in stars is similar to the slope of a black body continuum, so is temperature sensitive, making *B–V* very useful for measuring stellar temperatures.

The Balmer discontinuity, particularly for stars hotter than the Sun, is gravity (or luminosity) sensitive, so that *U–B* is useful as a luminosity indicator.

For cool stars, both *B–V* and *U–B* are sensitive to chemical composition differences, since the *U* and *B* bands are susceptible to the effects of line blocking and line blanketing on stellar continua. Photometric ultraviolet excesses measured relative to standard metallicity colours are therefore useful for segregating stars according to metallicity.

Standard two-colour (or colour-colour) diagram for the *UBV* system.

Plotted are the observed intrinsic relation for main-sequence stars of the indicated spectral types, the intrinsic locus for black bodies radiating at temperatures of 4000K, 5000K, 6000K, 8000K, etc., and the general effect on star colours arising from the effects of interstellar reddening.



The primary opacity source in the atmospheres of B and A-type stars is atomic hydrogen, which makes its presence obvious in the flux distributions of such stars with discrete discontinuities in the stellar continua at λ912Å (the Lyman discontinuity), λ3647Å (the Balmer discontinuity), and λ8206Å (the Paschen discontinuity).

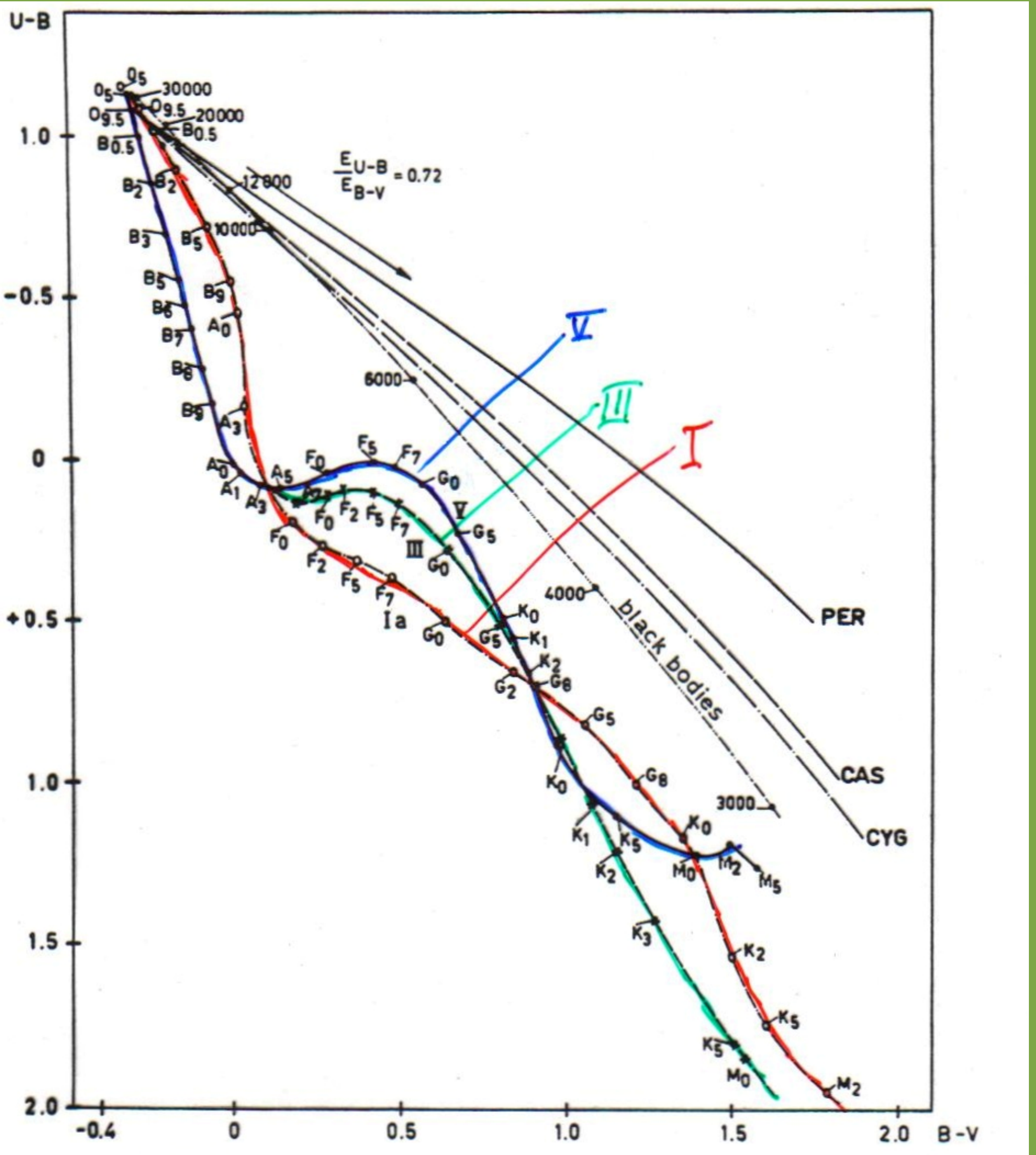
The primary opacity source in the atmospheres of F, G, and K-type stars is the negative hydrogen ion (H^-), which does not produce any discrete breaks in the flux output as a function of wavelength.

For the very hottest O-type stars, the primary opacity source is electron scattering, which also does not produce any continuum breaks.

The intrinsic relation for main-sequence stars in the two-colour diagram therefore falls close to the black body curve for very hot stars and stars of solar temperature.

It deviates noticeably from the black body curve for B and A-type stars because of atomic hydrogen opacity, and for K and M-type stars from the effects of spectral line and molecular band absorption in the blue spectral region.

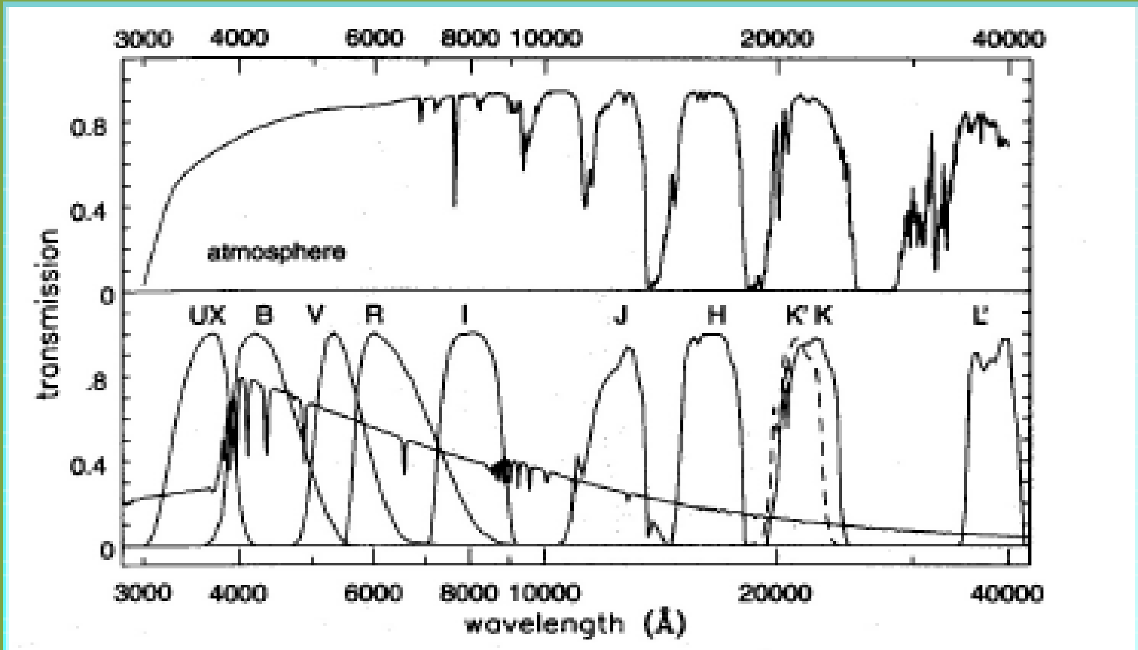
Intrinsic colours vary according to both the temperature and luminosity of stars, roughly as indicated here.



Distribution of various spectral types and luminosity classes, reddened O stars and black-bodies, in a diagram with $U-B$ as ordinate and $B-V$ as abscissa.

UBVRIJHKLMNO Systems

Band	$\lambda_{eff}(\mu m)$	$1/\lambda_{eff}$
U	0.36	2.78
B	0.44	2.27
V	0.55	1.82
R	0.70	1.43
I	0.88	1.14
J	1.25	0.80
K	2.2	0.45
L	3.4	0.29
M	5.0	0.20
N	10.2	0.10
O	~11.5	0.09



Intermediate Band Systems:

Strömgren System

Possible ambiguities in the interpretation of intrinsic stellar parameters with *UBV* colours led Bengt Strömgren to develop an alternate intermediate band system using an RCA 1P21 tube, but with narrow passband interference filters to isolate all but the ultraviolet wavelength bands (a glass filter was used for the latter). The parameters of the wavelength bands for the *uvby*, or Strömgren, system are:

Filter	λ_{eff}	$\Delta\lambda$ **(½-width)**
u **(ultraviolet)**	**3500Å**	**380Å**
v **(violet)**	**4100Å**	**200Å**
b **(blue)**	**4700Å**	**100Å**
y **(yellow)**	**5500Å**	**200Å**

The *u*-filter does not extend to the Earth's atmospheric cutoff, so is less susceptible to the problems of the Johnson *U*-filter.

Interference filters also reduce problems generated by atmospheric and interstellar extinction on the effective wavelengths of the filters.

The b and y bands are located in relatively line-free portions of the Paschen continuum, so that the $b–y$ index is temperature sensitive, the v band is located on the long wavelength side of the Balmer discontinuity, where the overlapping of lines from metallic atoms and ions, as well as from hydrogen Balmer series members, is noticeable, particularly for A, F, G, and K-type stars.

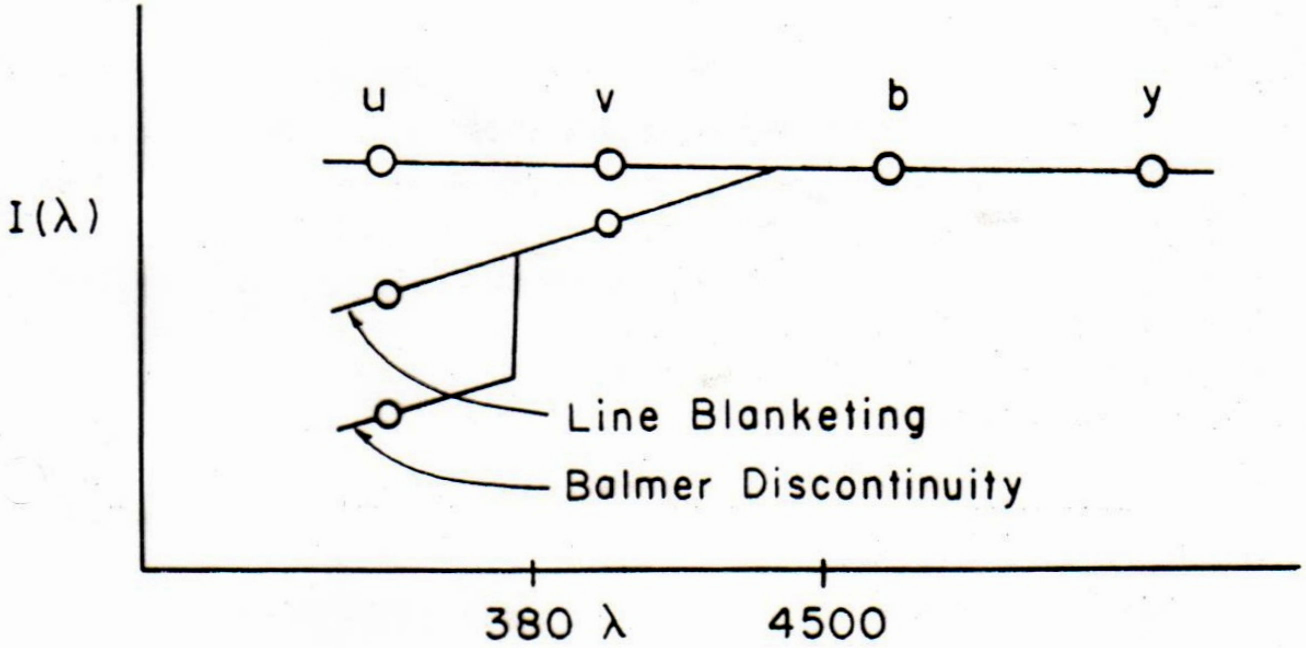
Strömgren designed a specific index to measure the depression of the stellar continuum in the v band: $m_1 \equiv (v–b) – (b–y)$, known as the "metallicity" index (m for metallicity).

The u band is located on the short wavelength side of the Balmer discontinuity, and can be combined with the v and b filters to give an index c_1 that is sensitive to the size of the Balmer jump, which is gravity dependent for hot O, B, and A-type stars.

Strömgren designed another index to measure the size of the Balmer discontinuity from the depression of stellar continua in the u band: $c_1 \equiv (u–v) – (v–b)$, known as the gravity index (c for the supergiant c designation).

e.g.

STRÖMGREN SYSTEM

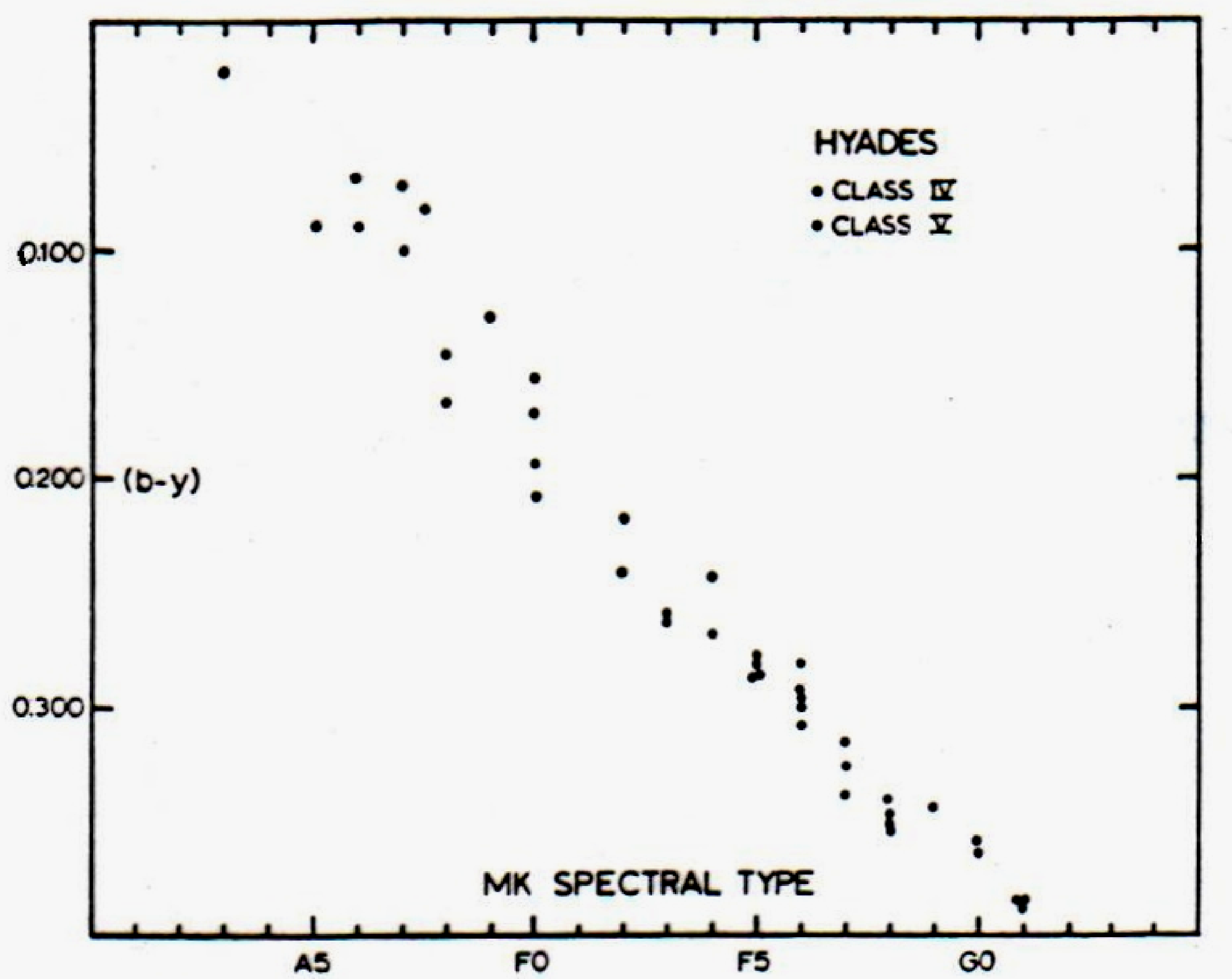


$(b-y)$ ← temperature and reddening sensitive

$m_1 = (v-b) - (b-y)$ ← metallicity sensitive

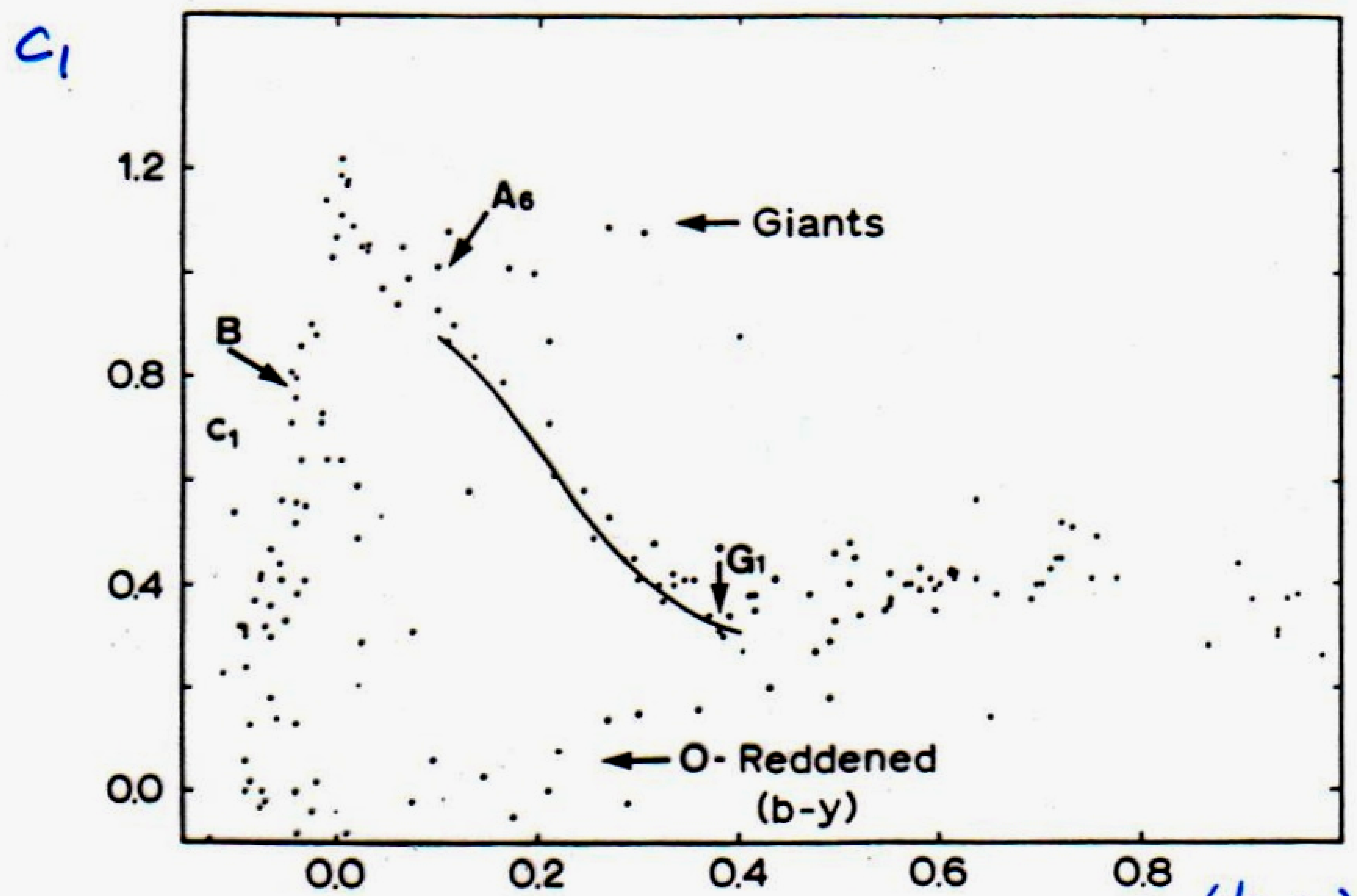
$c_1 = (u-v) - (v-b)$ ← luminosity sensitive (due to bracketing of Balmer jump)

The temperature dependence of the *b-y* index.



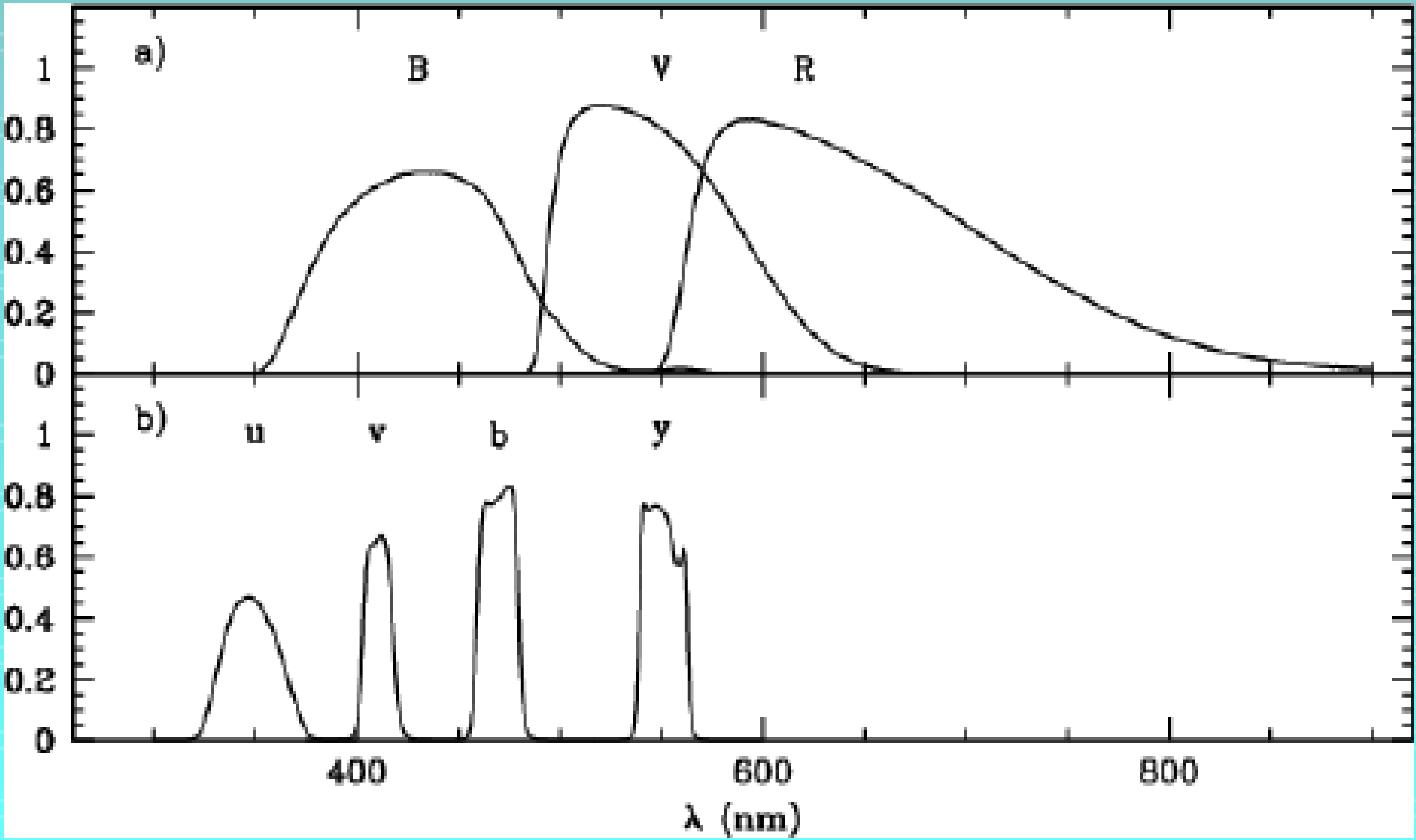
Relationship between $(b-y)$ and MK spectral type, by Crawford and Perry.

Calibration of c_1 versus (b-y).



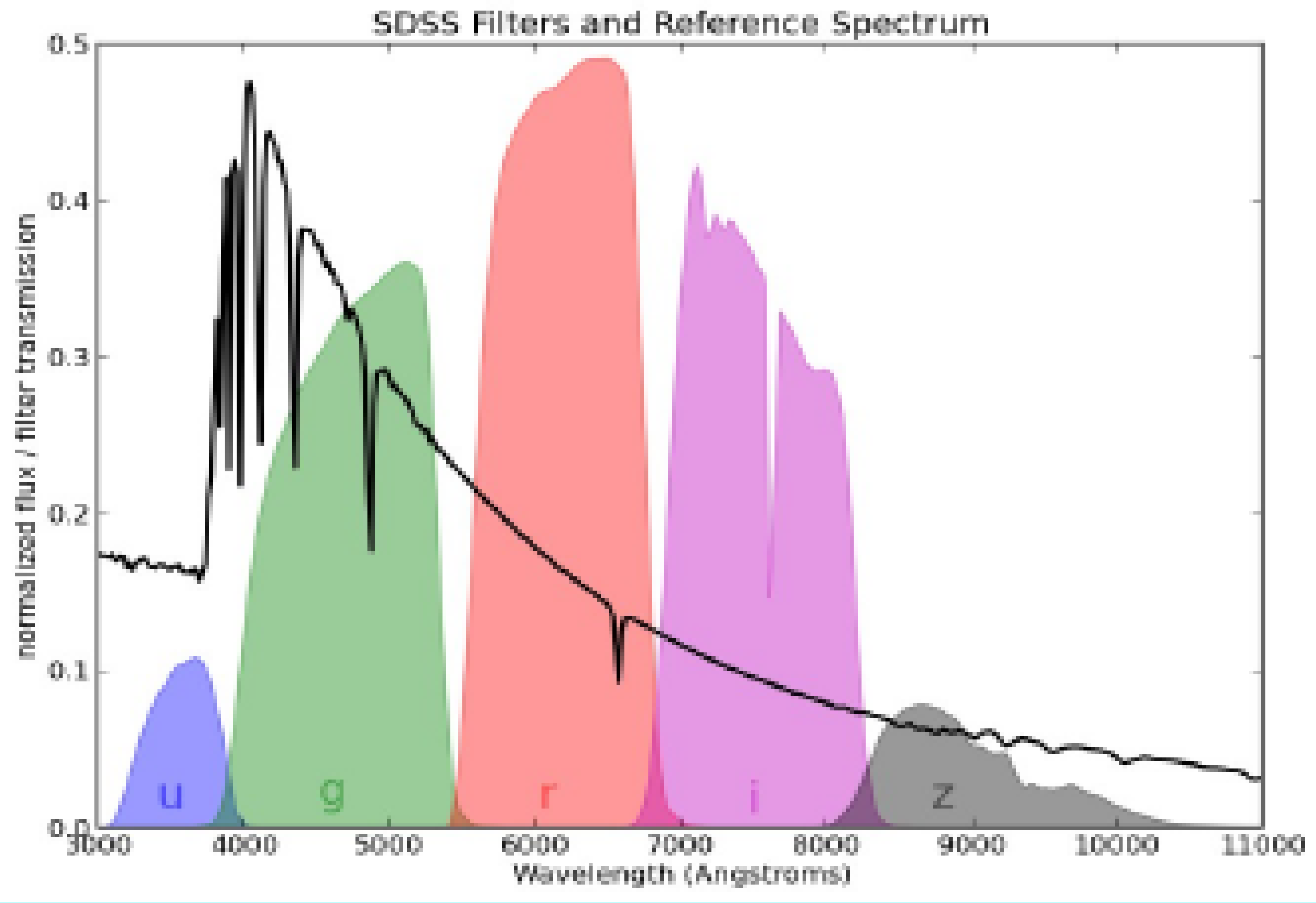
Variation of c_1 with the $(b-y)$ index. The continuous line represents a segment of the zero-age sequence (ZAMS).

A visual comparison of the Johnson and Stromgren filter systems.



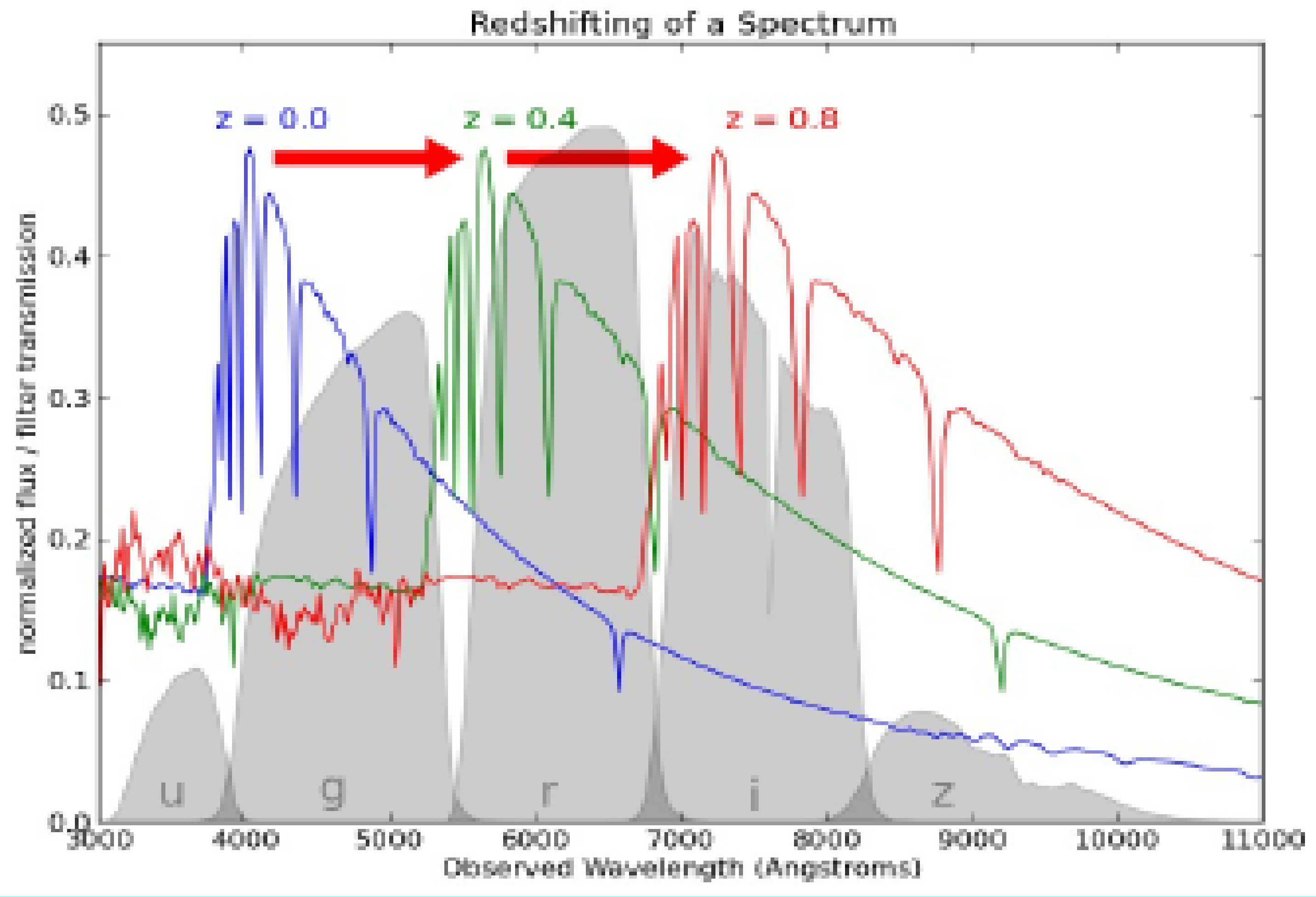
The *ugriz* filter system developed for the Sloan Digital Sky Survey is popular among extragalactic astronomers.

(Note: Black profile is representative spectrum of a star-forming galaxy. Sharp cutoff at 3646 Å corresponds to Balmer limit of hydrogen. Other absorption lines correspond to Balmer lines of hydrogen.)



The *ugriz* filter system developed for the Sloan Digital Sky Survey is popular among extragalactic astronomers.

(Notice the shift in wavelength of the Balmer limit with increasing redshifts.)



Narrow Band Systems:

Narrow band photometric systems are so-named because they employ very narrow passband filters to isolate specific wavelength regions of interest.

The most frequently cited is the *Hβ* photometric system, which uses two narrow-band filters (a wide filter of half-width 150Å and a narrow filter of half-width 30Å — see Crawford & Mander, AJ, 71, 114, 1966) to provide an index that measures the strength of the hydrogen Balmer *Hβ* line at λ4861Å in stellar spectra.

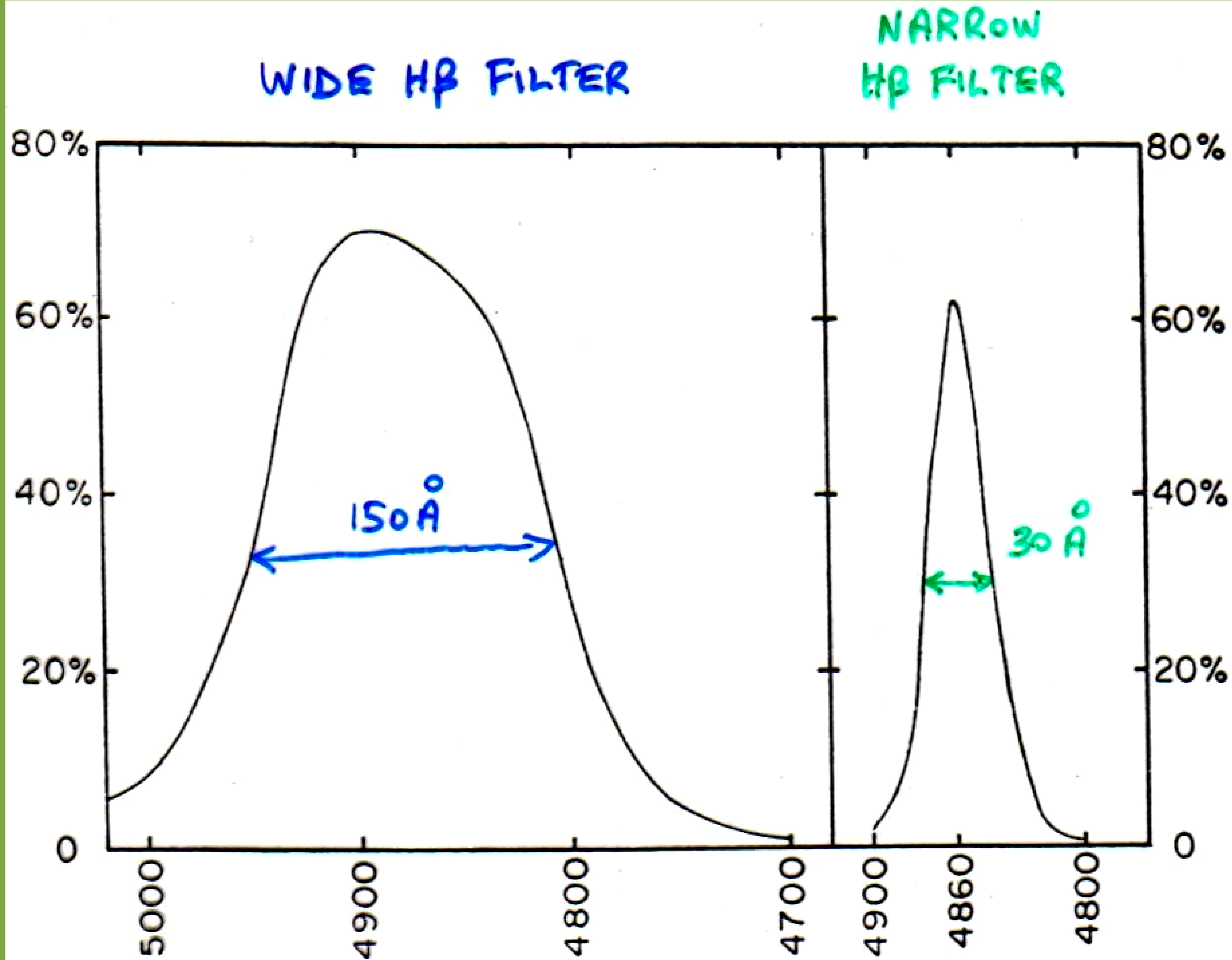
That feature proves to be gravity sensitive for stars hotter than spectral type ~A2, and temperature sensitive for cooler stars.

It is defined by:

$$\beta = 2.5 \log I(\text{wide } H\beta \text{ filter}) - 2.5 \log I(\text{narrow } H\beta \text{ filter}).$$

Since both filters are centered on the same wavelength, the index is insensitive to both atmospheric and interstellar reddening (i.e. observations can be made on partly cloudy nights!).

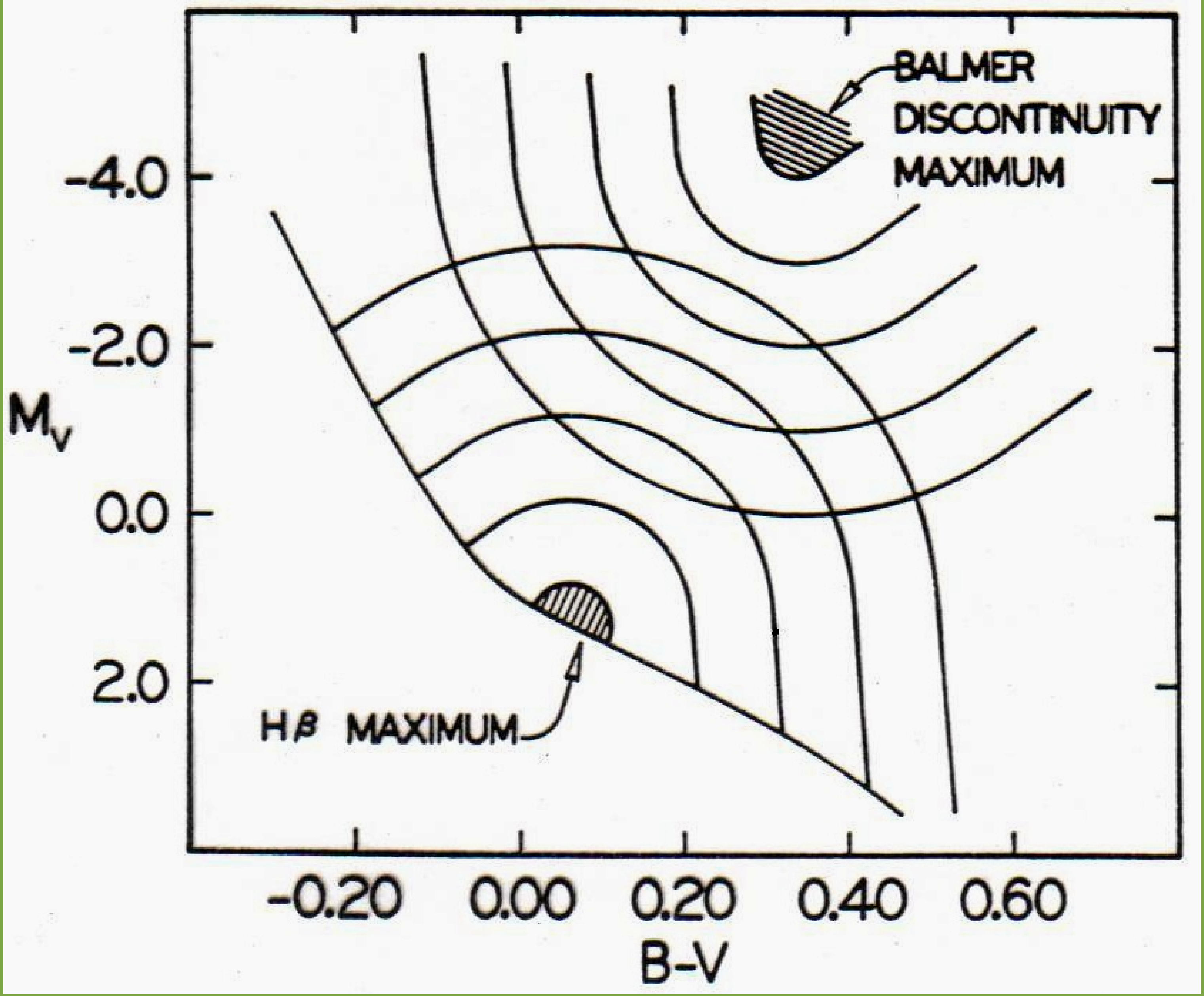
e.g.



Passbands of the Hβ photometric system, by Crawford and Mander.

$$\beta = 2.5 \log I_{WIDE} - 2.5 \log I_{NARROW}$$

The changing temperature and gravity dependence of *Hβ* depending upon spectral type (colour index).



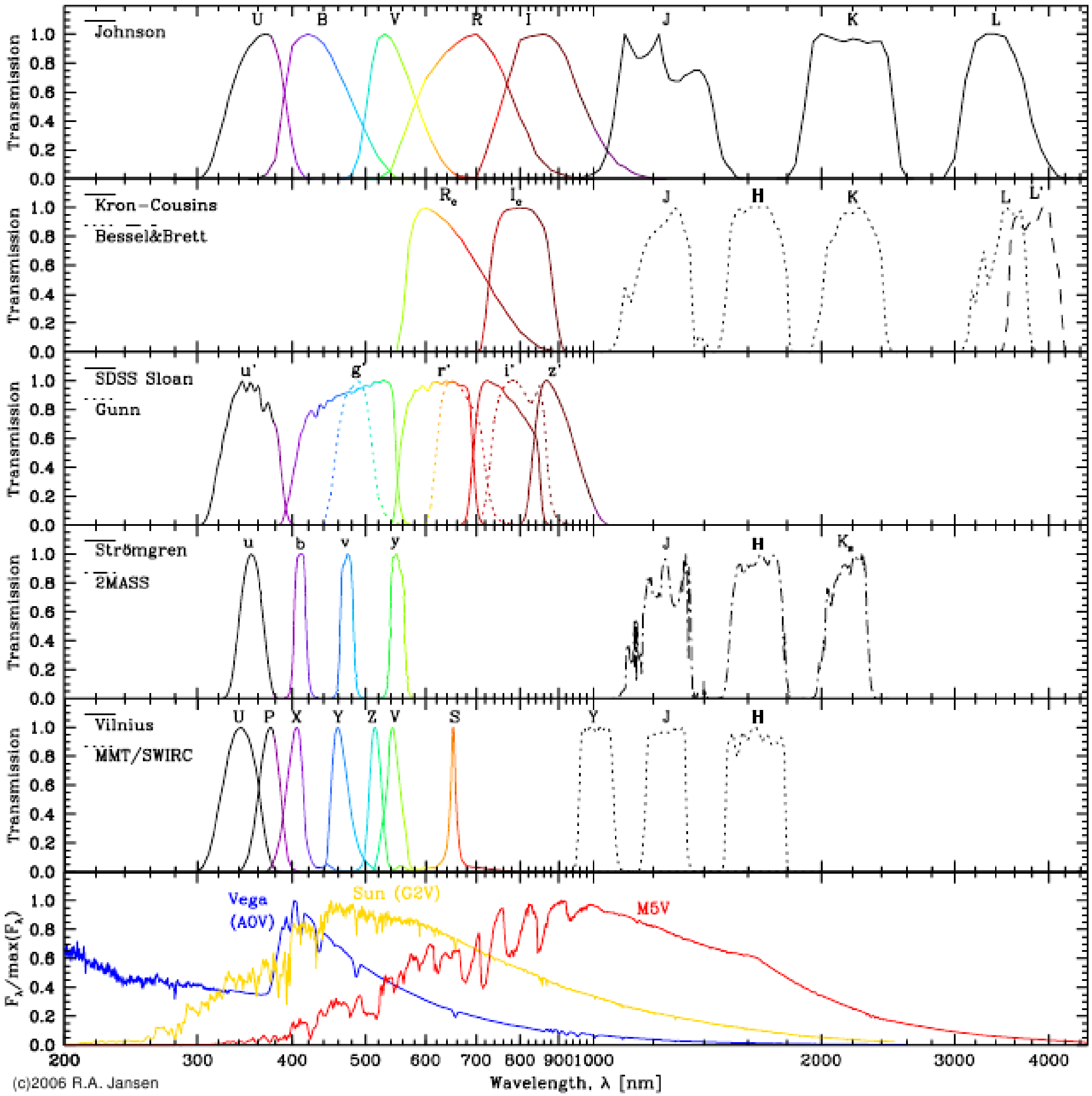
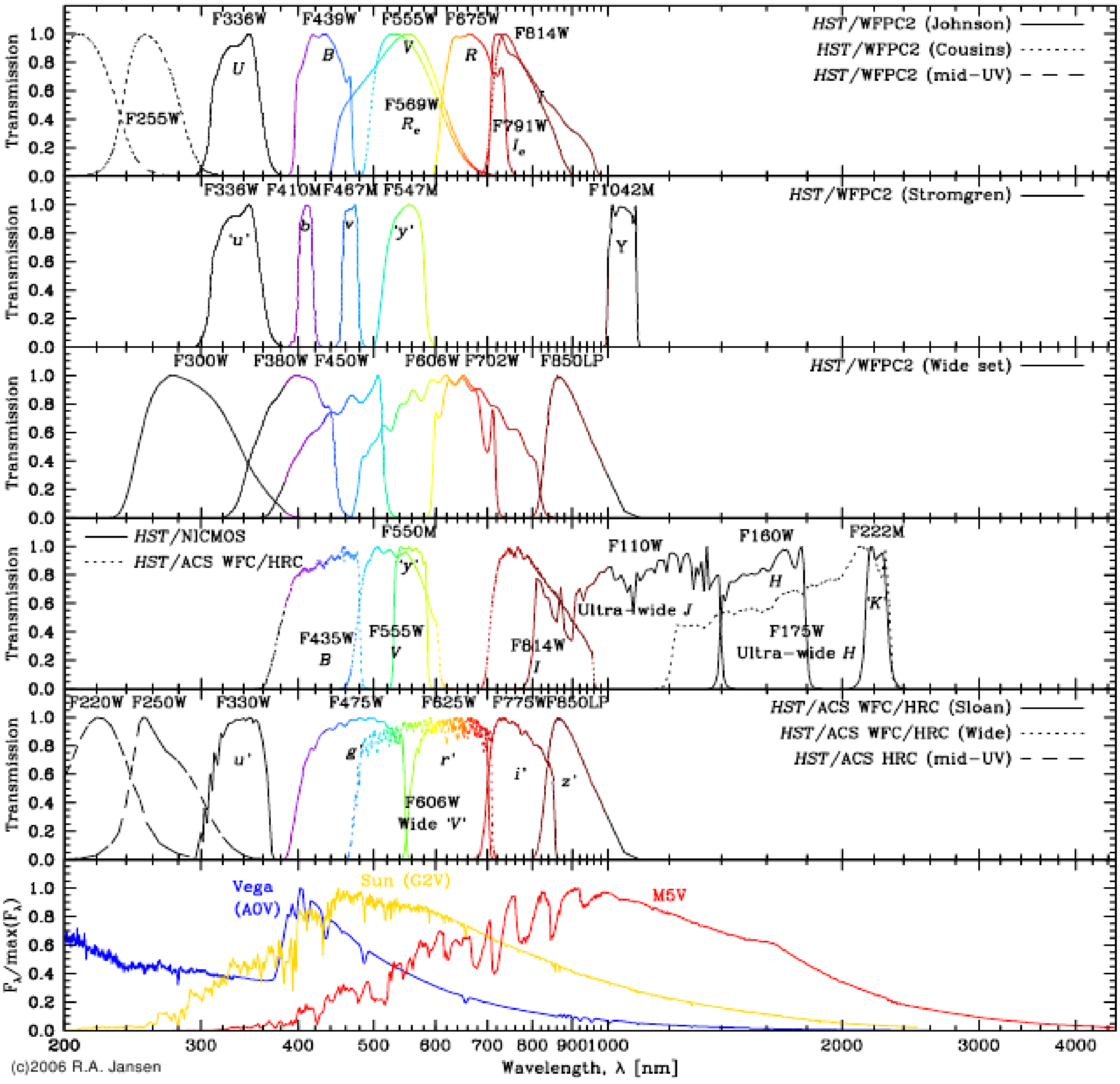


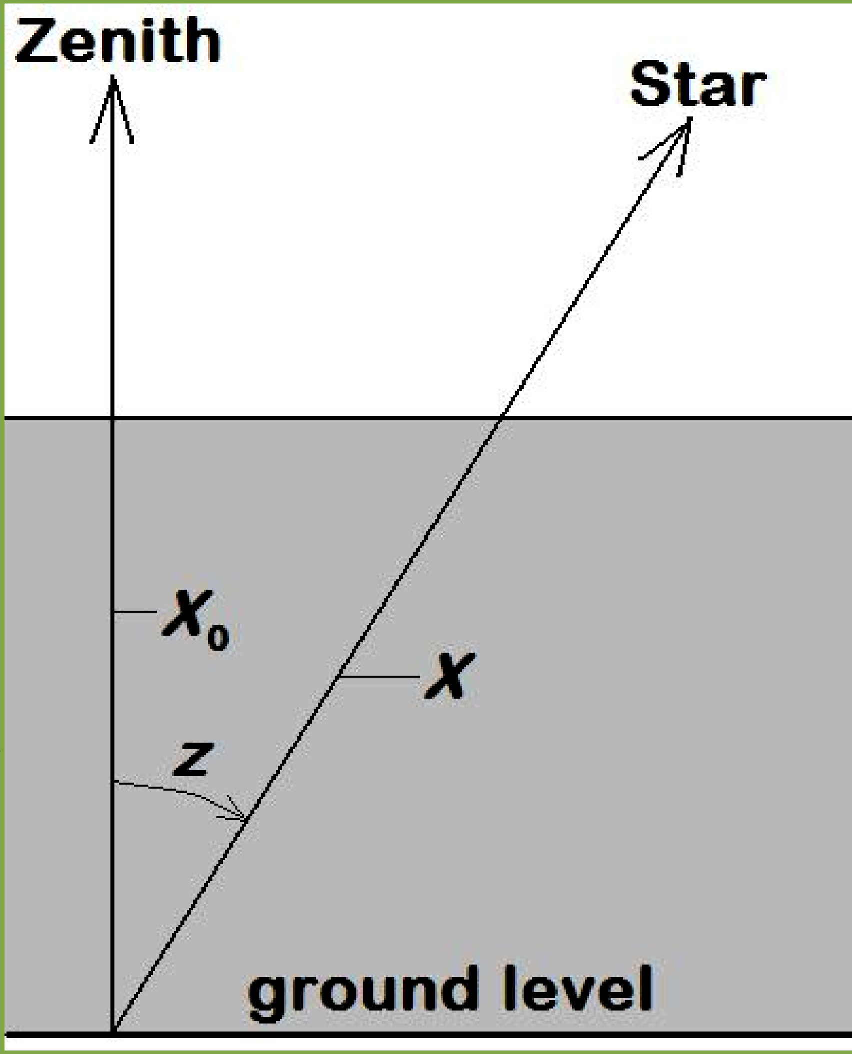
Figure 3: Overview of various filter sets (as labeled) and comparison with the spectra of an A0V (Vega), G2V (Sun) and M5V star.



HST/WFPC2 (Johnson)
HST/WFPC2 (Cousins)
HST/WFPC2 (mid-UV)
F336W F439W F555W F675W F814W
F255W F569W F791W
HST/WFPC2 (Stromgren)
F336W F410M F467M F547M F1042M
HST/WFPC2 (Wide set)
F300W F380W F450W F606W F702W F850LP
HST/NICMOS
HST/ACS WFC/HRC
F550M F110W F160W F222M
Ultra-wide J
F435W F555W F814W F175W
Ultra-wide H
F220W F250W F330W F475W F625W F775W F850LP
HST/ACS WFC/HRC (Sloan)
HST/ACS WFC/HRC (Wide)
HST/ACS HRC (mid-UV)
F606W
Wide 'V'
Vega (A0V)
Sun (G2V)
M5V
Transmission
Wavelength, λ [nm]
(c)2006 R.A. Jansen

Atmospheric Extinction Corrections

In the simple case where observations are made at small zenith distances, *z*, one can approximate the atmosphere using a flat slab model. In that case, the air mass, *X*, along the line-of-sight to a star at zenith distance *z* is given by:



$$X = \frac{X_0}{\cos z} = X_0 \sec z$$

$$X_0 \left[\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos H \right]^{-1}$$

where φ is the observer's latitude, δ is the star's declination, and H its hour angle.

The simple formula breaks down for large air masses, *X*, because of the Earth's curvature and the initial approximations.

e.g. z	$\sec z$	X
0°	1.000	1.000
30°	1.155	1.154
60°	2.000	1.995
70°	2.924	2.904
79°	5.241	5.120

Young, in *Methods in Experimental Physics*, 12A, 123, 1974, gives a simpler and more accurate formula, namely:

$$X = \sec z\left(1 - 0.0012\tan^2 z\right)$$

Air molecules decrease the light intensity of a star by the amount $dI = -I\tau_\lambda dx$, where $\tau_\lambda dx$ is the fraction of light lost through extinction over the distance dx, and τ_λ is the absorption coefficient per unit distance at wavelength λ.

So:

$$\frac{dI}{I} = -\tau_\lambda dx$$

and:

$$\int \frac{dI}{I} = \int \tau_\lambda dx$$

So:

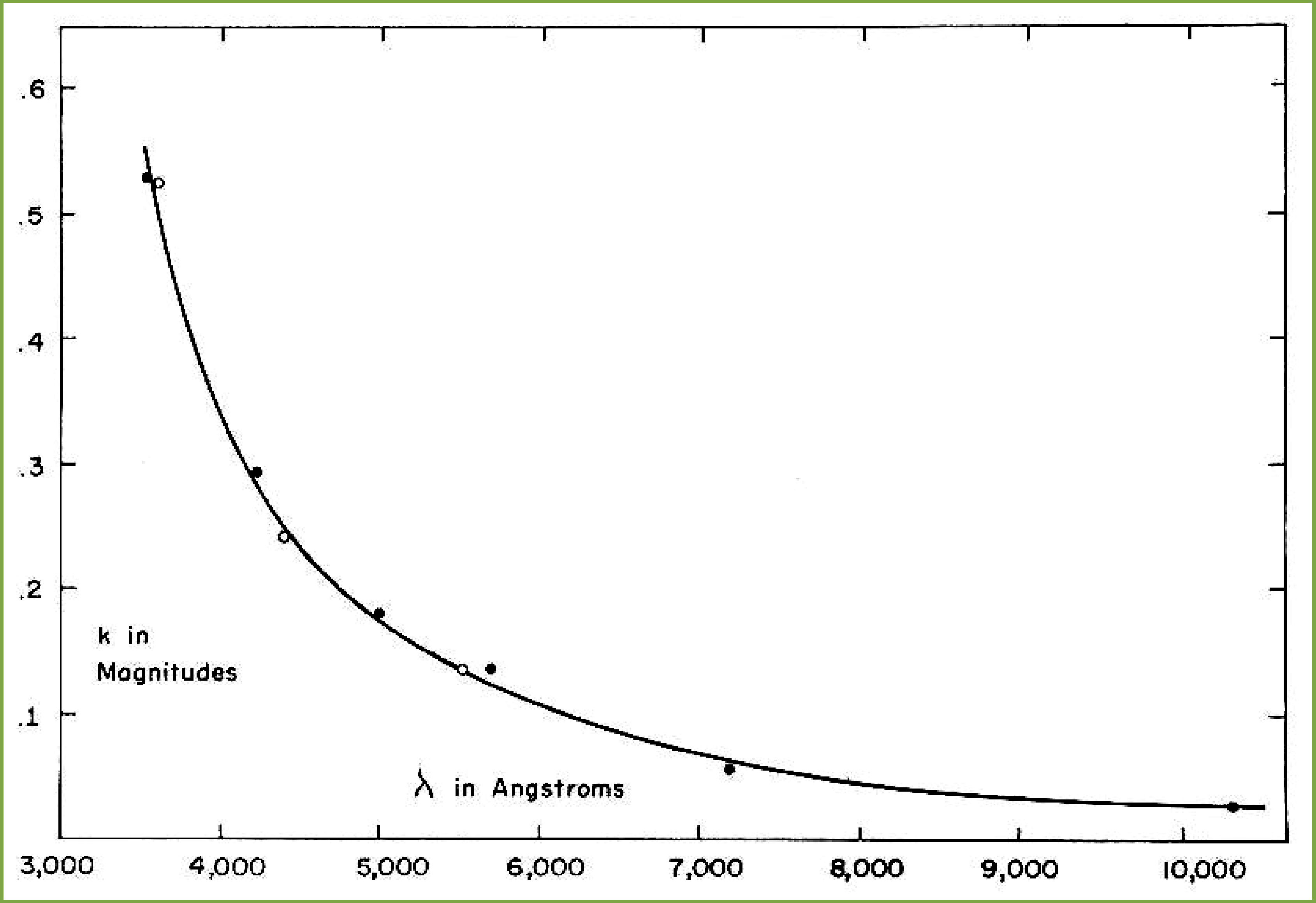
$$\log I - \log I_0 = -\tau_\lambda X$$

Since magnitudes vary as -2.5 log *I*, therefore:

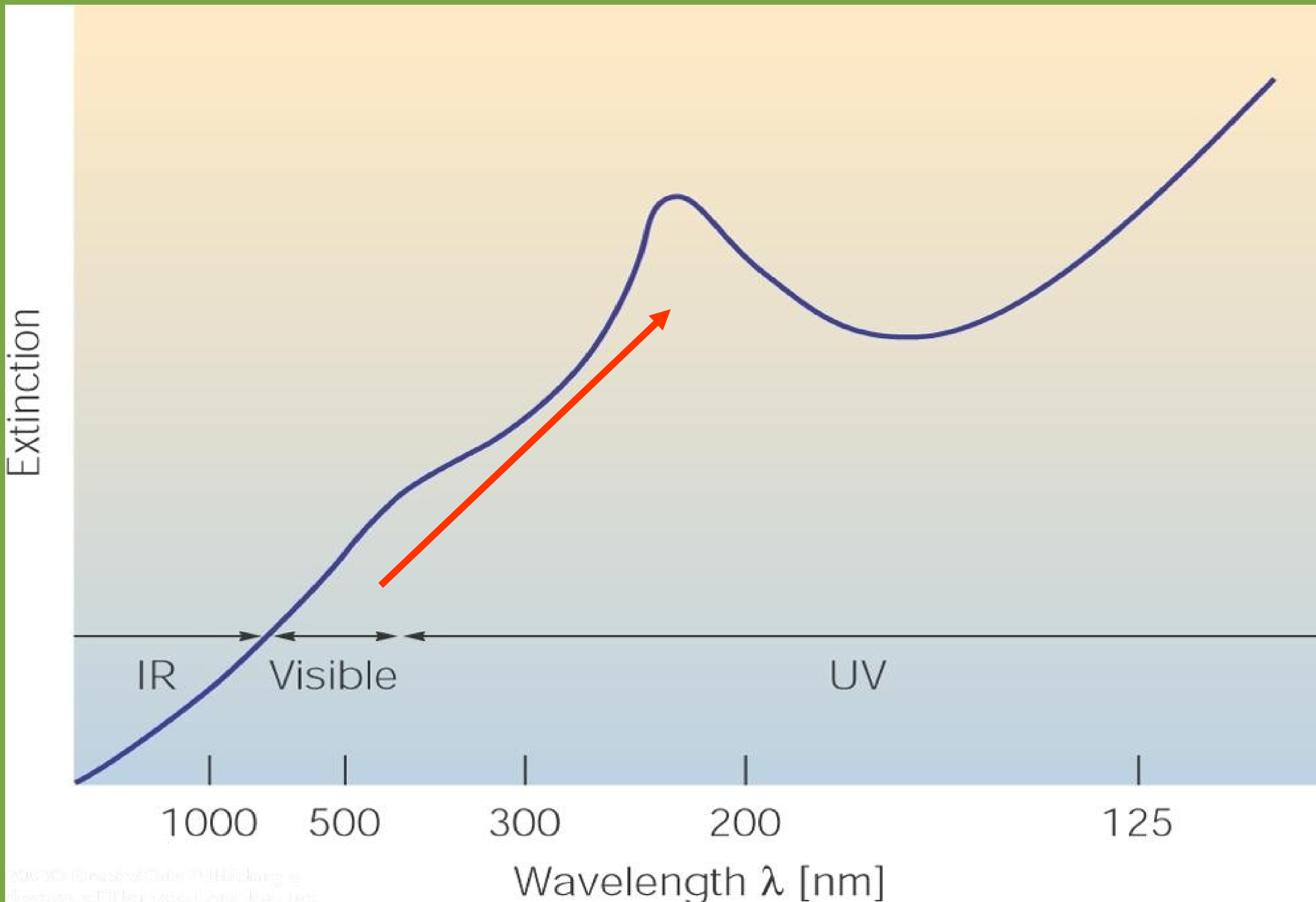
$$m = m_0 + 2.5\tau_\lambda X = m_0 + k_\lambda X$$

The extinction coefficient k_λ varies nightly with changes in moisture, air pressure, dust content of the air, etc.

Extinction is largest in the ultraviolet region and smallest in the infrared. Therefore, *k*-values increase exponentially with decreasing wavelength.

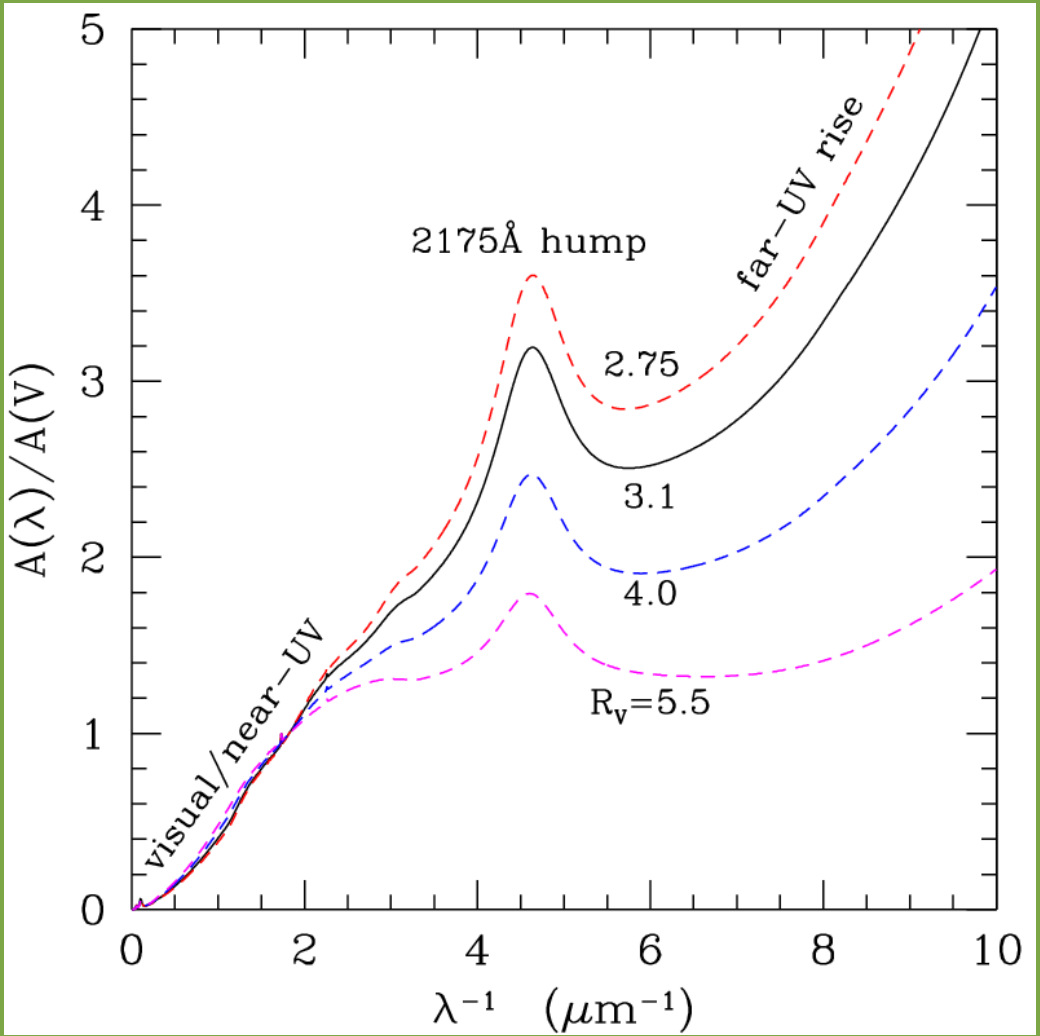


Interstellar Extinction Corrections



The Interstellar Medium absorbs light more strongly at shorter wavelengths.

Milky Way Interstellar Extinction: Grain Size



2 grain populations:

- a < 100 Å;
- a>0.1 μm;

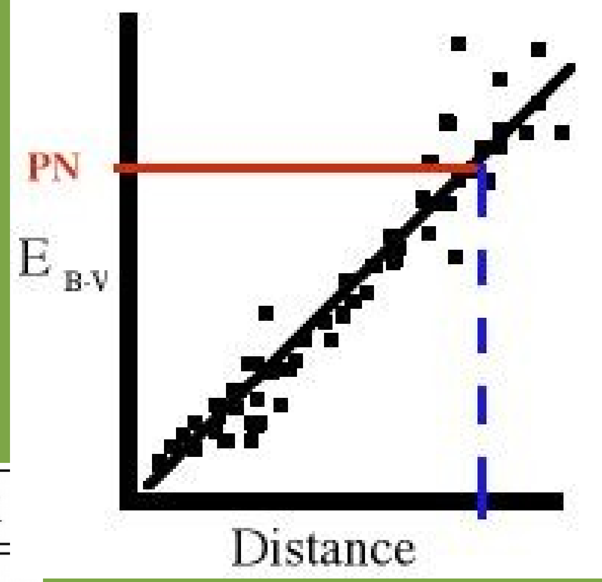
Characterized by $R_V=A_V/E(B-V)$;

- dense regions: larger R_V;
- larger $R_V \rightarrow$ larger grains;

2175 Å bump

- aromatic carbon;
- small graphitic grains or PAHs;

Effect of Extinction:



Extinction very patchy!

averages = 1.9 mags/kpc in plane of Galaxy in V

30 mags towards Galactic Centre

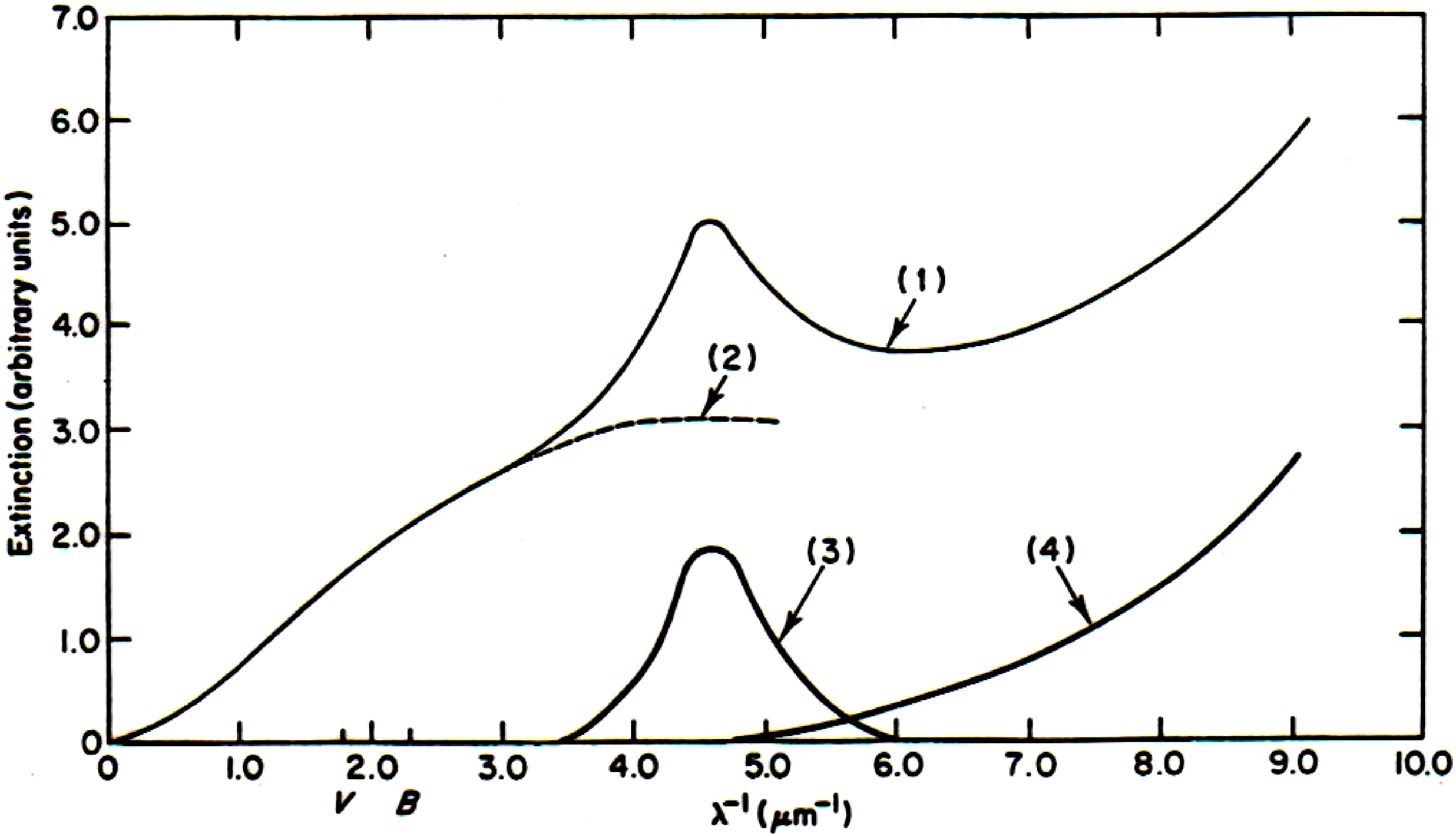
Wavelength	Extinction	Wavelength	Extinction
U (0.36 μm)	1.531	I (0.90 μm)	0.482
B (0.44 μm)	1.324	J (1.22 μm)	0.282
V (0.55 μm)	1.000	H (1.63 μm)	0.175
R (0.70 μm)	0.748	K (2.19 μm)	0.112

Effect stronger at short λ → objects appear red, hence *reddening* (e.g. Sunset)

10 mags of extinction in *V* (factor 10^4) = only 1.1 mags in *K* (IR)

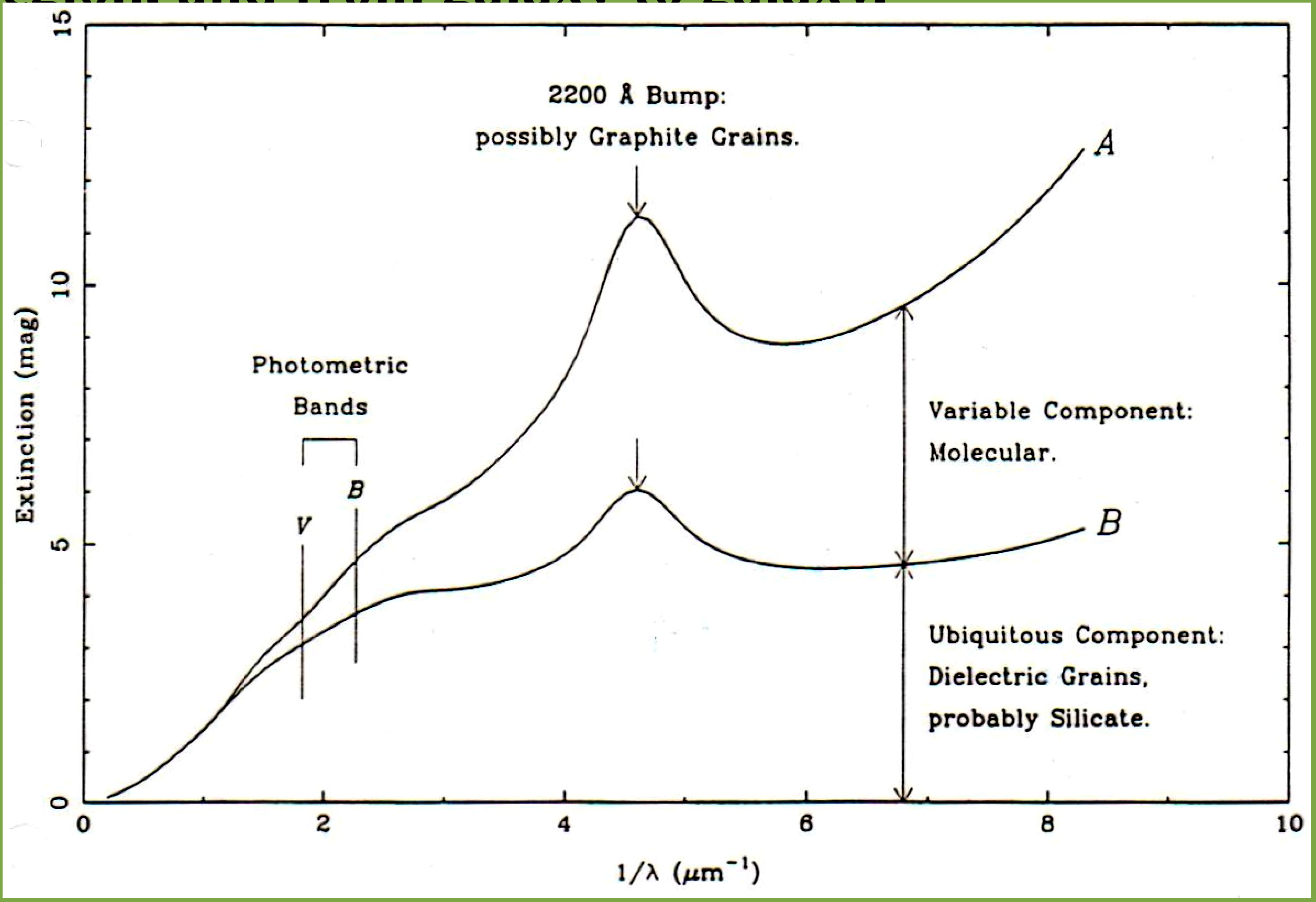
hence studies of Galactic Centre only performed in IR and beyond

The nature of interstellar extinction into the ultraviolet. The "standard" relation is shown.

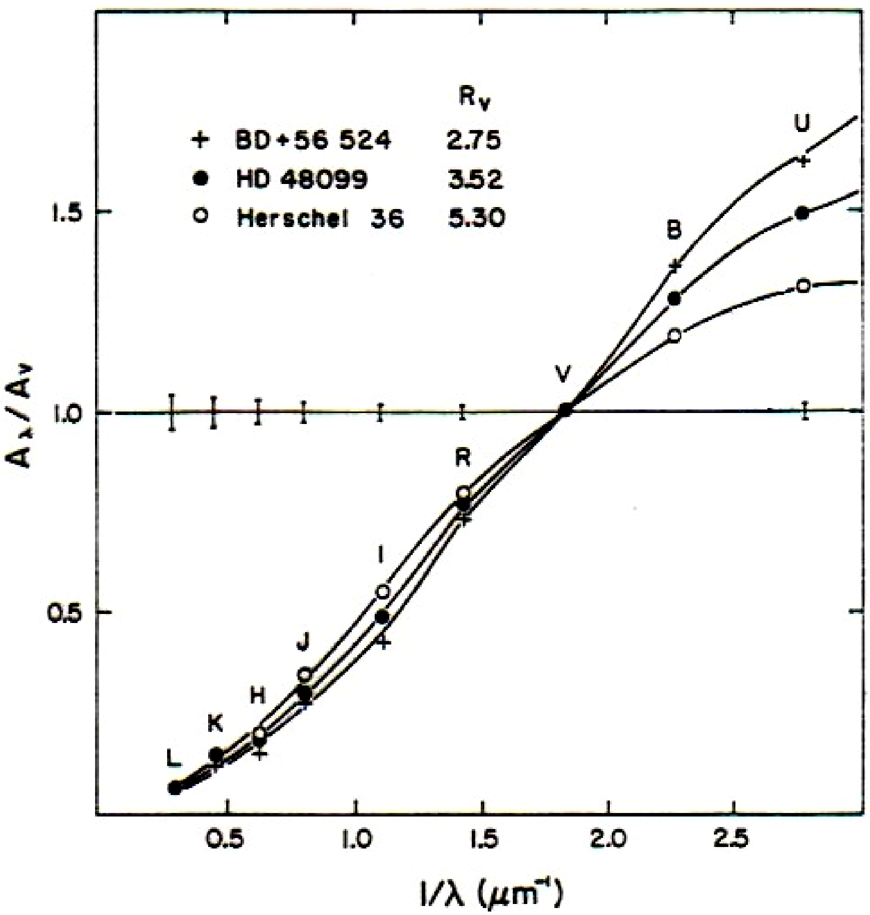


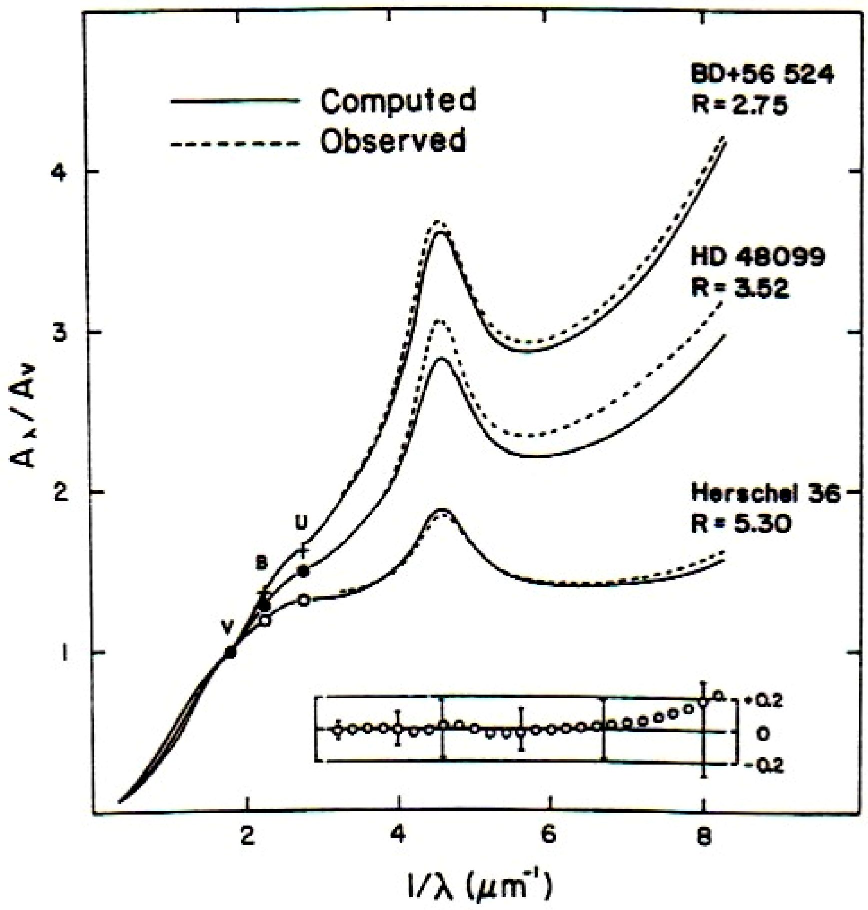
Schematic extinction curve. The mean extinction curve (1) is arbitrarily divided into portions to which the major contributions are made by classical-sized particles (2) and by very small particles (3) and (4)

The slope in the ultraviolet varies from region to region, and from galaxy to galaxy.



Examples of ultraviolet extinction extremes.





CARDELLI ET AL. (1989)

In the *UBV* system, we define the colour excesses:

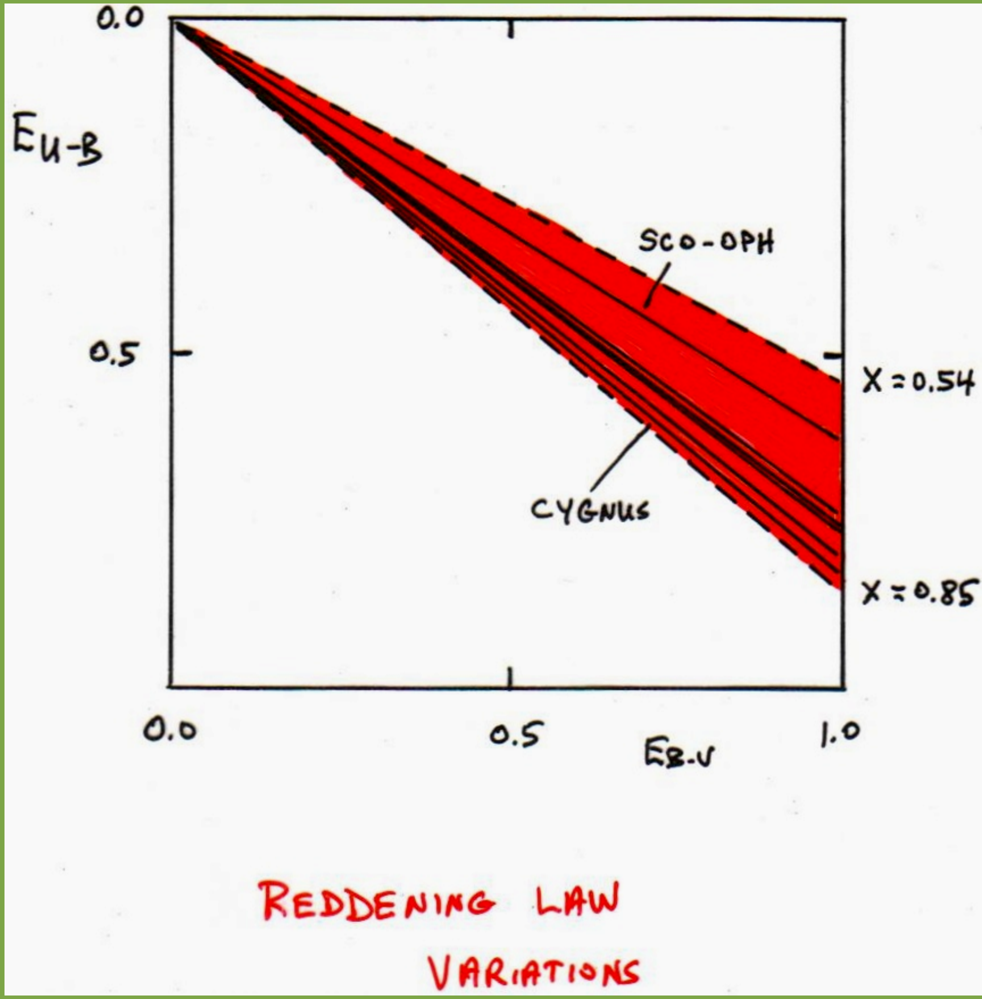
$E_{B-V} = (B-V)_{observed} - (B-V)_{intrinsic} = (B-V) - (B-V)_0$ and

$E_{U-B} = (U-B)_{observed} - (U-B)_{intrinsic} = (U-B) - (U-B)_0$,

and their ratio (~ reddening law)

$$E_{U-B} / E_{B-V} = X + Y E_{B-V}$$

X is the slope of the *UBV* reddening relation, and *Y* *(~0.02, can be ignored)* is the curvature term, which depends upon the amount of reddening.



The ratio $R = A_V/E_{B-V}$ is called the ratio of total to selective extinction, and generally is ~3.1 ±0.3 for most regions of the Galaxy.

The mean value of R seems to be slightly above the average value (~3.2) towards the anticentre and centre regions of the Galaxy (i.e. looking across spiral arms) and slightly below the average value (~2.8–3.0) looking along spiral arms (i.e. in Cygnus, etc.).

That can be explained by the preferential alignment (by the Davis-Greenstein mechanism) of dust grains by the magnetic fields associated with spiral arms.

Certain localized regions are characterized by values of R of ~5–6, which is the signature of dust pockets containing lots of particles of above-average size. Such regions are rare, and their existence is still a matter of debate in some cases (examples are Orion, Carina, etc., but see Turner 2012 where R ~ 4.0 in Carina).

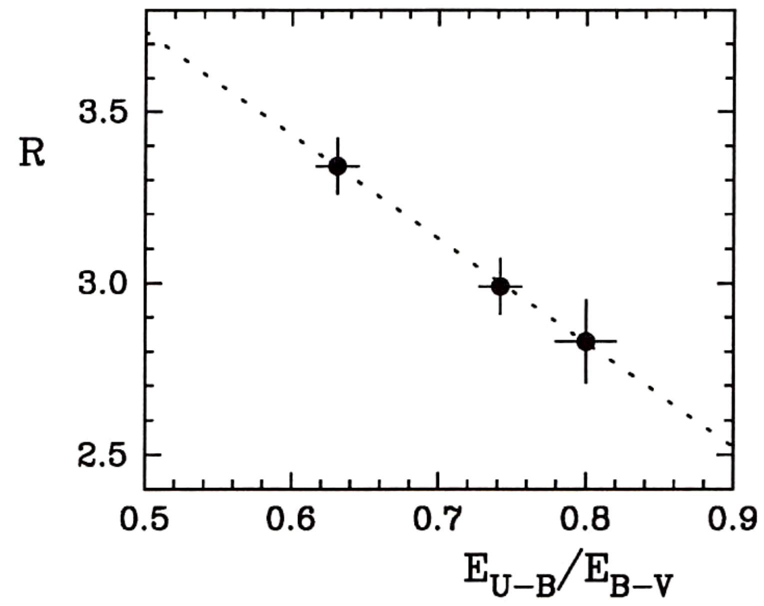


Figure 1. The dependence of the ratio of total to selective extinction $R = A_V/E_{B-V}$ on reddening slope $X = E_{U-B}/E_{B-V}$ from Turner (1994b).

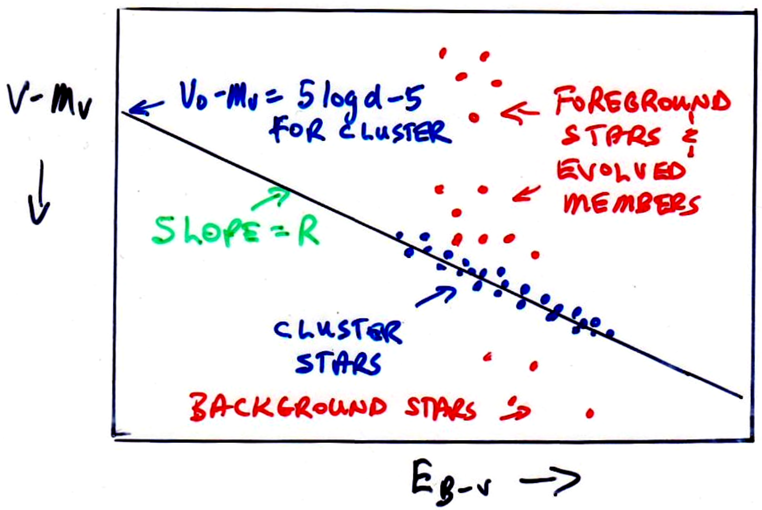
How the variable-extinction method is supposed to work (left), and the types of situations that occur in practice (right).

IN THE UBV SYSTEM,

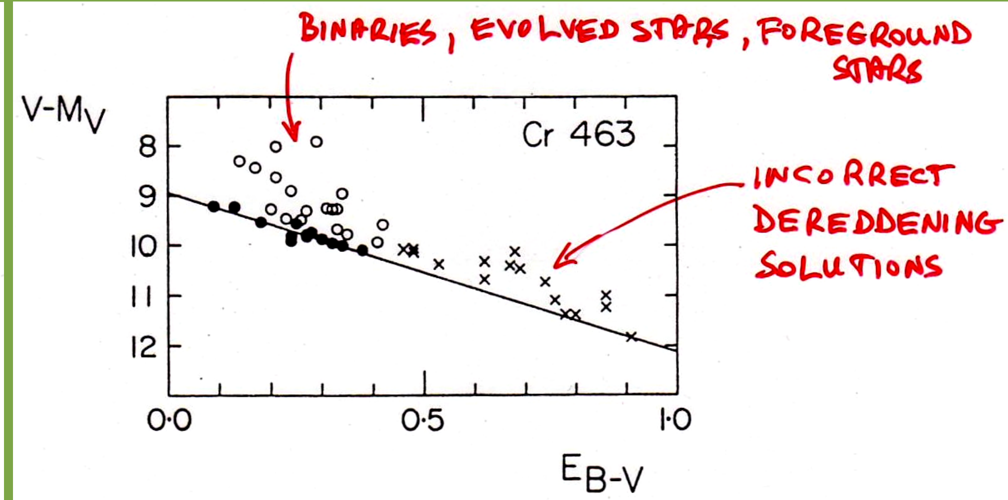
Distance modulus with extinction

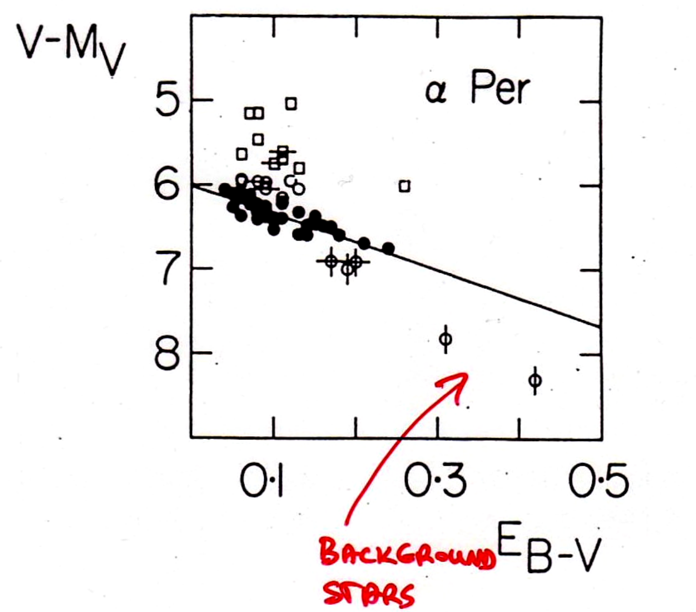
$$\underbrace{V - M_V}_{\text{DISTANCE MODULUS}} = \underbrace{5 \log d - 5}_{\text{CONSTANT FOR CLUSTER STARS}} + R \times E_{B-V}$$

i.e. $V - M_V = \text{CONSTANT} + R \times E_{B-V}$



WHEN M_V DETERMINED FROM A ZAMS.





Examples of star clusters with uniformly reddened stars.

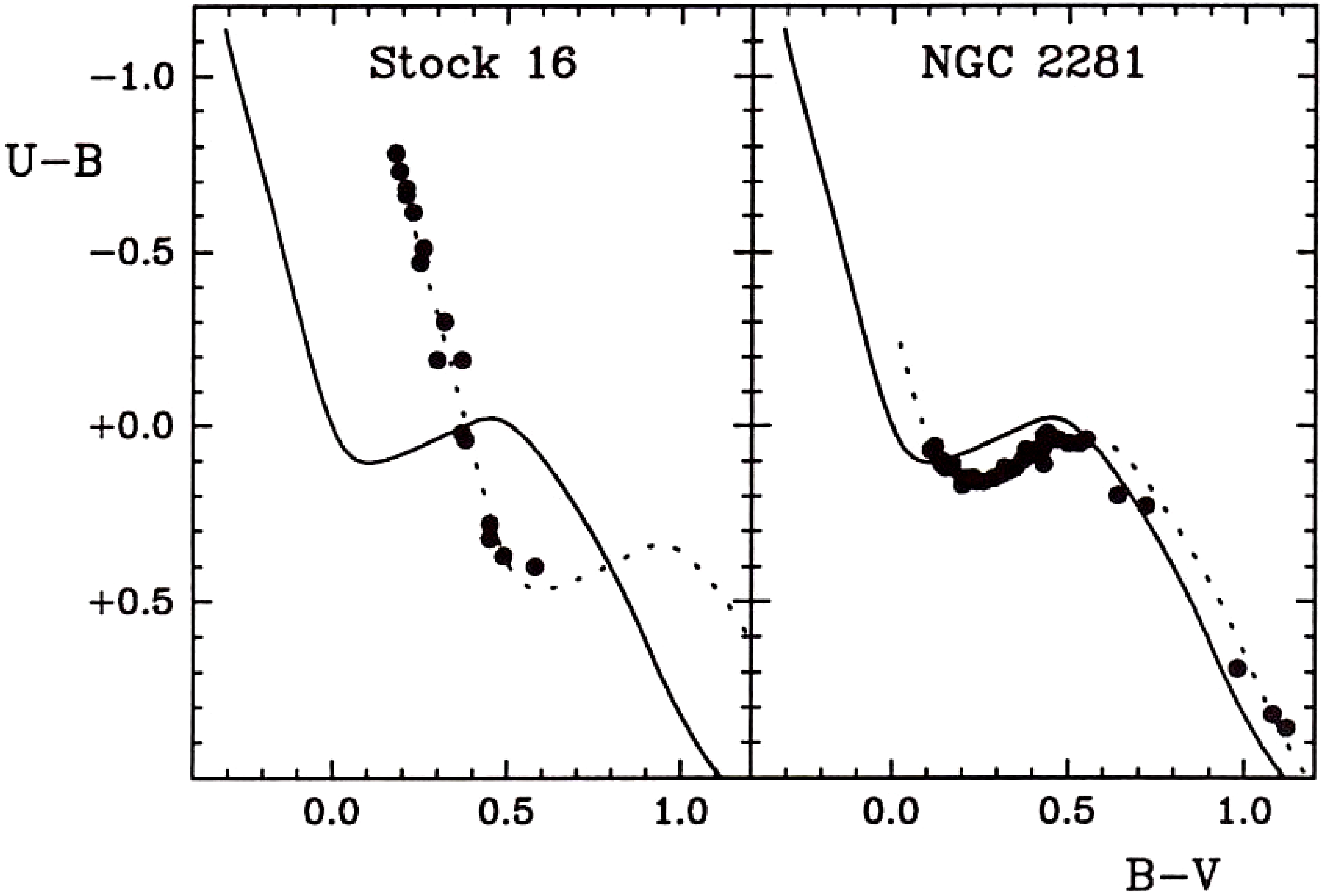


Figure 2. Color-color diagrams for Stock 16 (left) and NGC 2281 (right). The intrinsic relation for main-sequence OBAFGK stars (solid curved line) is plotted as a dotted line for the mean reddening of cluster stars.

Examples of star clusters exhibiting small (left) and large (right) amounts of differential reddening.

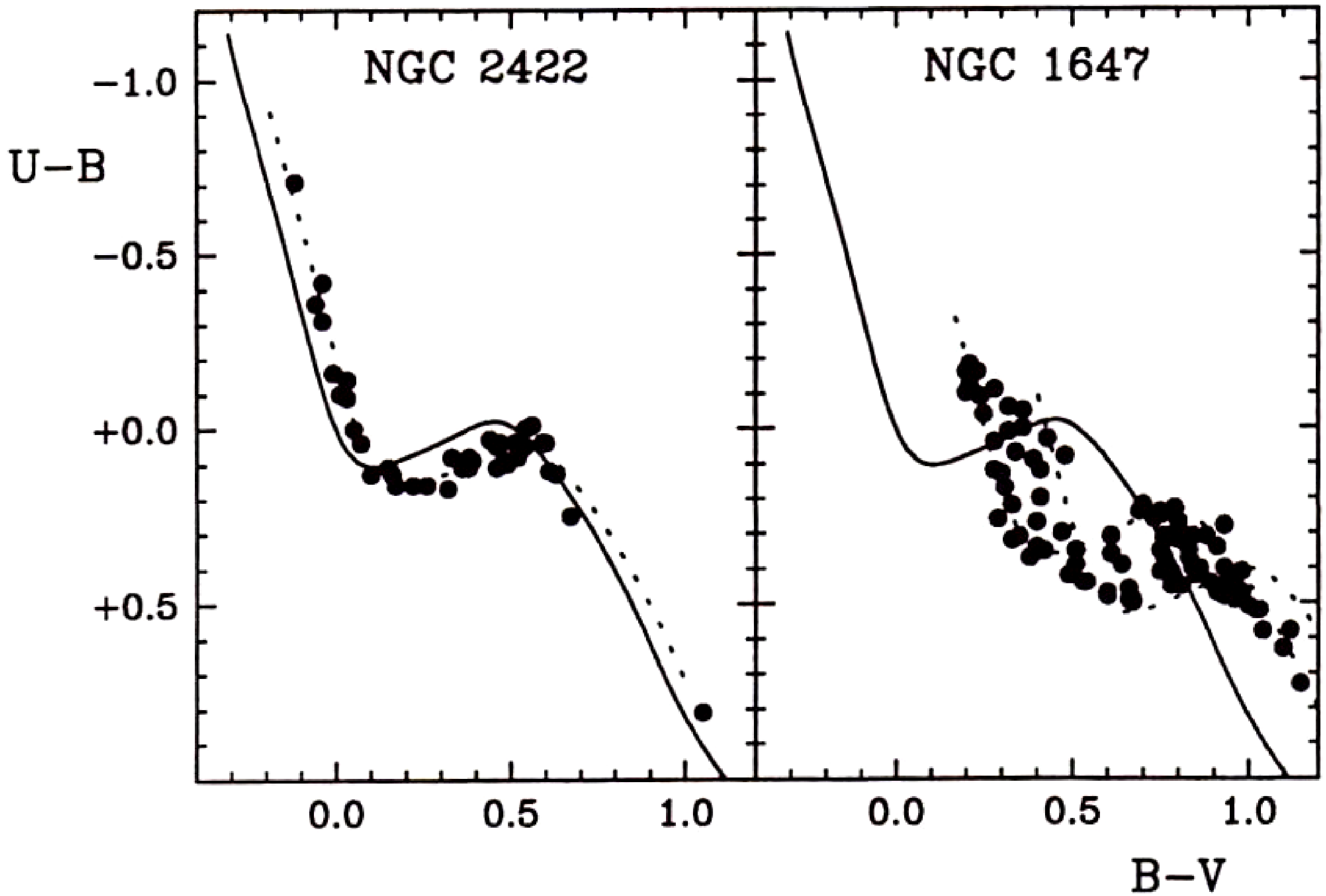
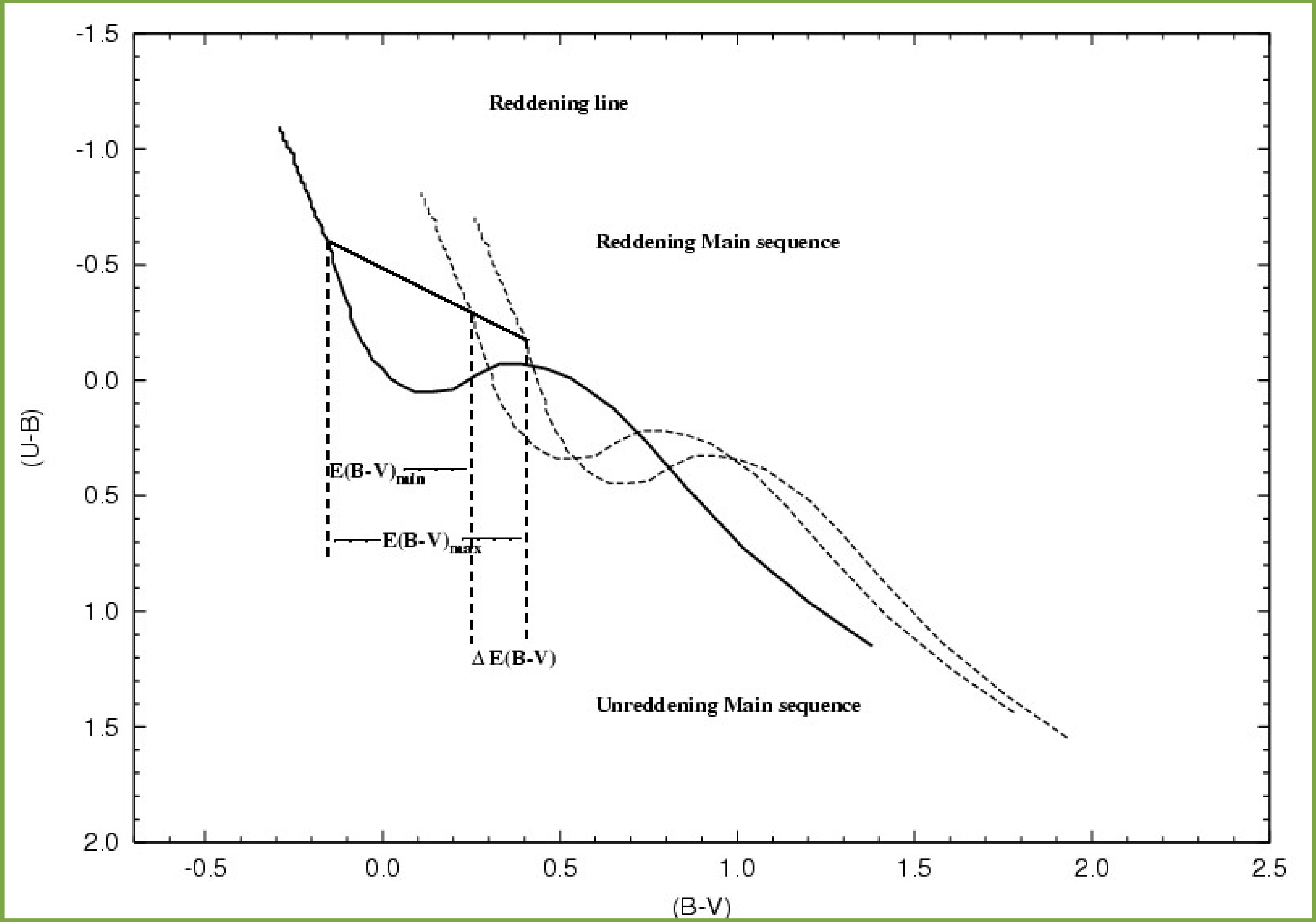


Figure 3. Color-color diagrams for NGC 2422 (left) and NGC 1647 (right). The dotted lines again represent the reddened intrinsic relation for OBAFGK stars, and for NGC 1647 both the minimum and maximum reddenings are indicated.

Reddening

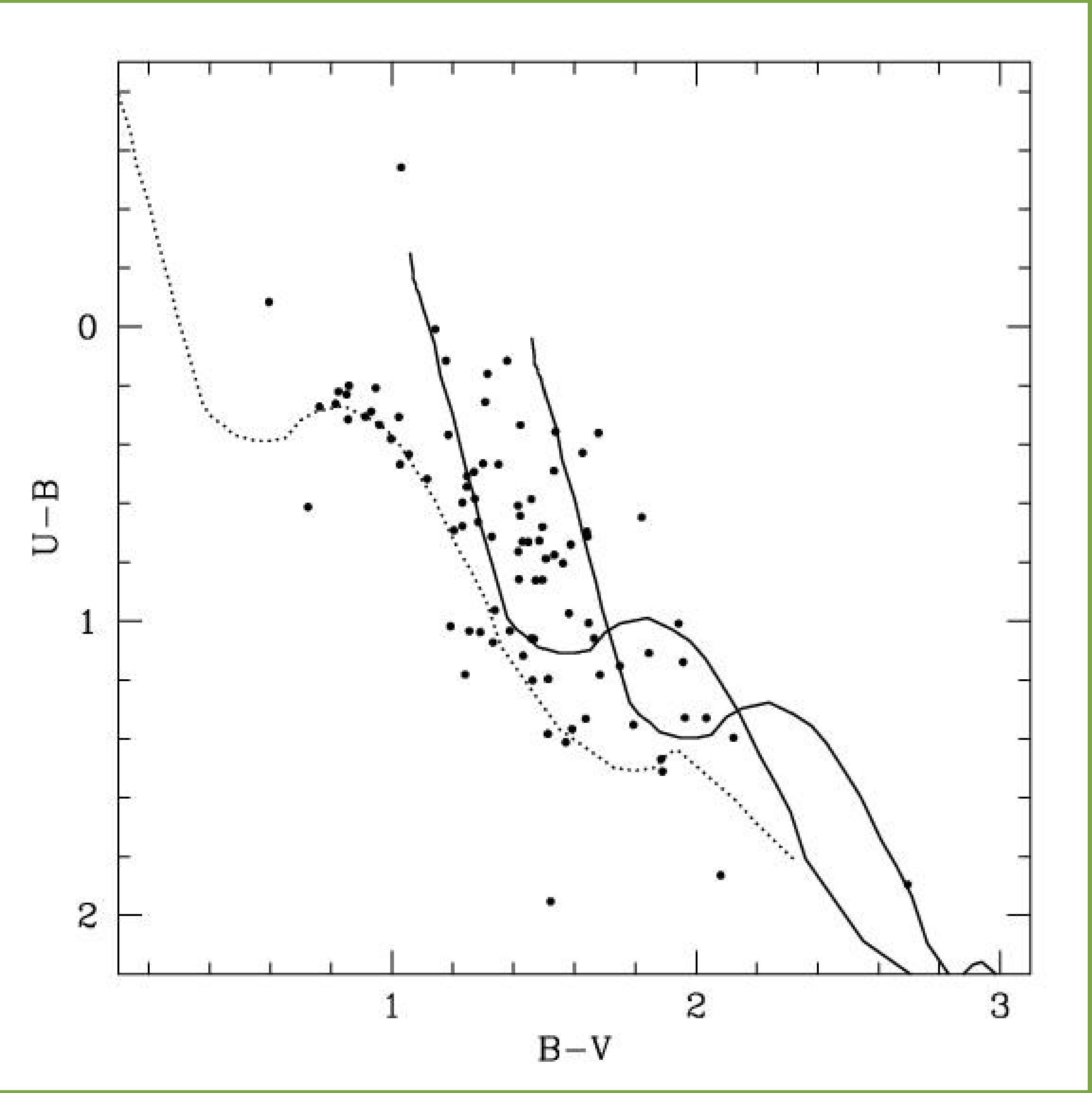
Important use of colour to measure *interstellar extinction*

$$E(B–V) = (B–V)_{Observed} - (B–V)_{intrinsic}$$ **(color excess)**



Be 59

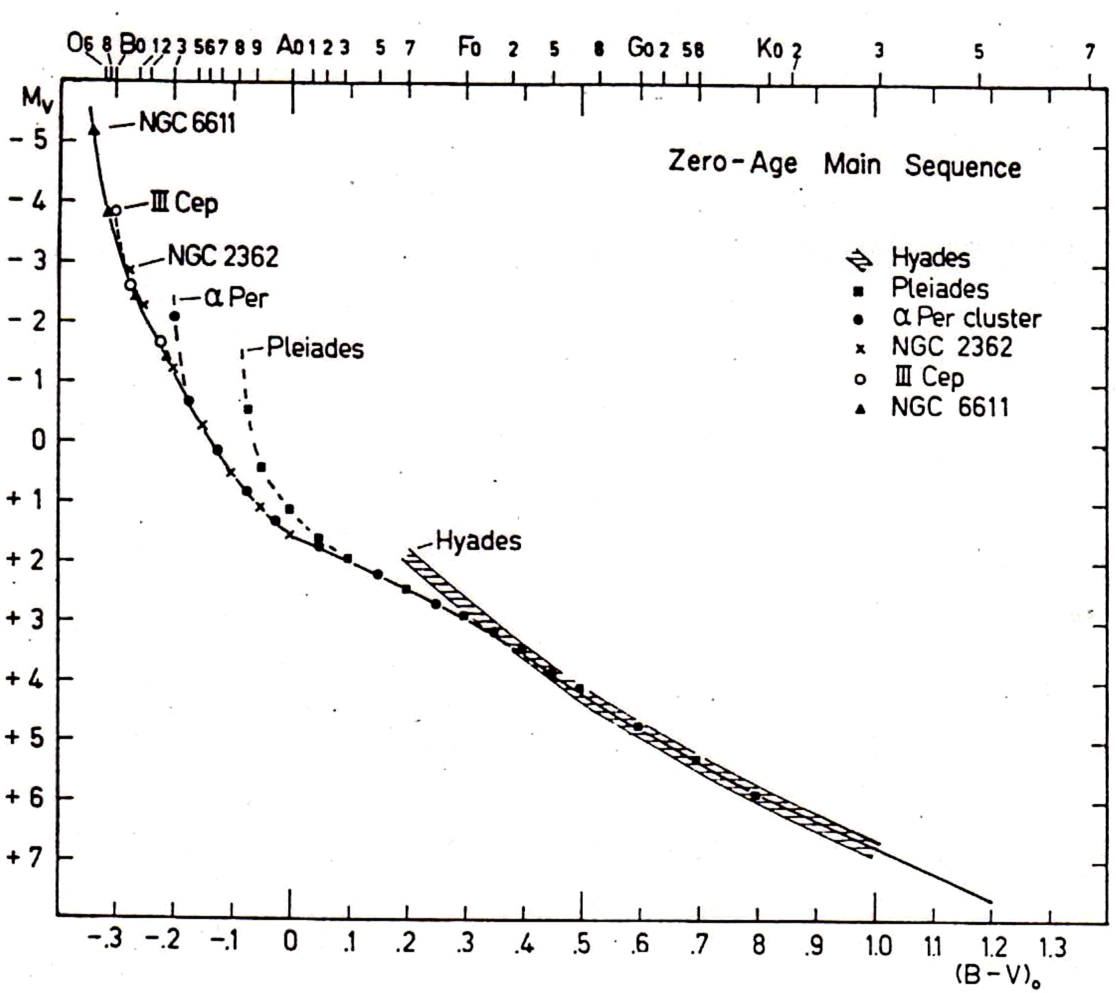
Colour excess



$(B\text{-}V)_* - (B\text{-}V)_0 = E(B\text{-}V) = 1.6 – 1.8$ mag

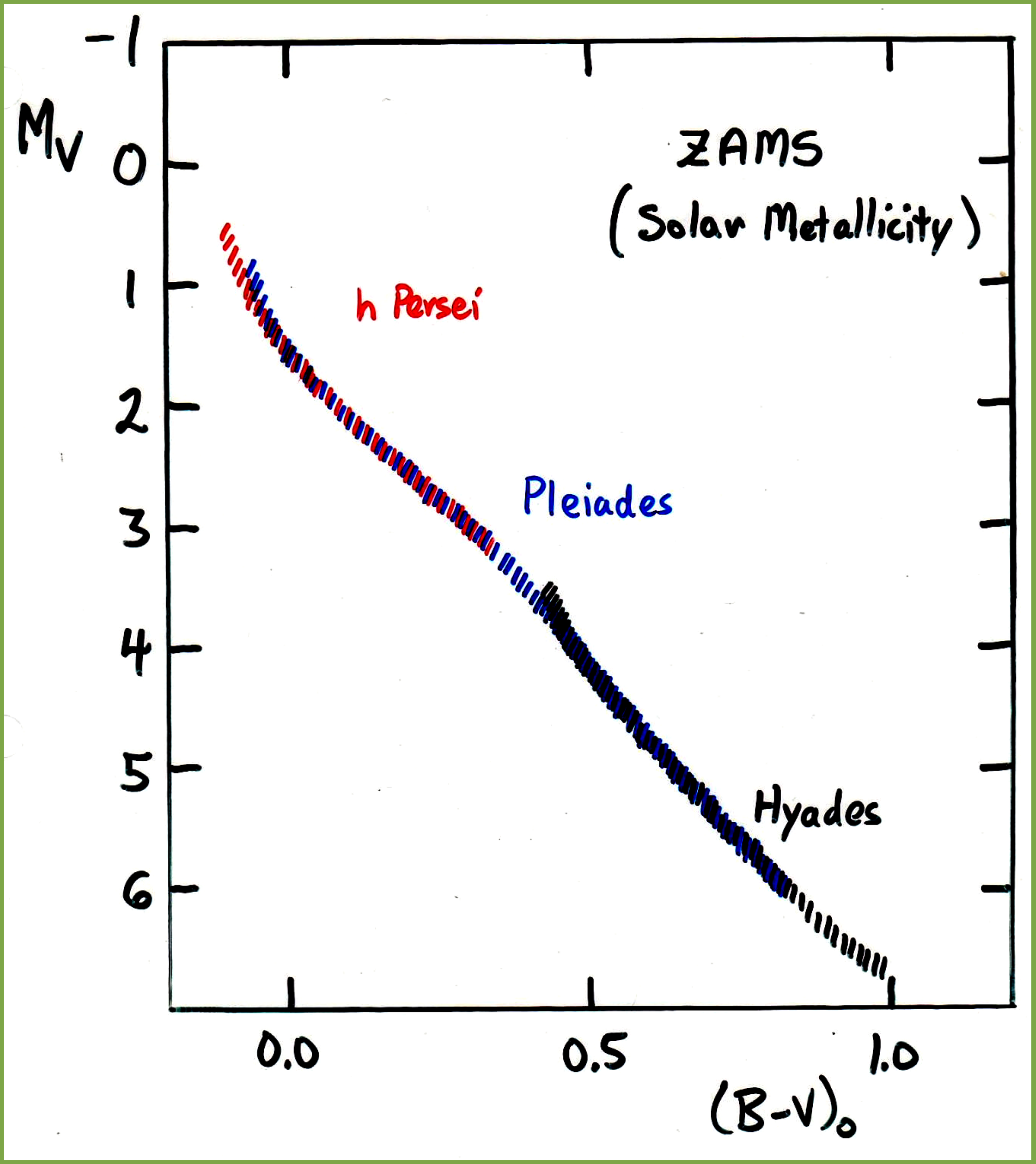
The zero-age main sequence, as constructed from overlapping the main sequences for various open clusters, all tied to Hyades stars using the moving cluster method.

BLAAUW'S (1963) ZAMS



The zero-age main sequence ("ZAMS") for visual absolute magnitudes, as defined by the non-evolved parts of the main sequences of the clusters indicated in the diagram.

The present-day zero-age main sequence (ZAMS) for solar metallicity stars.



Why it is important to correct for differential reddening in open clusters: removal of random scatter from the colour-magnitude diagram.

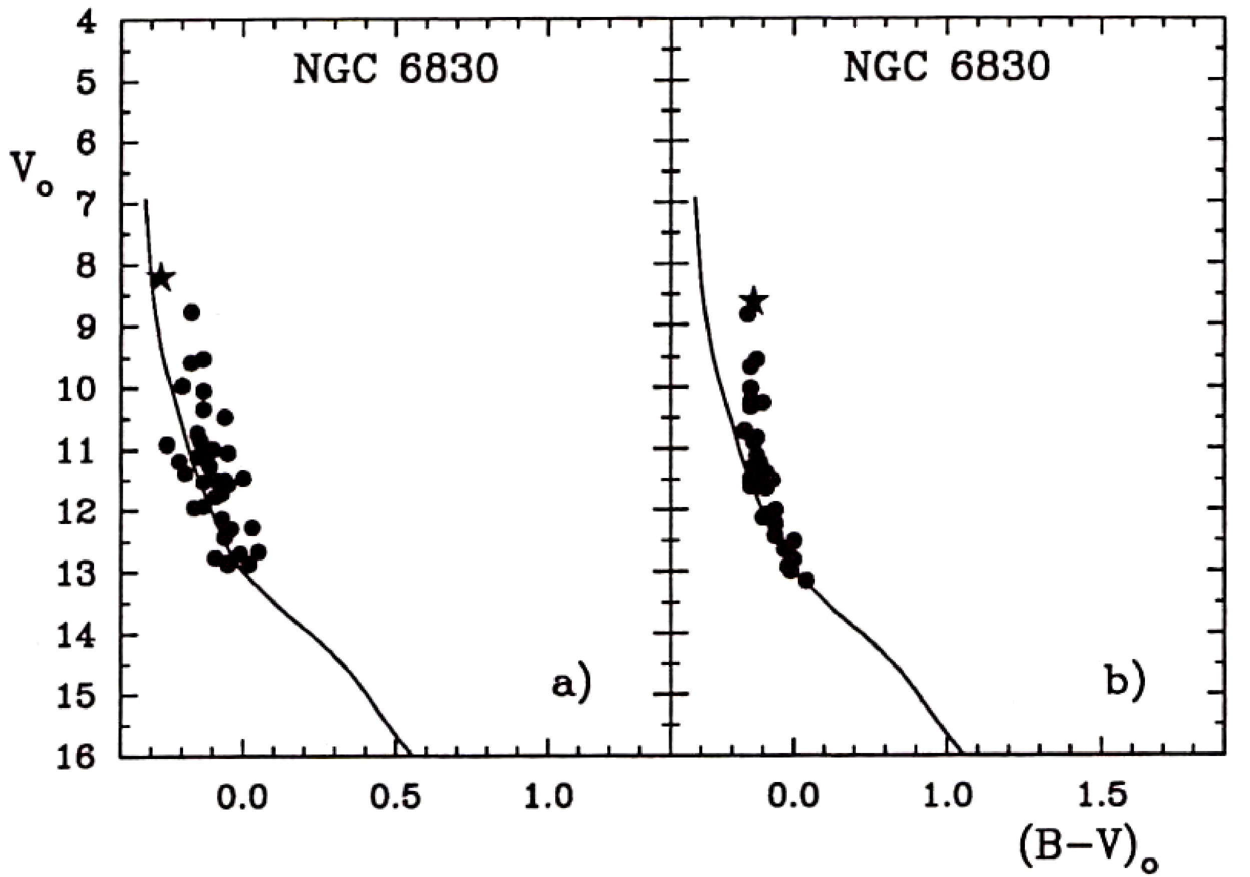
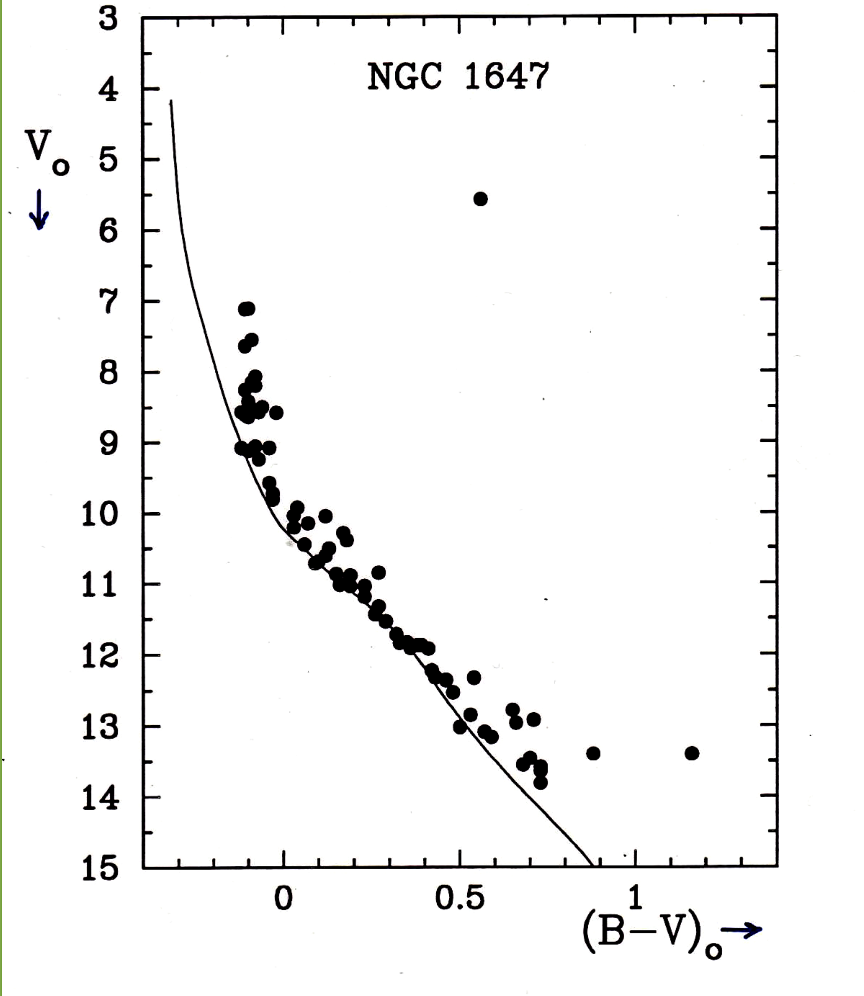
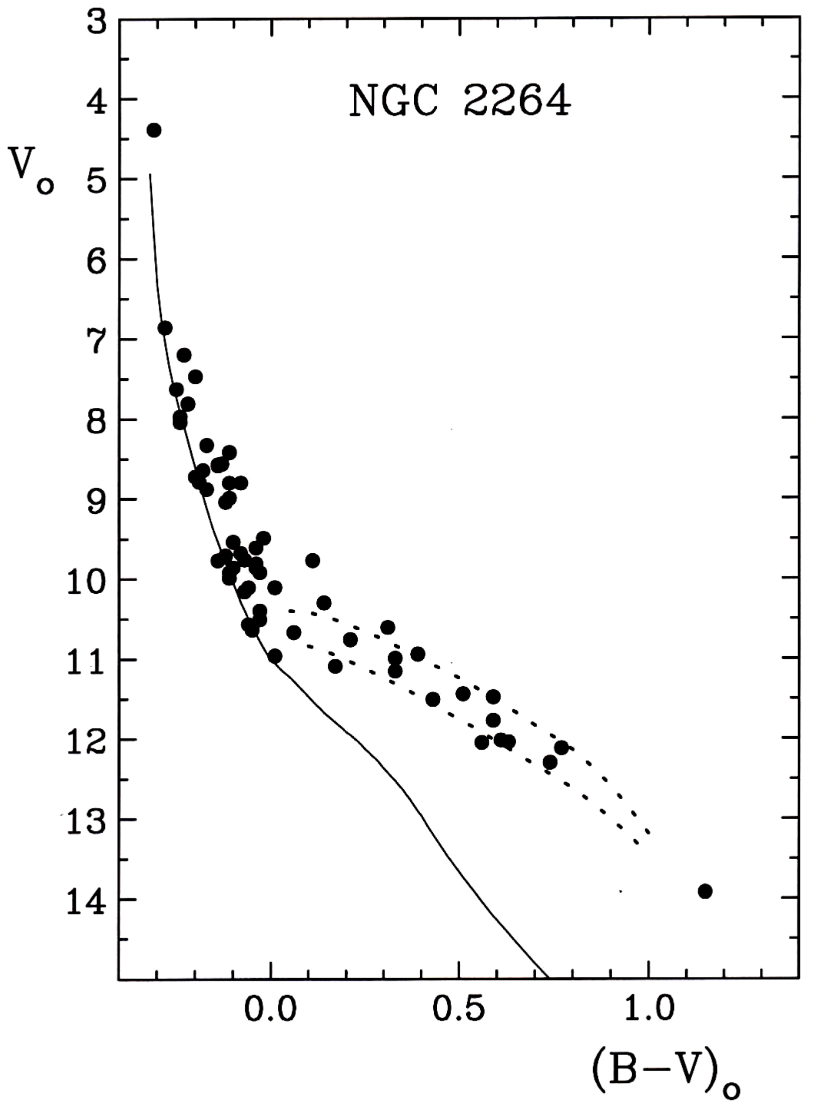


Figure 4. Unreddened color-magnitude diagrams for NGC 6830 based upon an adopted mean cluster reddening (a) and upon individual reddenings for cluster stars (b). The zero-age main sequence is the solid curved relation. The indicated star is a normal B5 III member of the evolved cluster main sequence.

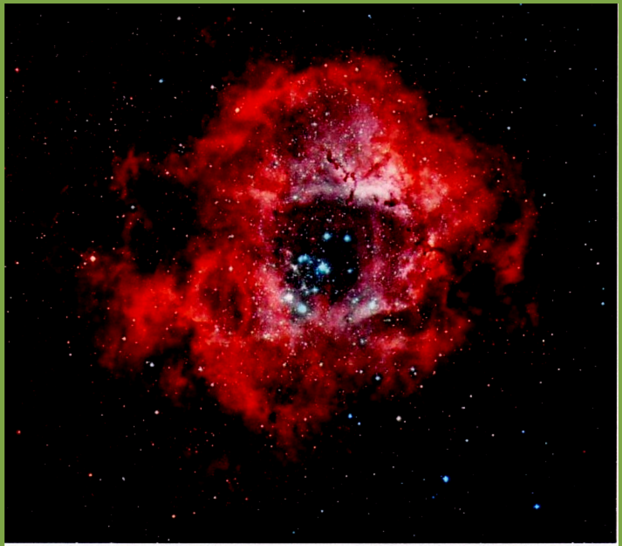
Typical open cluster colour-magnitude diagrams corrected for extinction. Note the pre-main sequence stars in NGC 2264 (right) and the main-sequence gaps in NGC 1647 (left).



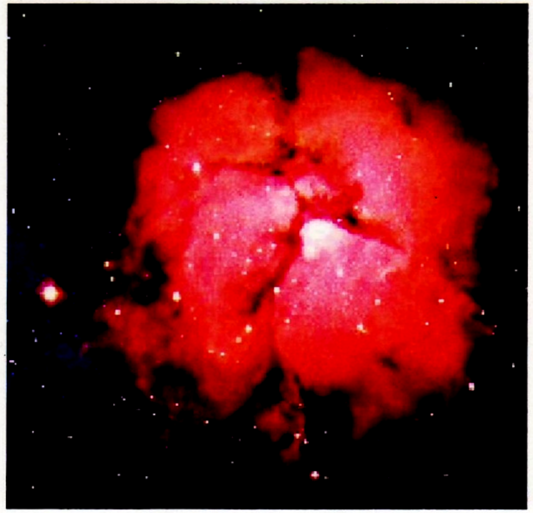
The unreddened colour-magnitude diagram for the open cluster NGC 1647.



Many young clusters are also associated with very beautiful H II regions.

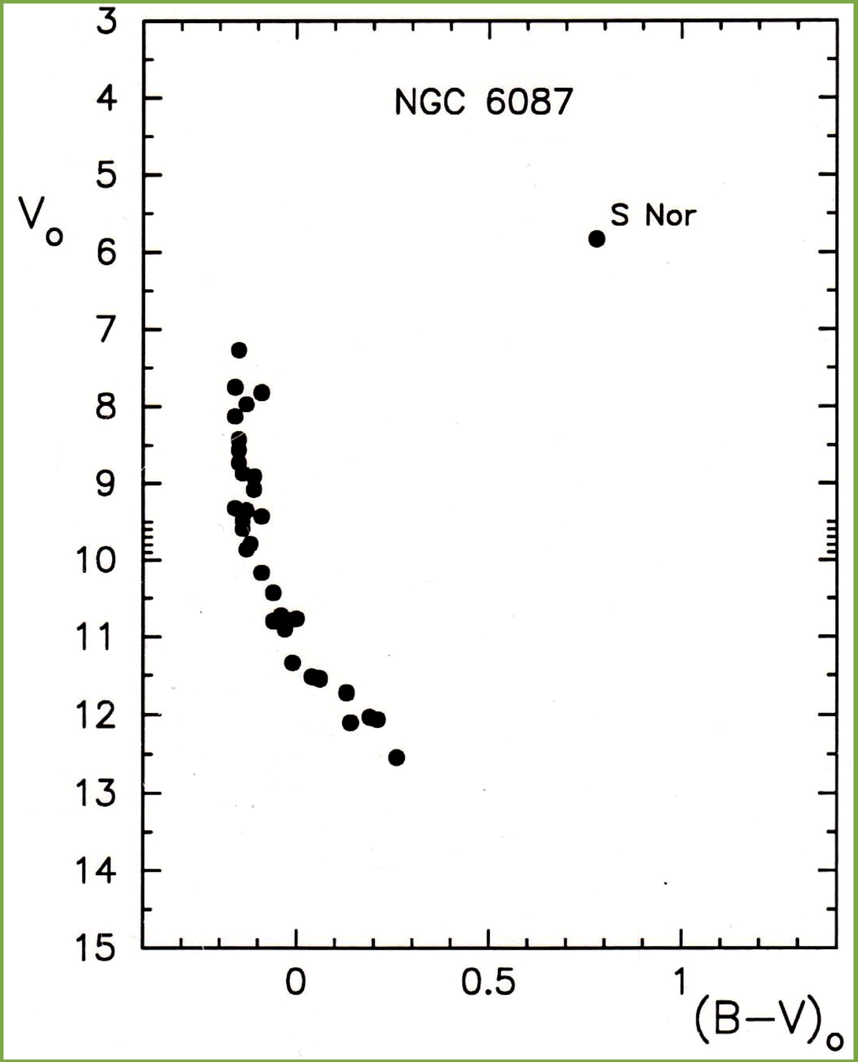


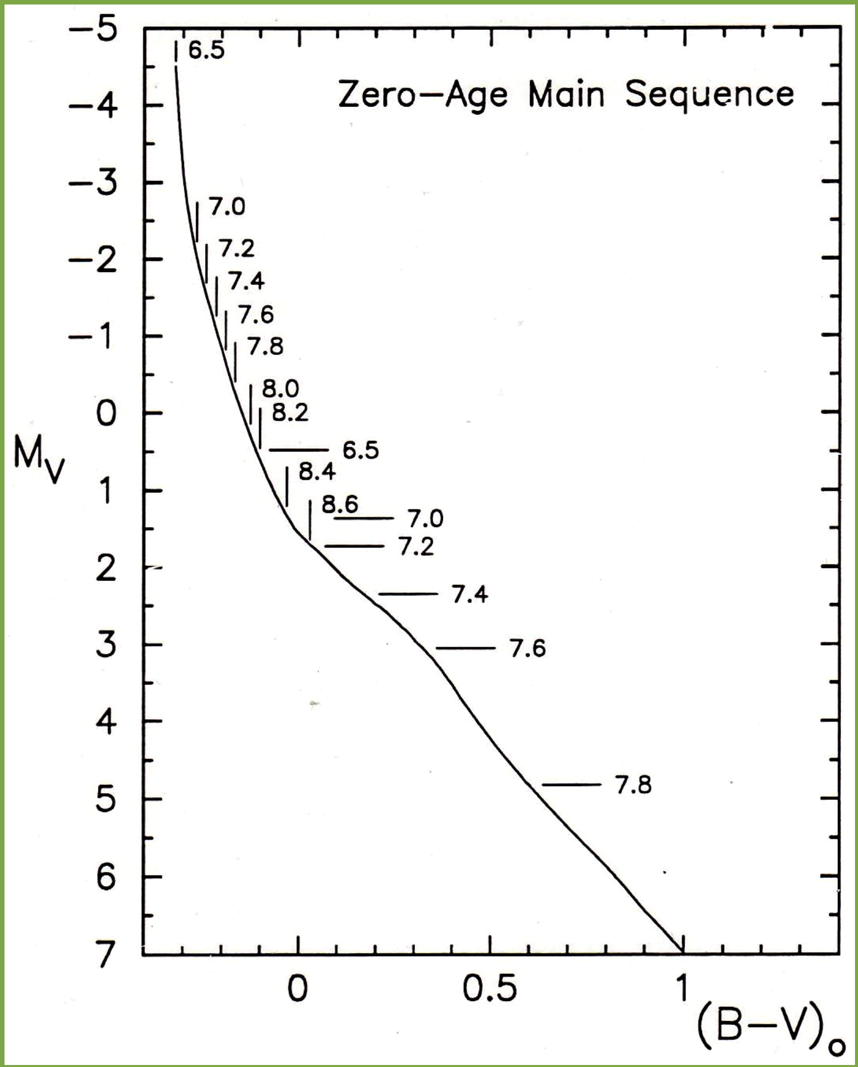
Rosette Nebula, NGC 2237-44. An example of evolved H II region.



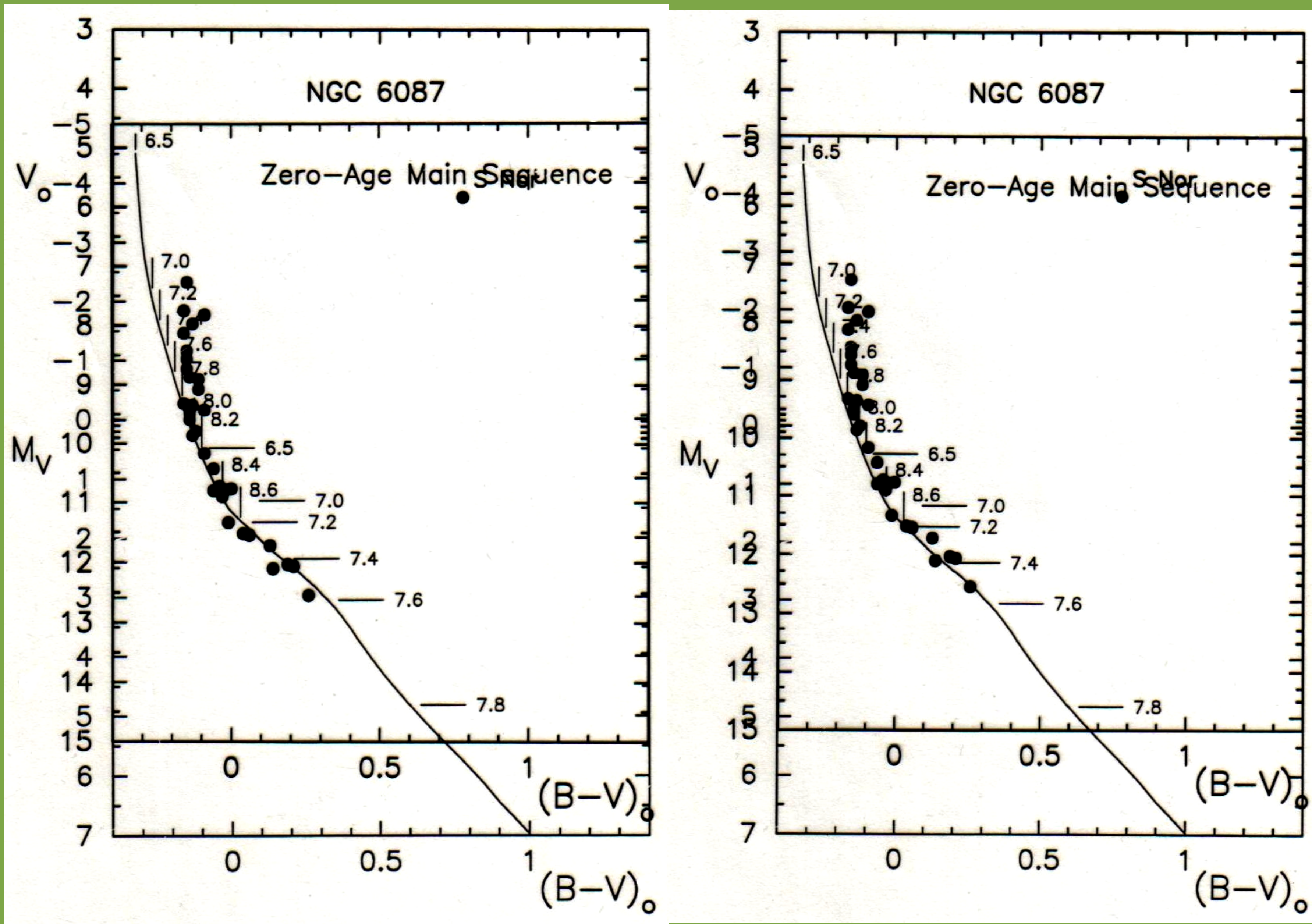
Trifid Nebula, M20. An example of a young H II region.

ZAMS fitting can be done by matching a template ZAMS (right) to the unreddened observations for a cluster (left). The precision is typically no worse than ±0.05 (~2.5%).

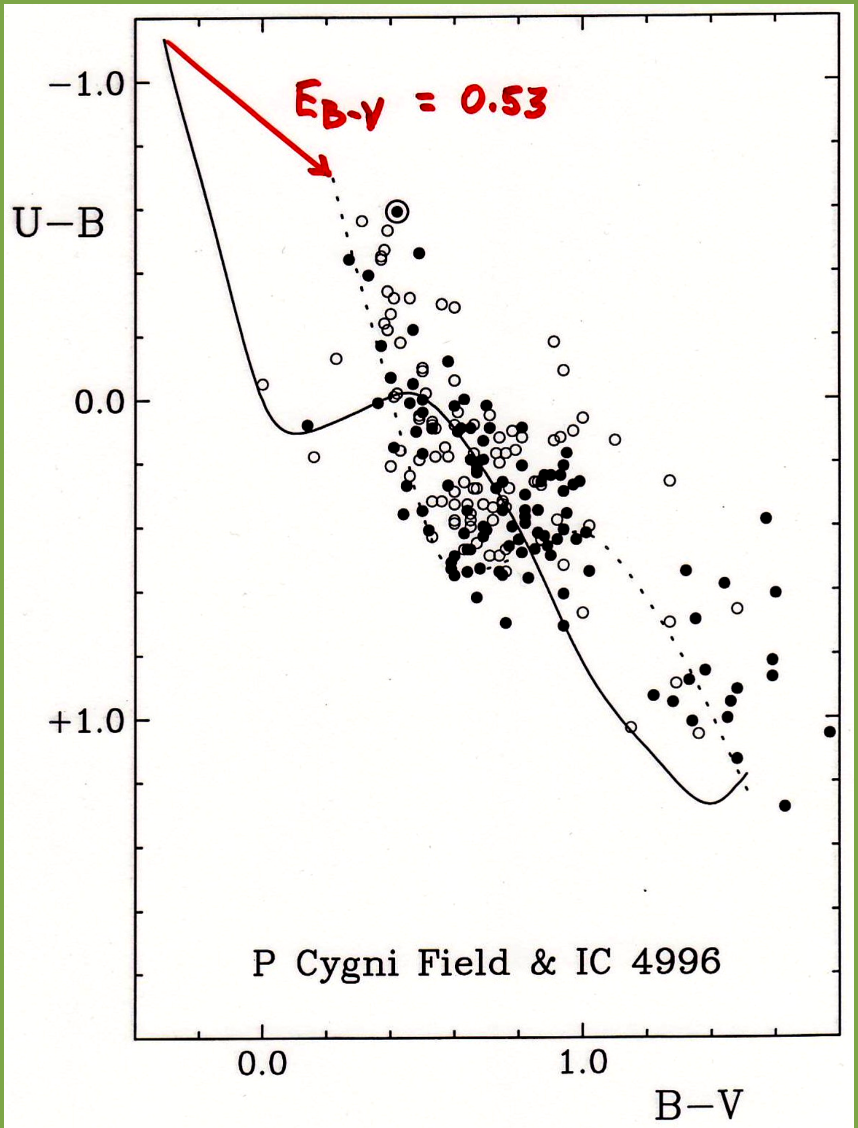


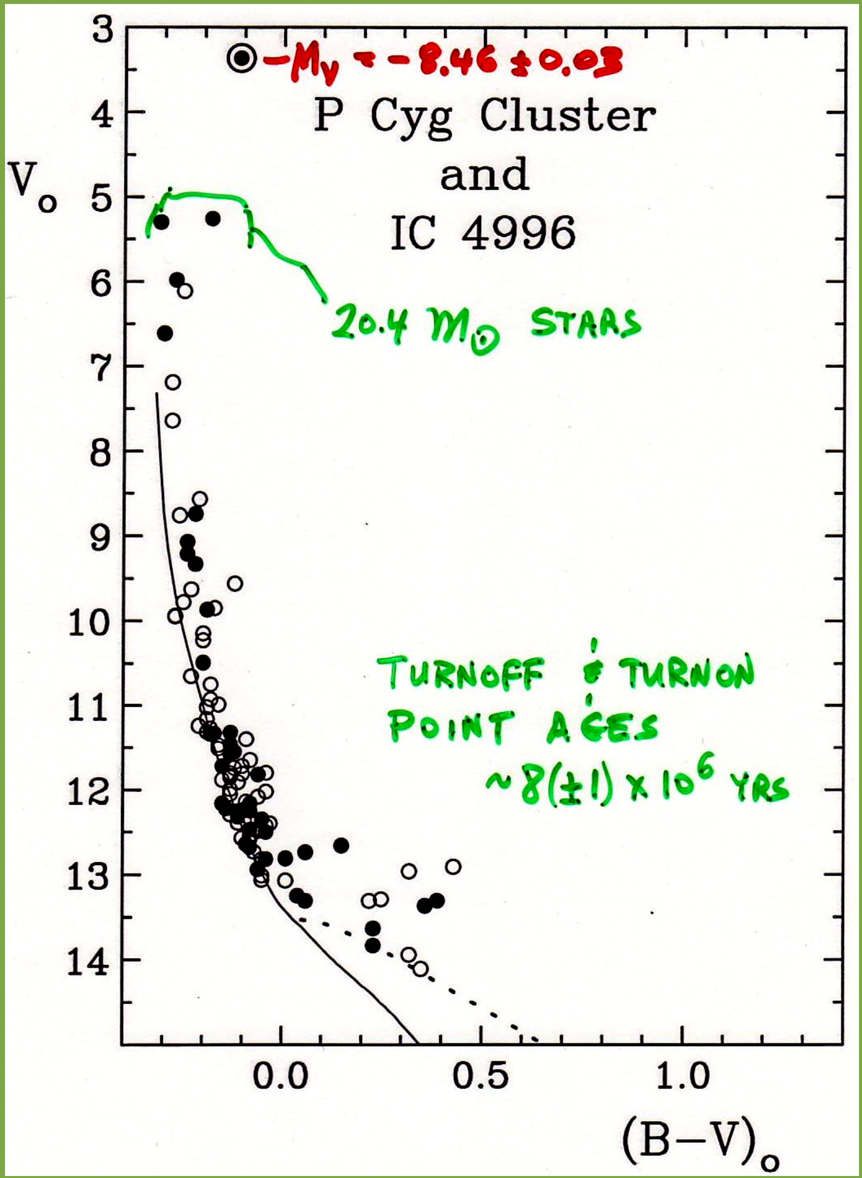


Main-sequence fitting can be good to a precision of ±0.1 magnitude (±5%) in V_0-M_V (or better) after dereddening.

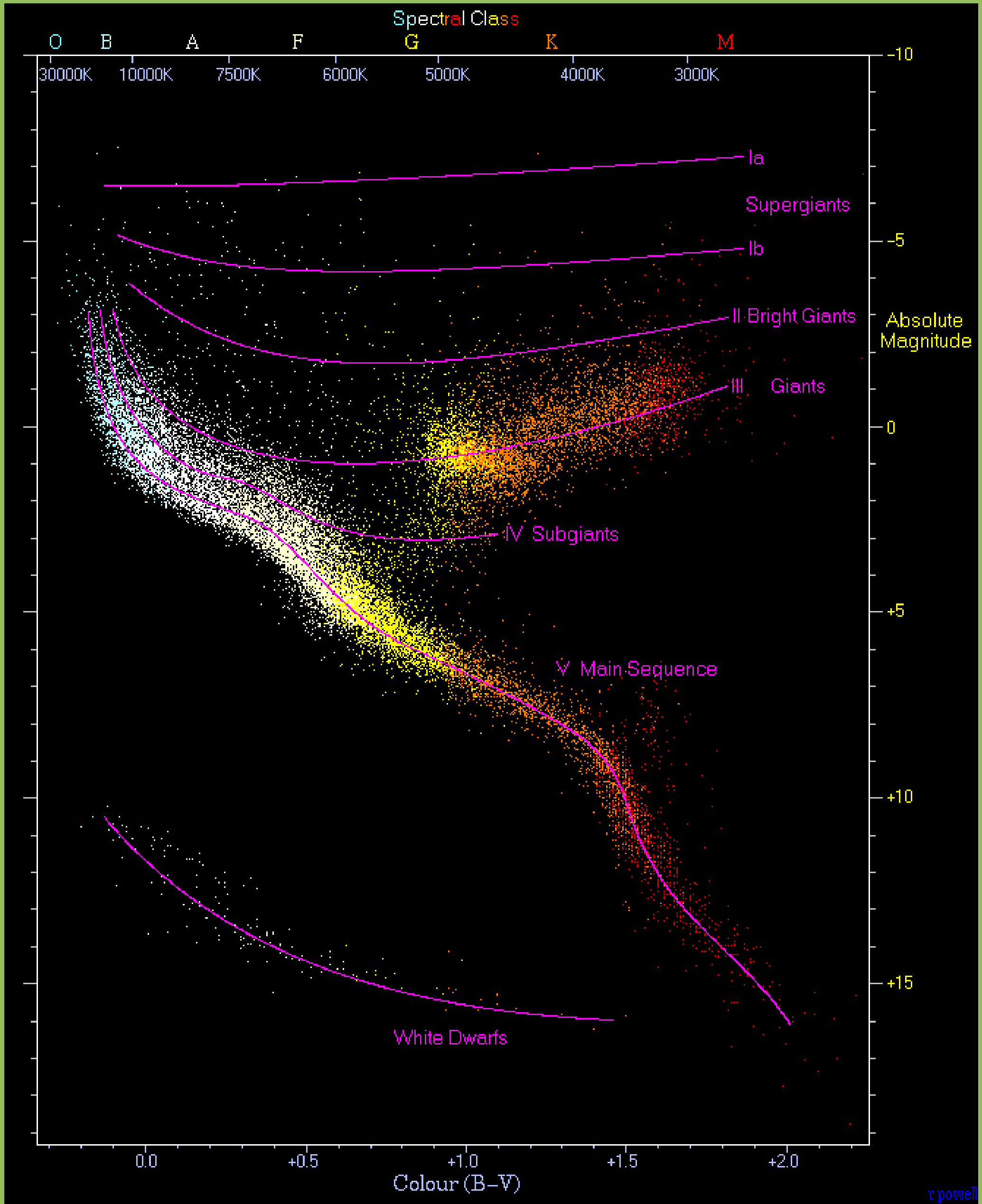


The reddening (left) and ZAMS fit (right) for the P Cygni cluster, an example of the usefulness of cluster studies.





The colour-magnitude diagram



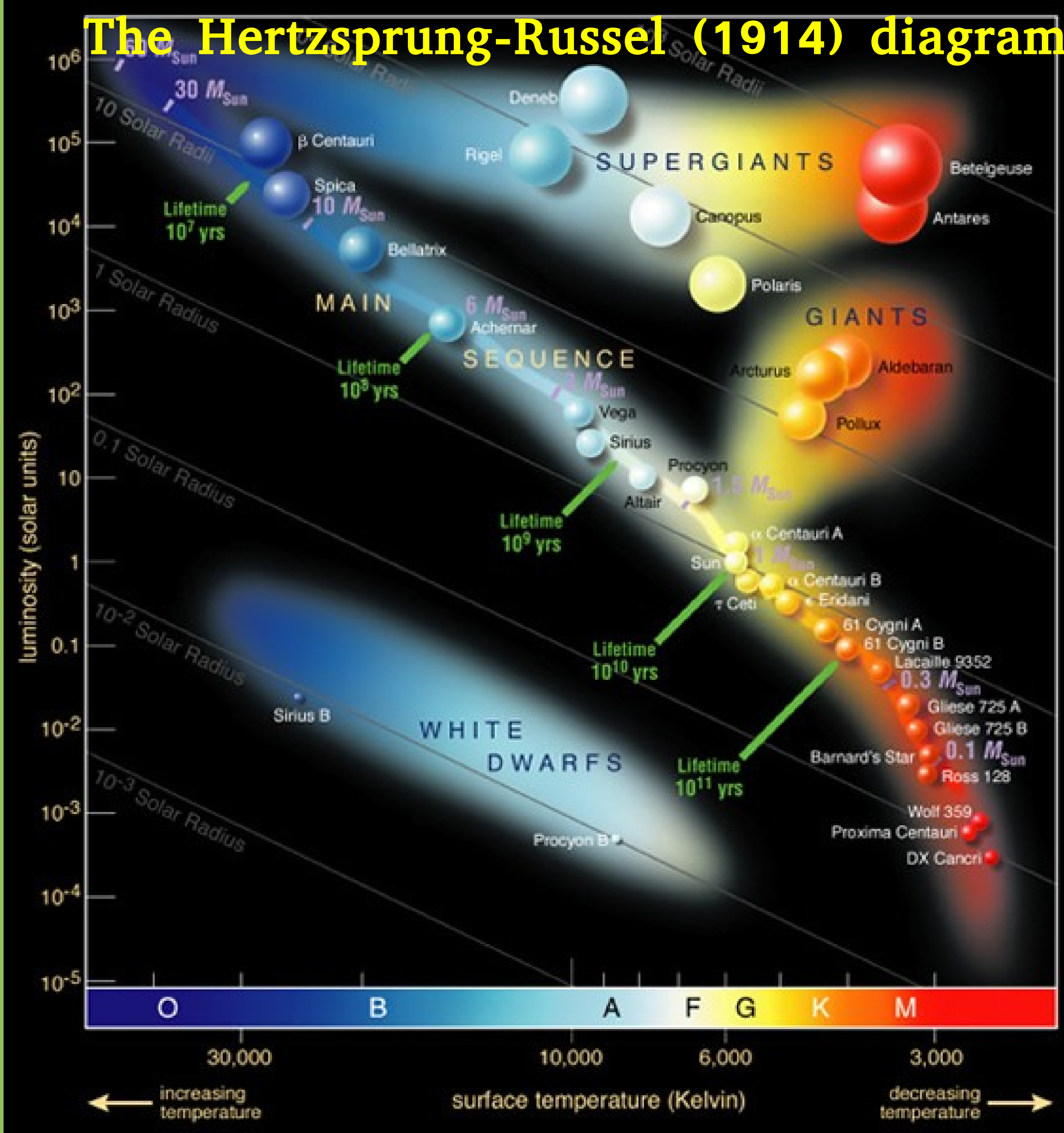
Precise parallax measurements allow us to plot a *colour-magnitude diagram* for nearby stars.

- The Hertzsprung-Russel (1914) diagram proved to be the key that unlocked the secrets of stellar evolution
- Colour is independent of distance, since it is a ratio of fluxes:

$$\frac{f_{red}}{f_{blue}} = \frac{4\pi r^2 L_{red}}{4\pi r^2 L_{blue}} = \frac{L_{red}}{L_{blue}}$$

- Absolute magnitude (y-axis) requires measurement of flux *and* distance

The Hertzsprung-Russel (1914) diagram




Thanks