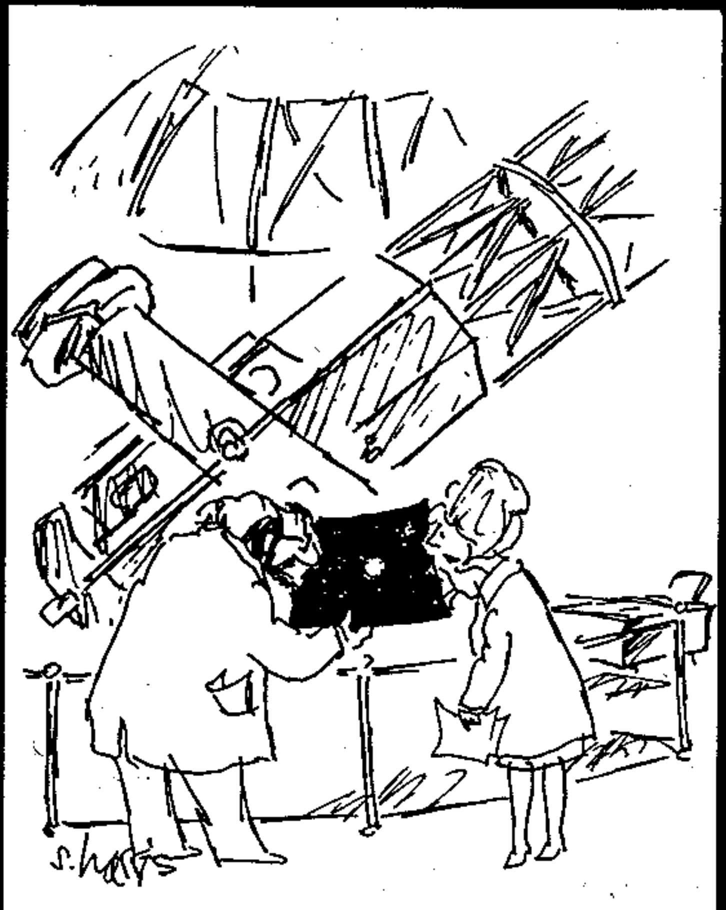
Optical/IR Observational Astronomy

Photometry I



"It's somewhere between a nova and a supernova
... probably a pretty good nova."

David Buckley, SALT

Recap: Magnitudes

- **Magnitude difference are related to the ratio of intensities:**

$$m_1 - m_2 = -2.5\ log\frac{I_1}{I_2}$$

or

$$\frac{I_2}{I_1} = 2.512^{m_1 - m_2}$$

- **For any given measurement *system* (telescope-instrument-detector combination), the measured intensity depends on:**
  1. **The actual intensity of the object**
  2. **The sensitivity of the *system*, which depends upon:**
  - **Effective collecting area of the telescope**
  - **The "throughput" of the instrument (e.g. filters, optics)**
  - **The QE (Quantum Efficiency) of the detector (e.g. photomultiplier, CCD, etc.)**

- **We refer to the *instrumental magnitude*, defined as:** $m = -2.5\ log\ I$
- **To be able to compare measurements between different systems, we use the following:**

$$m = -2.5\ log\ I + constant$$

- **The constant is referred to as the *zero point* of the system, and is determined for a specific telescope-instrument-detector combination.**
- **In terms of *flux density* (ergs cm^{-2} s^{-1} Å^{-1})**

$$m(\lambda) = -2.5\ logF(\lambda) - 21.1$$

Absolute Magnitudes

- The ***absolute magnitude*** ***(M)*** is the *apparent* magnitude of a star as it would be seen at a distance of 10 parsecs (pc)

- Consider a star observed at two different distances, *r*:
  - *At it's actual distance, $r_1 = d$*
  - *At a hypothetical distance of $r_2 = 10$ pc*

- The intensity, *I*, (flux density, measured per square metre at the telescope) of a star $\propto 1/r^2$ (inverse square law of intensity)

- Total luminosity, *L*, of the star is therefore the product of *I* and the total area through which this radiation passes, so:

$$L = I_1 4\pi r_1^2 \quad = \quad I_2 4\pi r_2^2$$

$$\Rightarrow \qquad I_1 / I_2 \quad = \quad (r_2 / r_1)^2$$

So,

$$m_1 - m_2 = -2.5 \log (I_1/I_2) = m - M = -2.5 \log (r_2/r_1)^2 = -5 \log (10/d)$$

Absolute Magnitudes

- So for a star at an *actual* distance, *d,* the magnitude *difference* between the *apparent (m)* and *absolute (M)* magnitudes is given as:

$$m - M = 5\ log\ d - 5$$

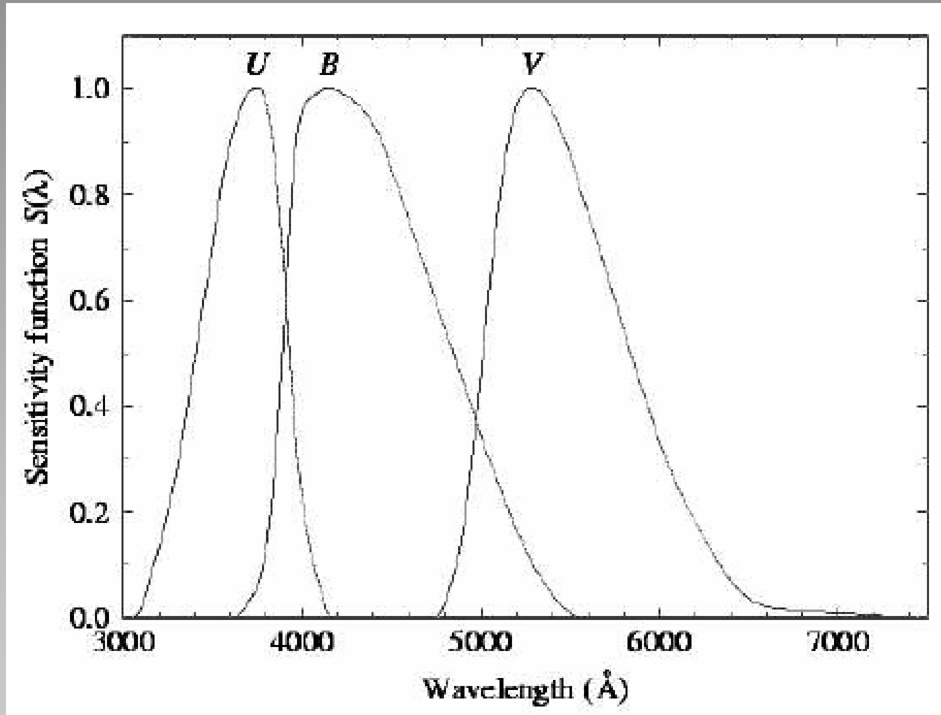
[known as distance modulus]

  – Or in terms of the parallax:

$$m - M = -5\ log\ \pi - 5$$

[π = 1/d arcsec]

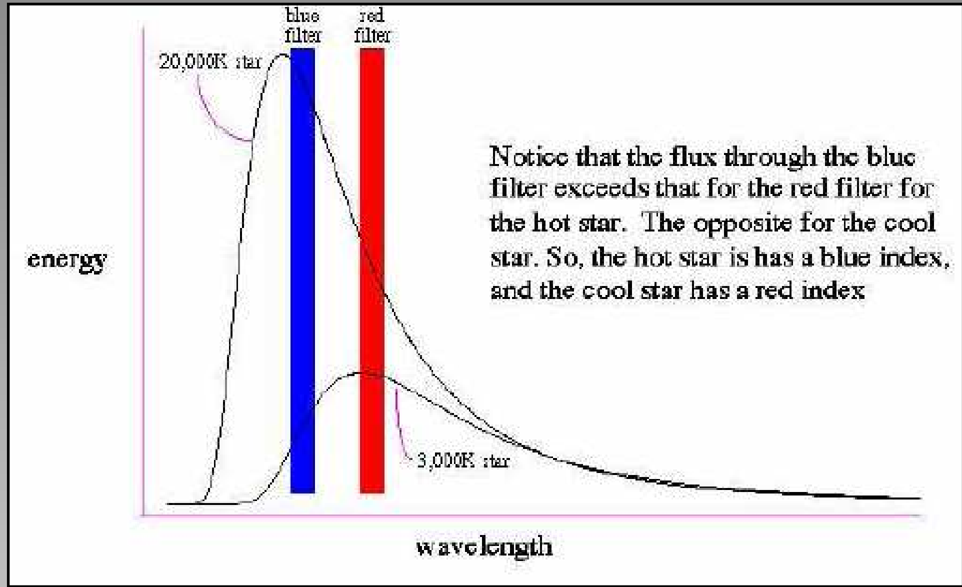
- The *apparent* magnitude (*m*) is invariably measured with a specific *filter*, typically the *visual (V)* of the first *accurate* photometric system, namely the Johnson, or *UBV*, system based on the first photomultipliers (1P21)
- m_V is therefore the *apparent* magnitude measured through the *V*-band filter.



Filter	*λ(Å)*	*Δλ(Å)*
U	3600	560
B	4400	990
V	5500	880

Bolometric Magnitudes

- The relative ***apparent magnitudes*** ***(m)*** measured through different filters depend on the *colours* or *temperatures* of the object
- For thermal sources (e.g. stars), the hotter the bluer:
- Define the ***bolometric*** magnitude as the *total* magnitude of a star over *all* wavelengths, measured at $d = 10$ pc
- Related to the integrated intensity of a ***spectral energy distribution (SED)***
  - The area under SED curve → bolometric intensity → bolometric magnitude
  - $M_{bol} \propto \int F_\lambda d\lambda$



- For a ***black body***, F_λ is the **Planck function** which defines the SED as a function of ***temperature*** and λ:

$$F_\lambda = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{\frac{hc}{\lambda kT}}-1}$$

Integrated energy (area under SED):

$= \int F_\lambda d\lambda = \sigma T_{eff}^4$ **(Stefan-Boltzman law)**

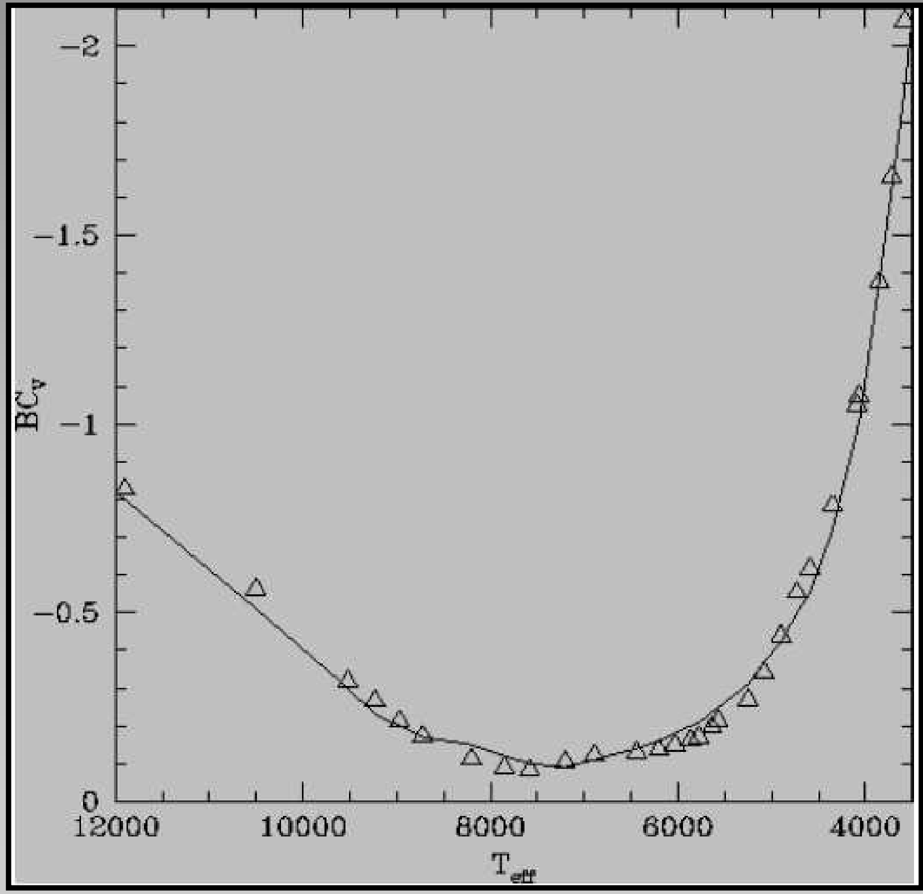
- ***Colour index is the difference of magnitudes measured through two different filters: e.g. B – V***

Bolometric Magnitudes

- **Star SED's *approximate* black bodies, so *colour index* is an indicator of *temperature.***
- **Bolometric correction (*BC*) is the *difference* between the *bolometric* and *absolute V*-band magnitude:**

  $BC_V = M_{bol} - M_V$

- **The correction is most extreme for stars much *hotter* or *cooler* than ~6000 – 8000K**
  - **More UV flux for hot stars**
  - **More IR flux for cooler stars**
  - **Effects of spectral lines Sun-like stars**



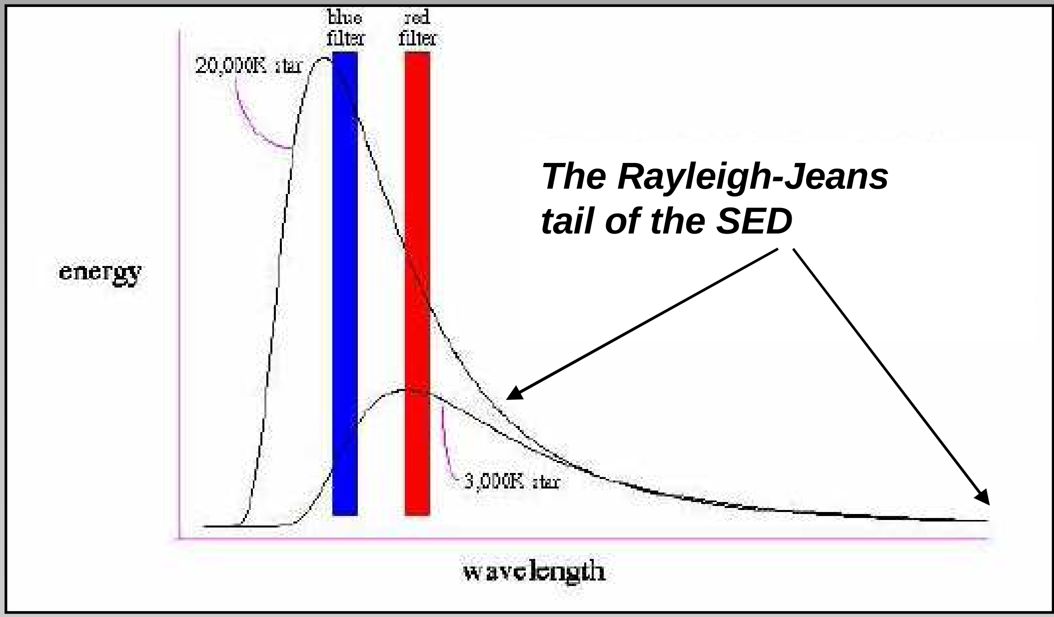
Other Aspects of the Black Body Distribution

- **Wien Law:**
  - **Peak of the Planck function is given as function of wavelength**

$$\lambda_{max} = \frac{2898}{T} \mu m$$

  - **The Sun's effective temperature is ~5800K $\Rightarrow \lambda_{max} = 0.5\mu m$**
  - **Coincidence that the eye's peak QE is at this wavelength?**

- **Rayleigh-Jeans tail**
  - **For $\lambda >> \lambda_{max}$ we are said to be in the "Rayleigh-Jeans tail" of the SED**
  - $F_\lambda \propto \lambda^{-4}$

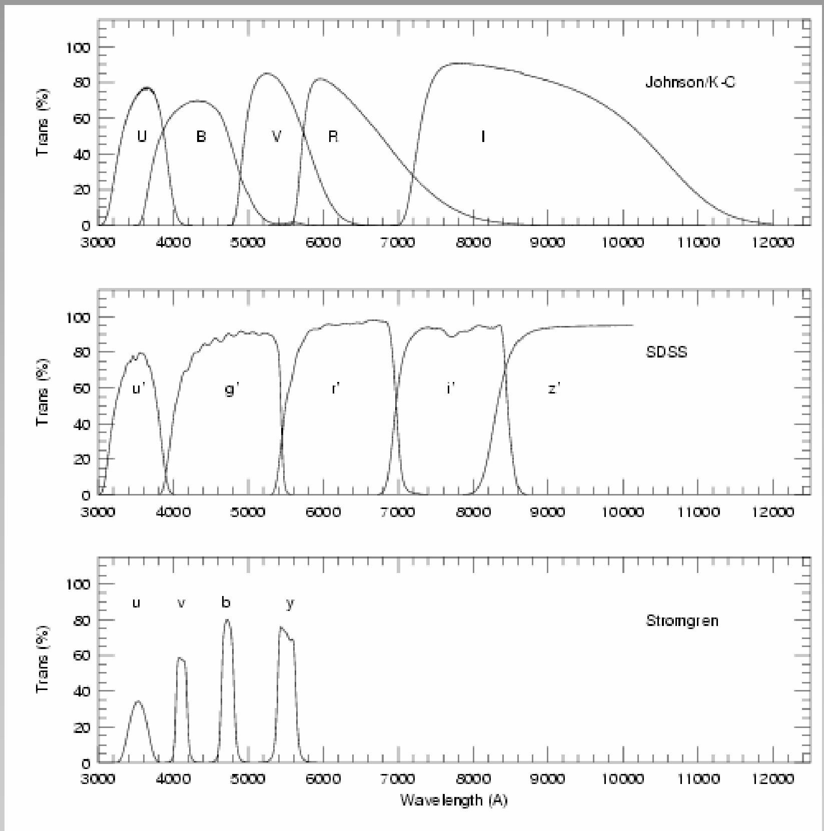


Photometry I

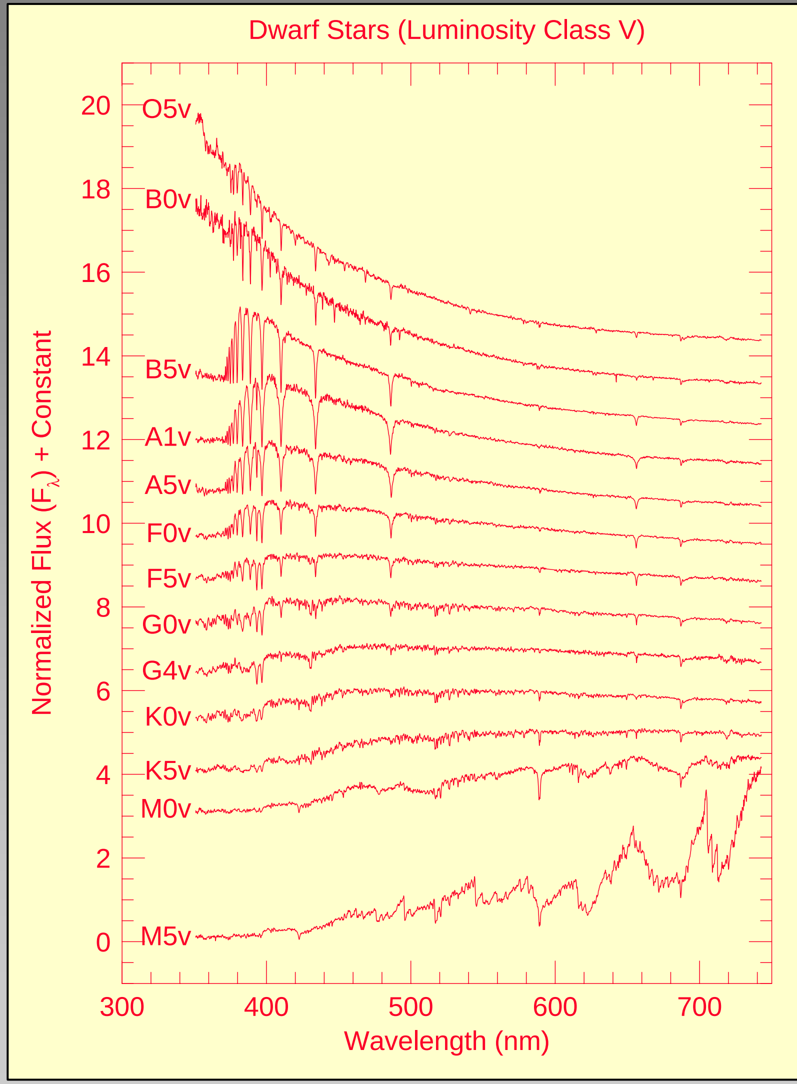
Photometric Systems:

Filters chosen to discriminate various parameters, e.g. temp, gravity, abundance.

Measured fluxes/magnitudes are *product* of passbands and the SEDs.

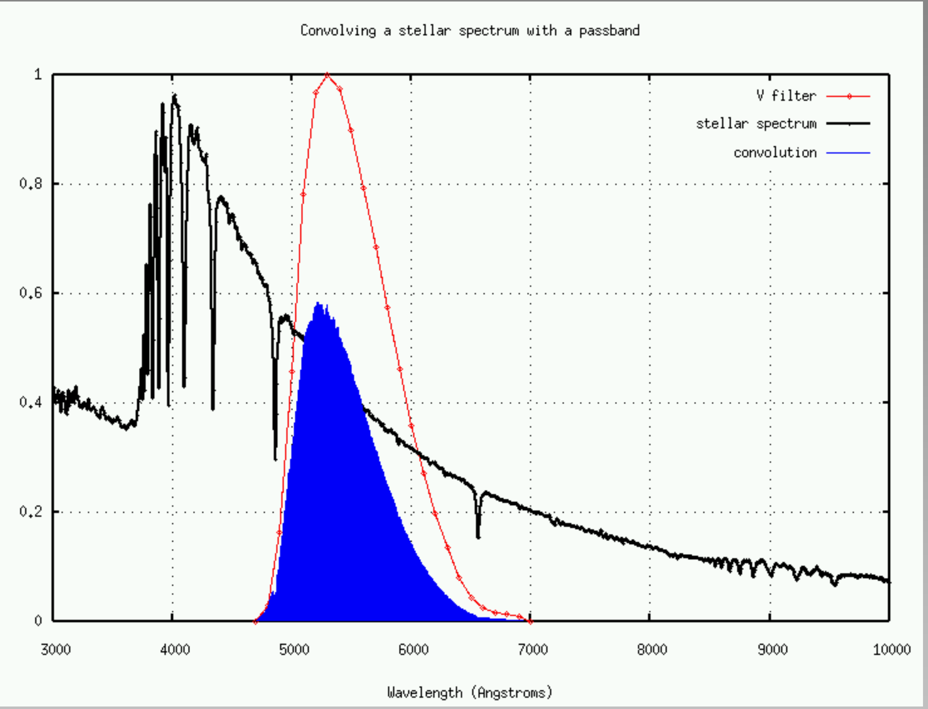


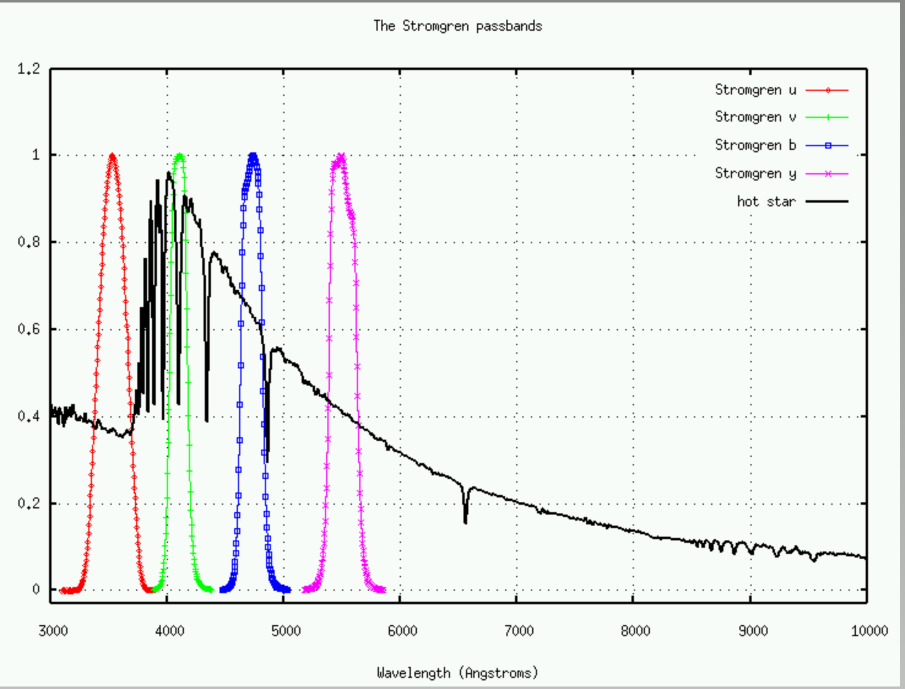
X



= magnitude$_{filter}$ (e.g. m_V)

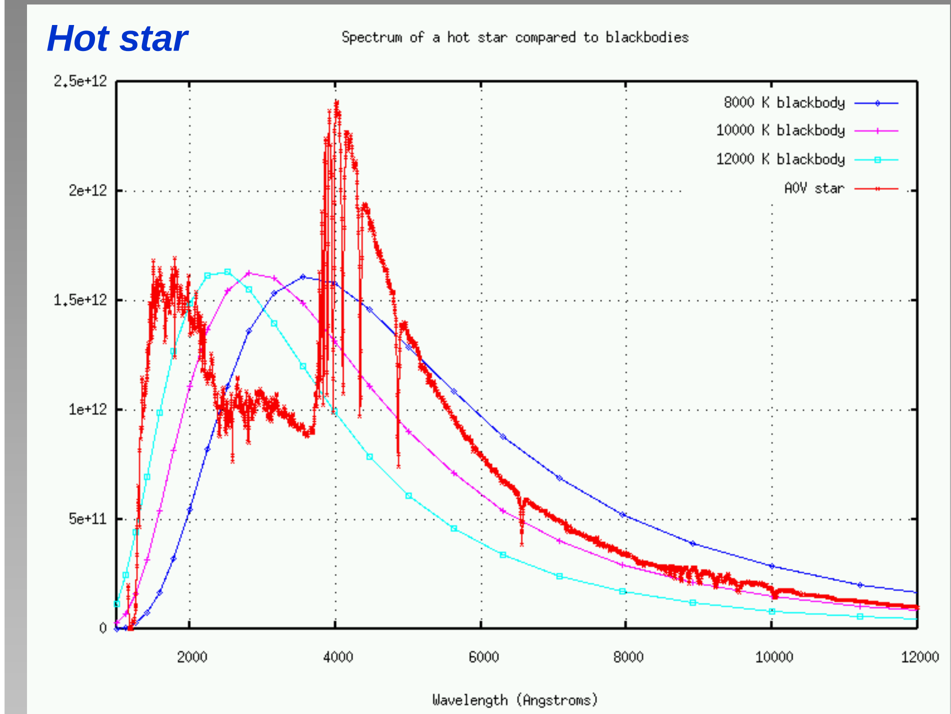
'convolved' filter responses

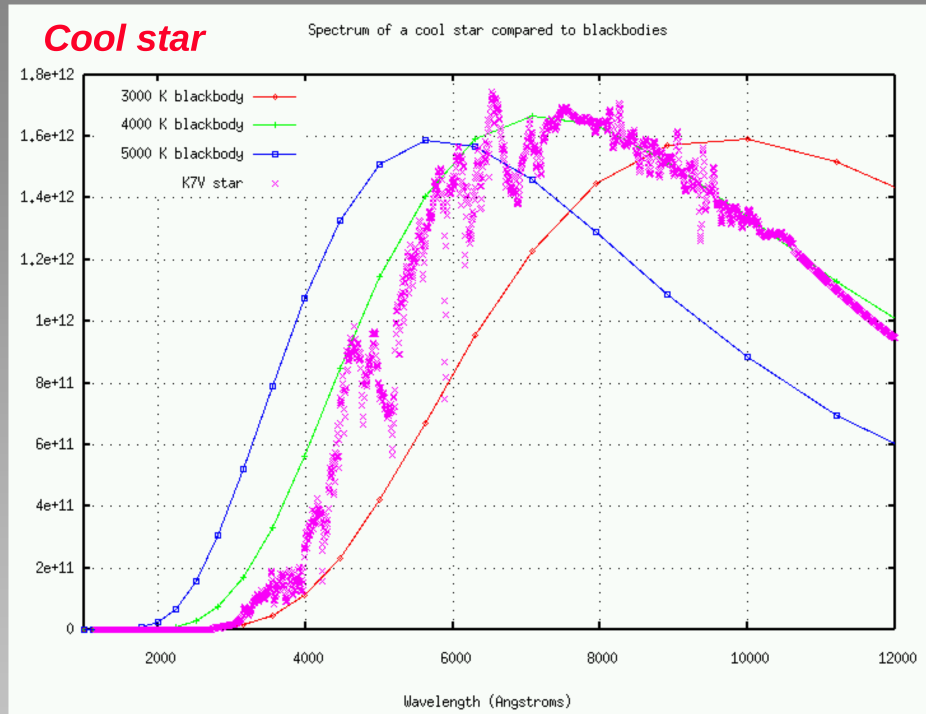




- **Colour of source determines the filter's *effective* wavelength**
  - **Need to take account of this is determining mags/colours**

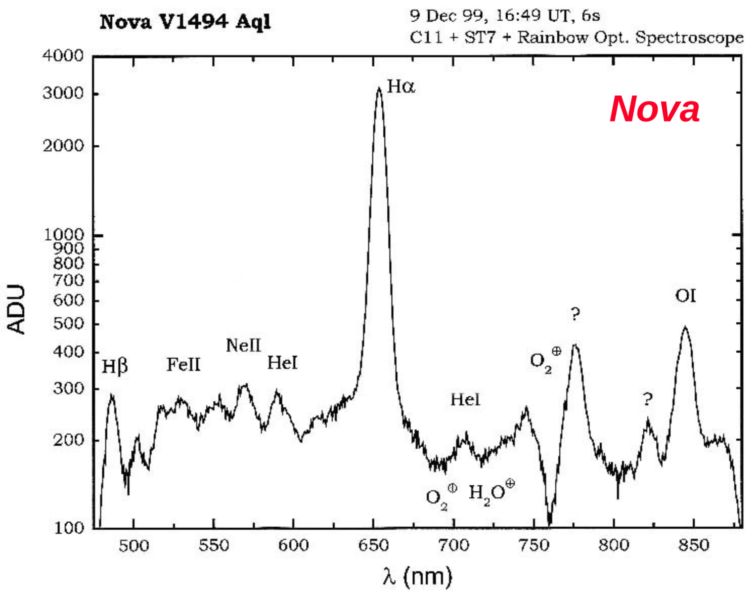
Real SEDs vs. Blackbodies

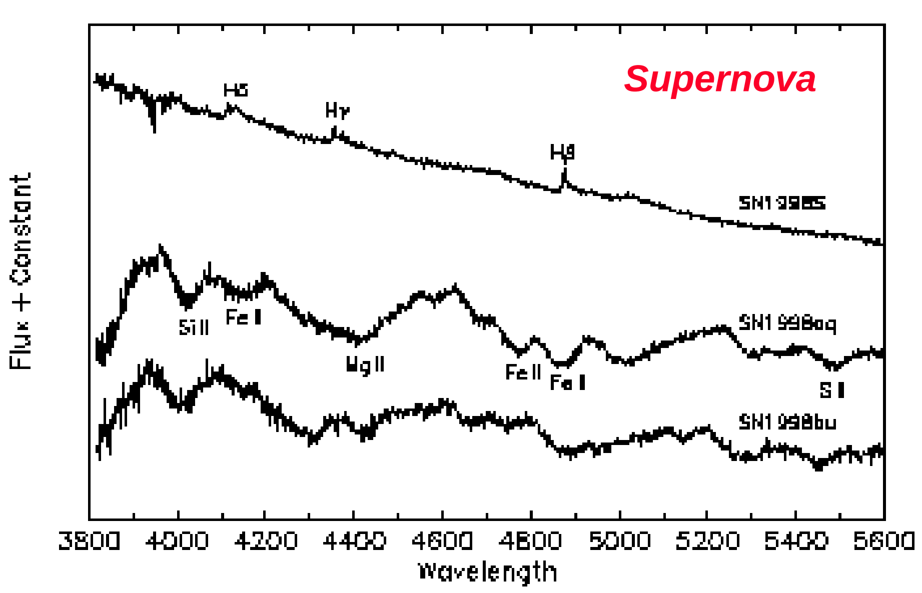


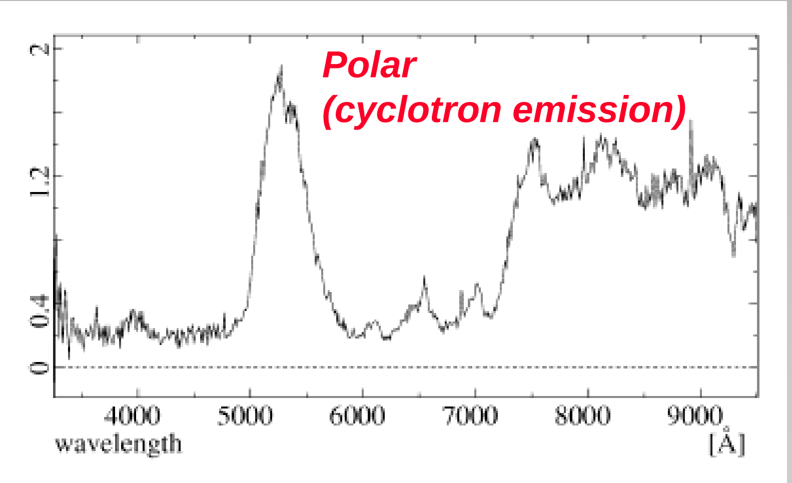


- **Sometimes stellar SEDs are a poor match to blackbodies**
- **Presence of spectral features (e.g. Balmer jump, spectral lines, line blanketing) affects mags/colours**

Real SEDs vs. Blackbodies



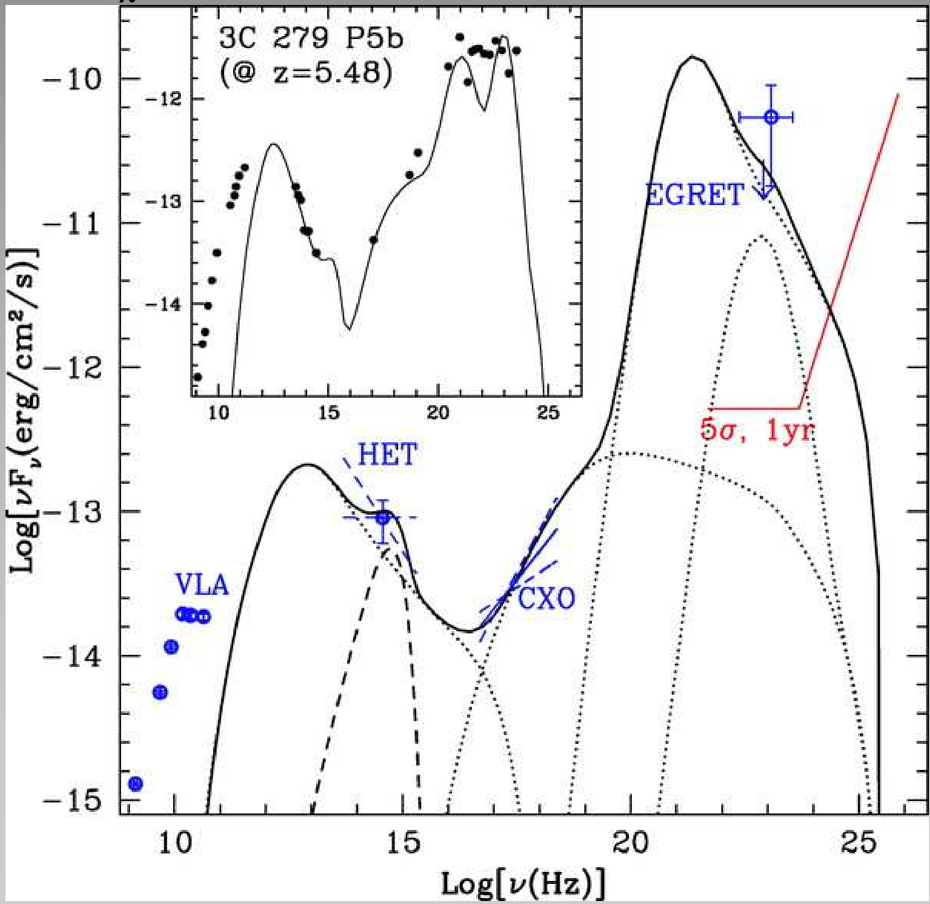


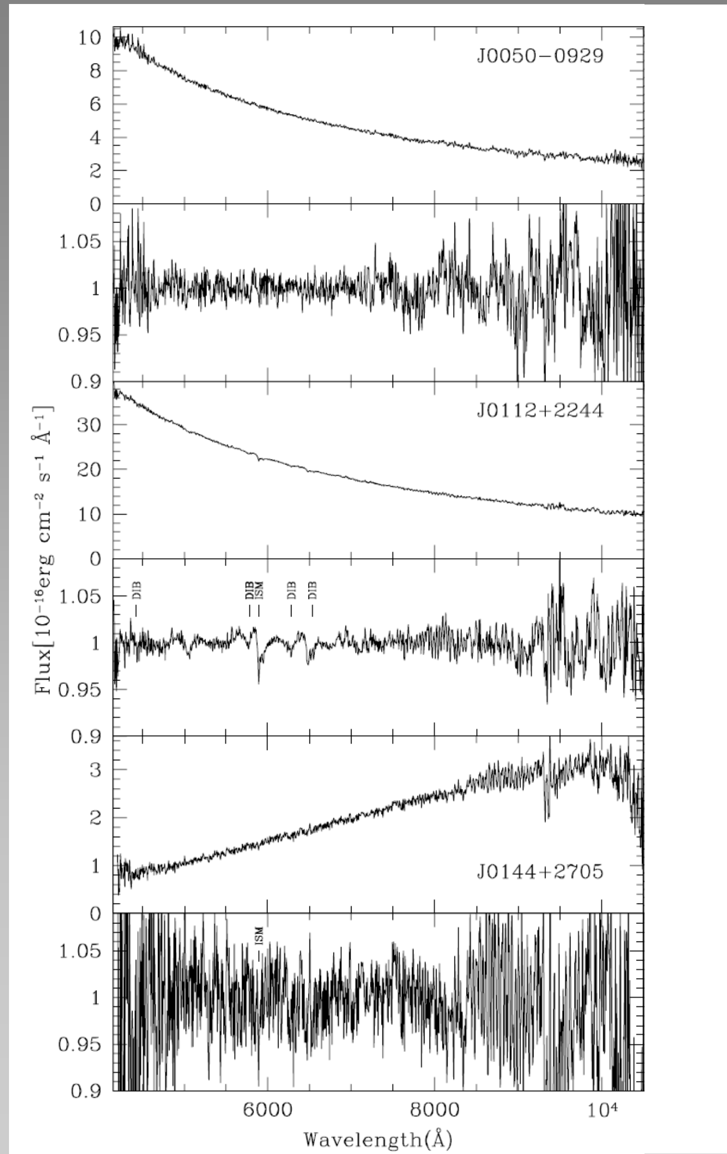


- **Even greater departures from blackbodies for some objects (e.g. novae, supernovae, non-thermal sources)**

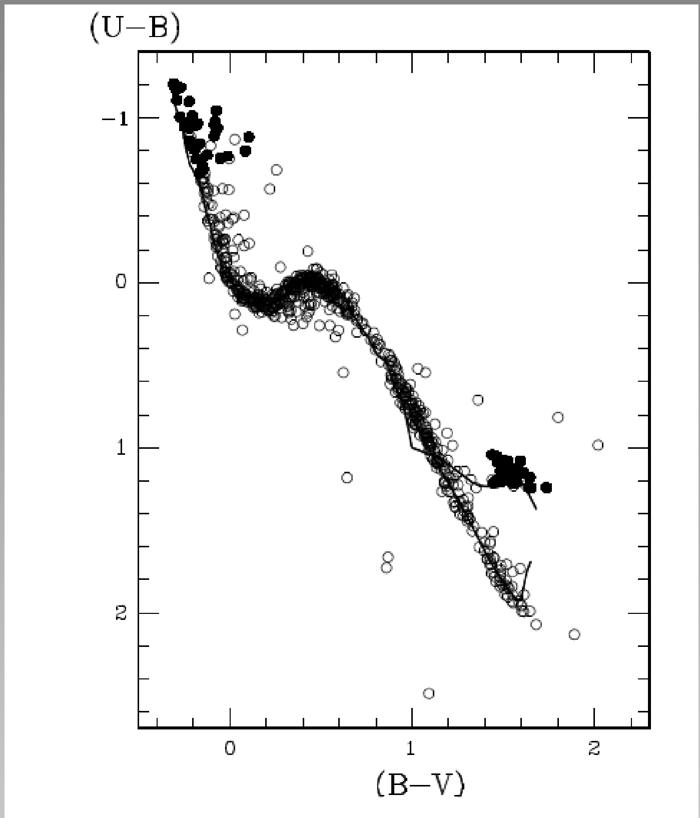
Non-blackbody SEDs

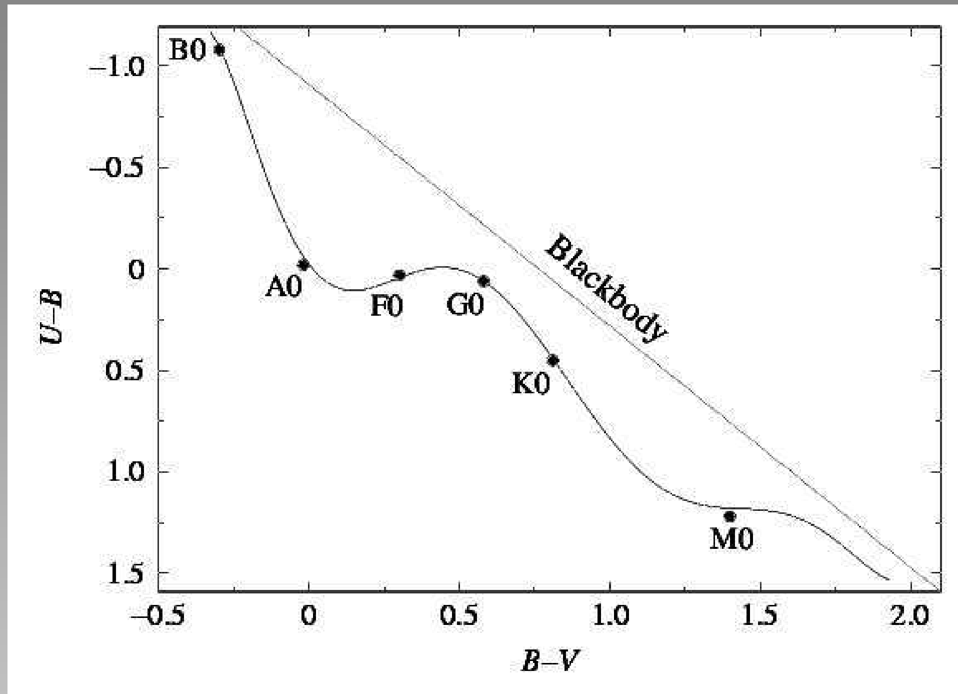
- **Power Law SEDs common in active galaxies (e.g. blazars)**
  - $F_\lambda \propto \lambda^{-\alpha}$





Two-Colour diagrams





For V = 0 star:

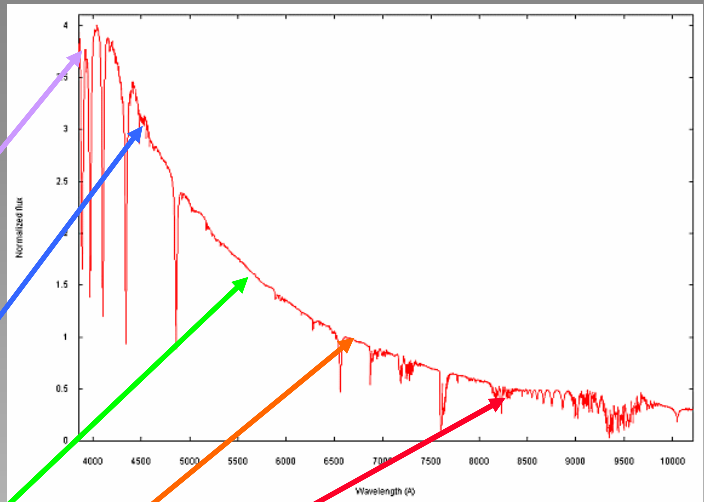
$f^0_\lambda = 3.63 \times 10^{-9}$ *erg* s^{-1} cm^{-2} $Å^{-1}$

$f^0_\nu = 3.63 \times 10^{-20}$ *erg* s^{-1} cm^{-2} Hz^{-1}

$\phi^0_\lambda / h\nu = 1005$ *photons* cm^{-2} s^{-1} $Å^{-1}$

- **Define colour indices:**
  ***U – B* and *B – V* = 0 for *A0* spectral type**
- **A0 defined by Vega (*T_{eff} = 9550, log g = 3.95, log Z/$Z_\odot$* = – 0.5*)***

Standard Fluxes for a *V* = 0 A0 star



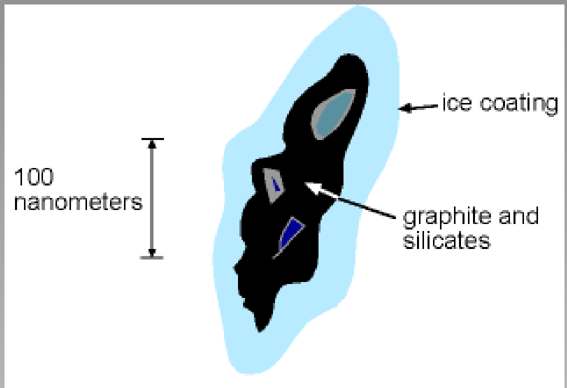
	U	B	V	R	I	J	H	K	Kp	L	L*
λ_{eff}	0.366	0.438	0.545	0.641	0.798	1.22	1.63	2.19	2.12	3.45	3.80
f_{ν} •	1.790	4.063	3.636	3.064	2.416	1.589	1.021	0.640	0.676	0.285	0.238
f_{λ} •	417.5	632	363.1	217.7	112.6	31.47	11.38	3.961	4.479	0.708	0.489
$zp(f_{\nu})$	0.770	-0.120	0.000	0.186	0.444	0.899	1.379	1.886	1.826	2.765	2.961
$Zp(f_{\lambda})$	-0.152	-0.602	0.000	0.555	1.271	2.655	3.760	4.906	4.780	6.775	7.177

f_{ν} (10^{-20} ergs cm^{-2} sec^{-1} hz^{-1})
f_{λ} (10^{-11} ergs cm^{-2} sec^{-1} Å^{-1})
$mag_{\lambda} = -2.5 \log(f_{\lambda}) - 21.100 - zp(f_{\lambda})$
$mag_{\nu} = -2.5 \log(f_{\nu}) - 48.598 - zp(f_{\nu})$

- **Fluxes for *U = B = V = R = I = J = K = K' = L = L* = 0***

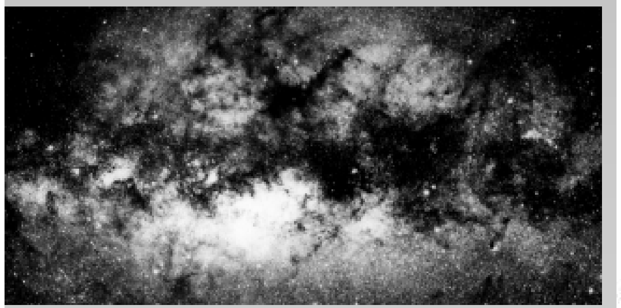
Interstellar Dust

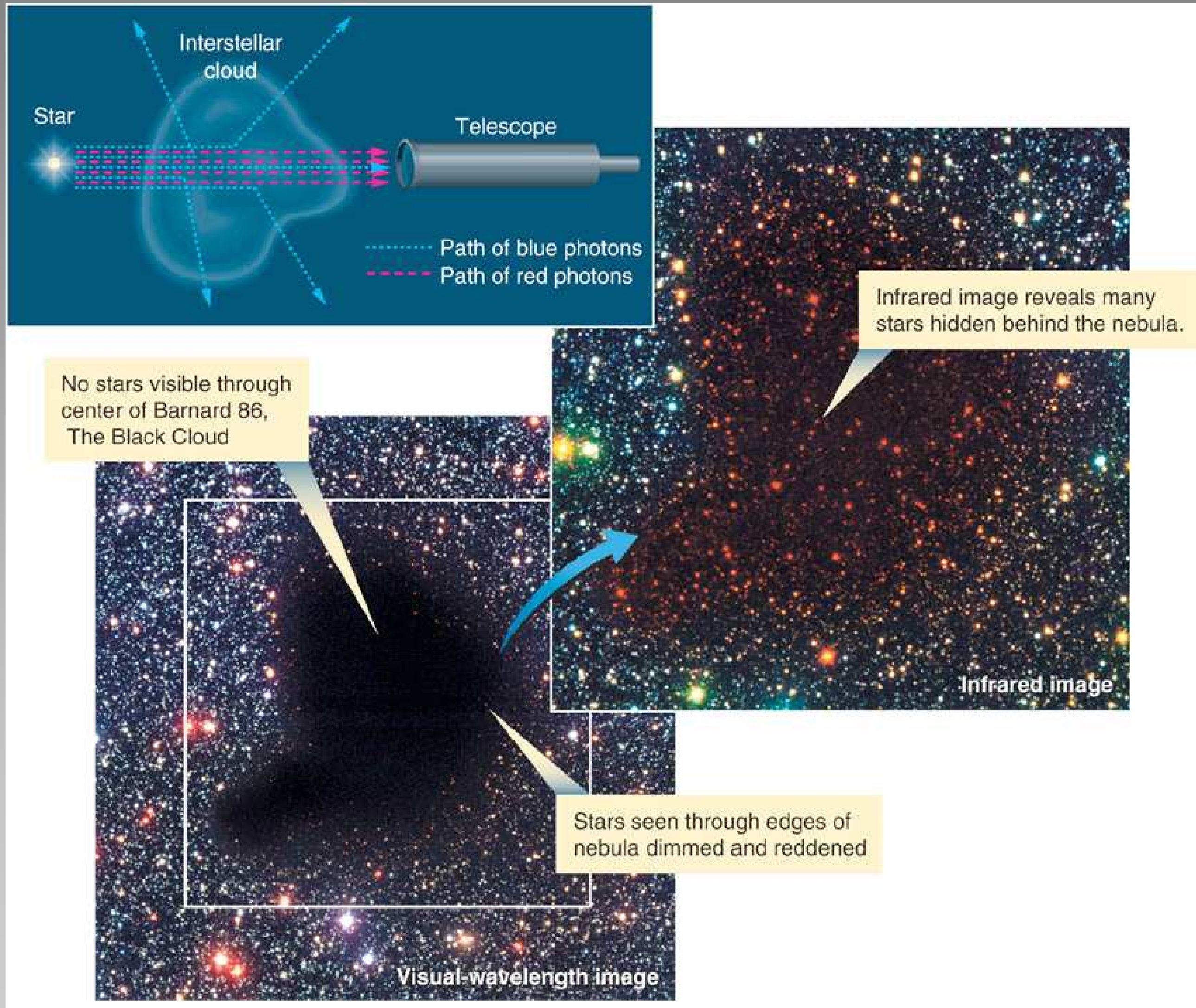
- **Interstellar space contains *dust***
  - ***Carbon & silicates***



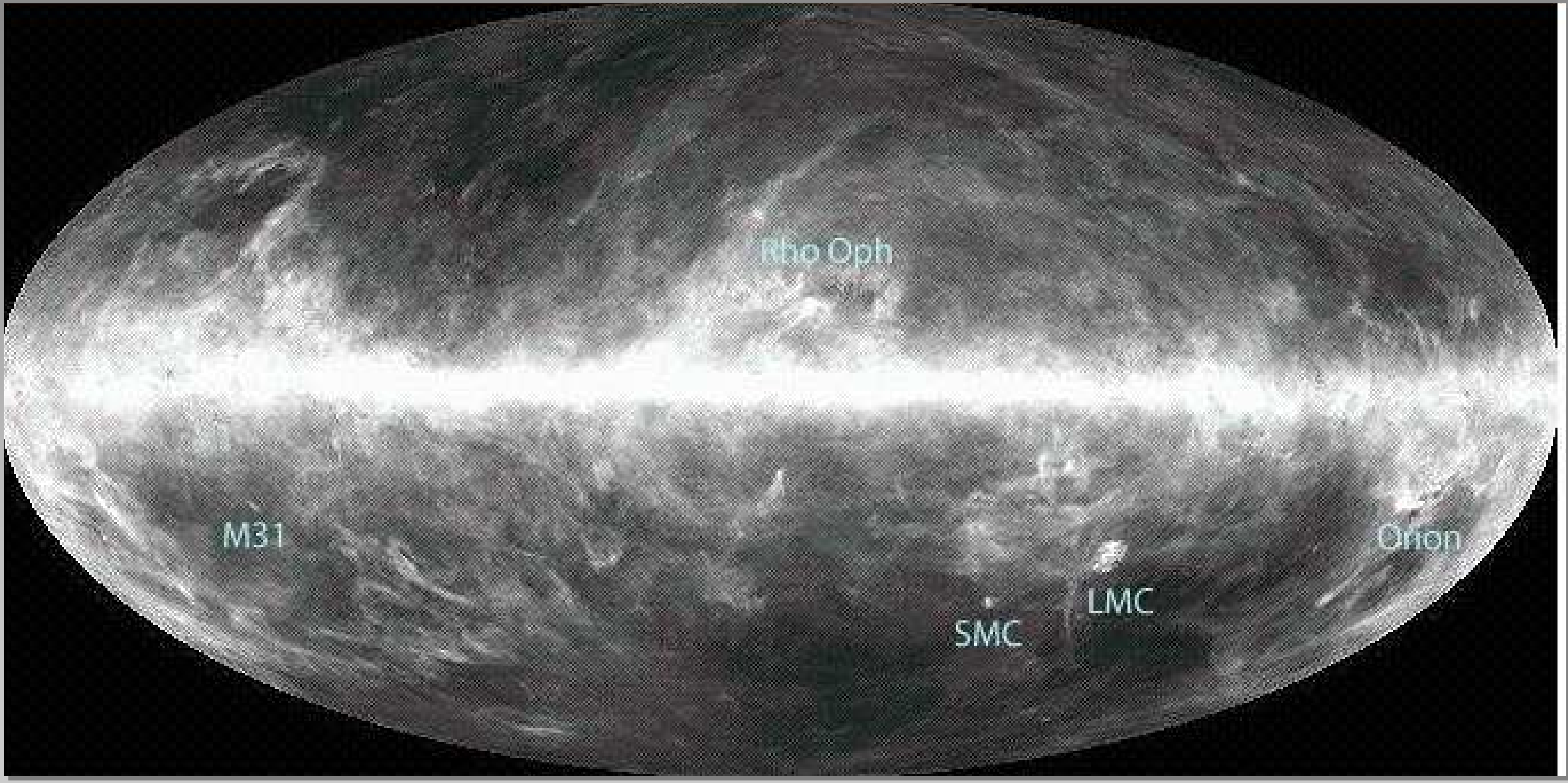
A typical dust grain (note the tiny scale!).

- **Causes light to be absorbed, preferentially in the blue**





Galactic Dust



Dust emission at 100μm in Galactic coordinates

Galactic Dust

<u>Statistics for galactic dust:</u>

- **Total dust mass is ~1 per cent of mass of interstellar medium (ISM), the remainder is gas**

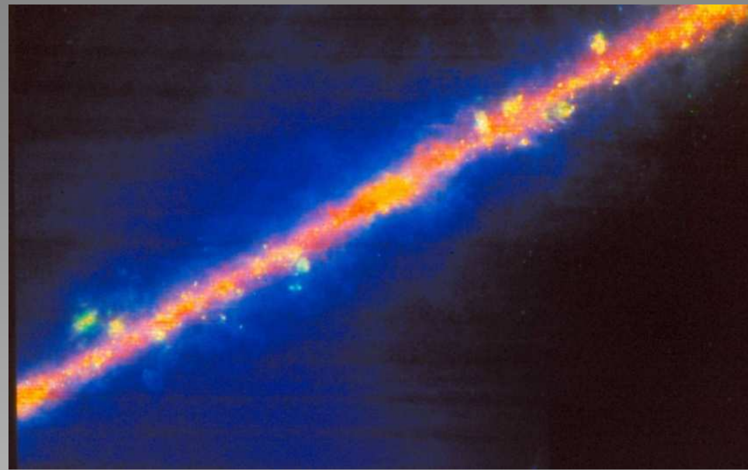
- **Mean dust density in the galactic disk is**

$$n_{dust} \sim 10^{-6} \text{ grains/m}^3$$

- **Compare this to mean gas density of**

$$n_{gas} \sim 10^{+6} \text{ gas atoms/m}^3$$

- **Mean visual extinction in galactic plane (*b* = 0º) is ~ 1 to 2 magnitudes (in the *V*-band) for each kiloparsec (1 kpc = 1000 pc) of distance, but the distribution is very patchy.**



IRAS (Infrared) image of the Milky Way showing dust in galactic plane

Optical/IR Observational Astronomy

Photometry I

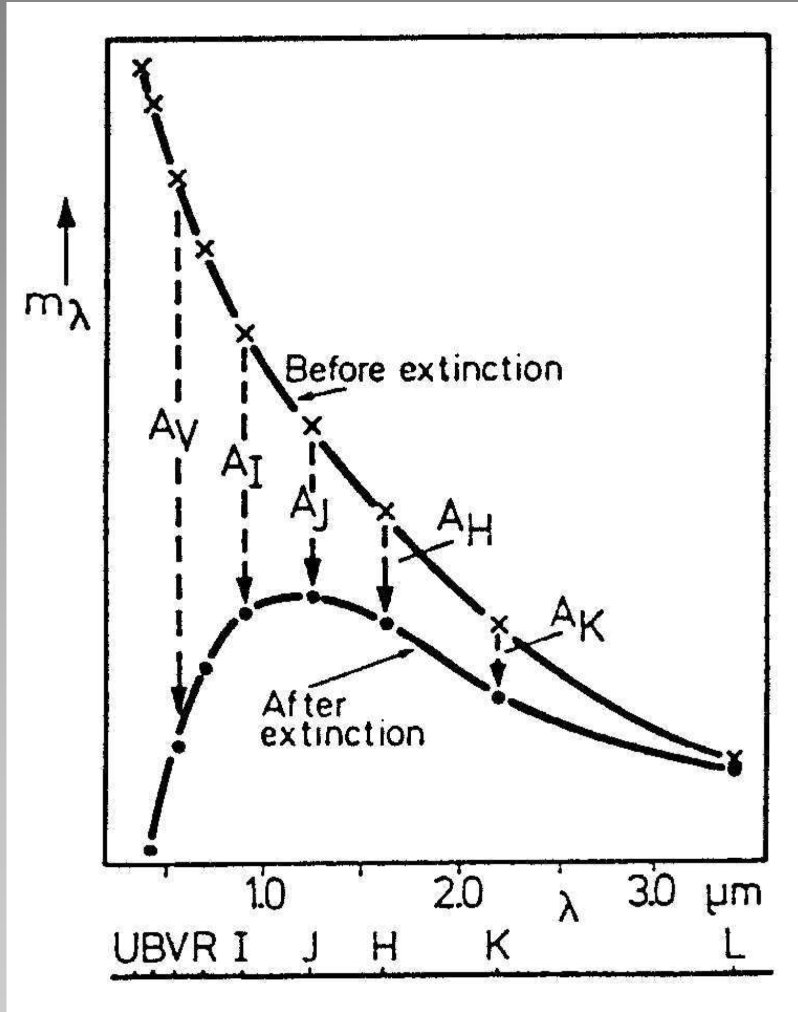
Interstellar Dust Extinction & Reddening

- **Apparent magnitudes of objects affected**
  - Appear ***dimmer***
  - Before determining distances, need to correct for interstellar absorption
- **Modified distance modulus:**

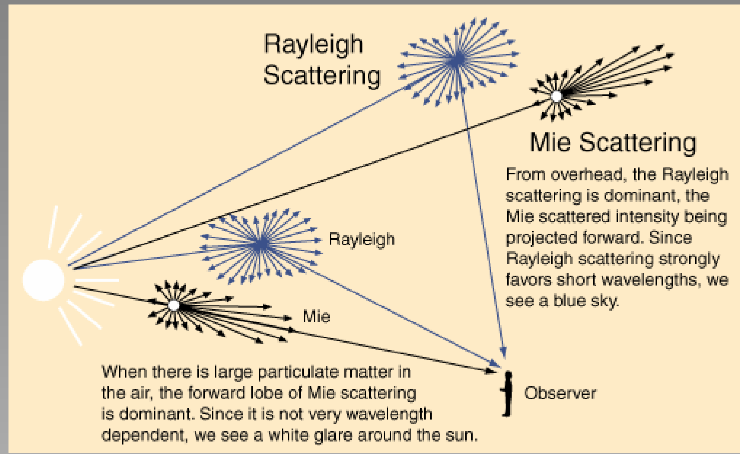
$$m_V - M_V = 5\log d - 5 + A_V$$

  - Absorption measured in *magnitudes* of extinction, A_λ
- **In addition, absorption is *wavelength dependent***
  - Shorter wavelengths affected most
  - Objects are *reddened*
  - Colours appear *redder*

$$E_{B-V} = (B-V)_{obs} - (B-V)_0$$



Interstellar Dust Extinction & Reddening

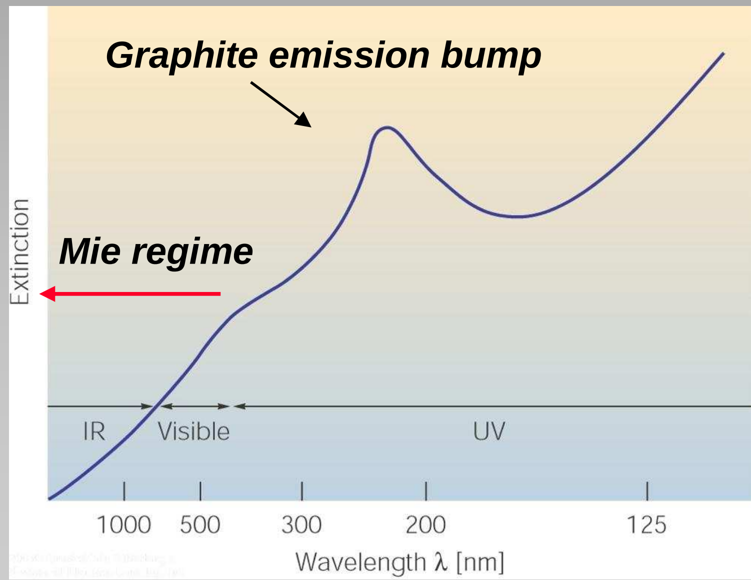


- Ratio of ***extinction*** to ***reddening*** defined as:

$$R_V = \frac{A_V}{A_B - A_V} = \frac{A_V}{E(B-V)}$$

also know as the ratio of ***total*** to ***selective absorption***

- This ratio is ~3.2 and is determined by the physics of the dust (grain size, shape, scattering)

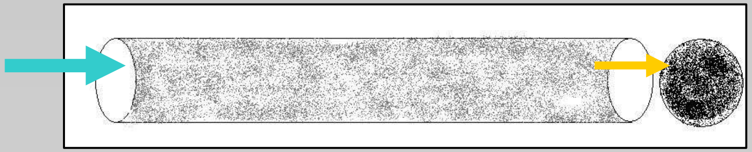


- Mostly dust particles >100nm scatter by Mie scattering, which dominates from the near UV (>~350nm) to the IR

$A_V \propto 1/\lambda$ (Whitford law)

- *In terms of column density:*

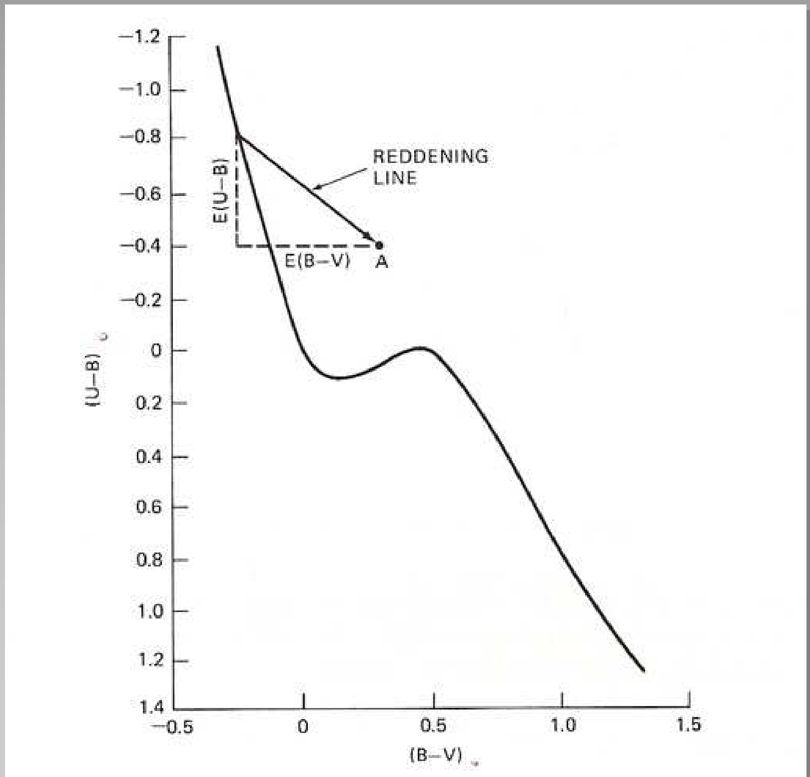
$$E(B-V) = \frac{N_H}{5.8\times10^{25}\,m^{-2}}$$

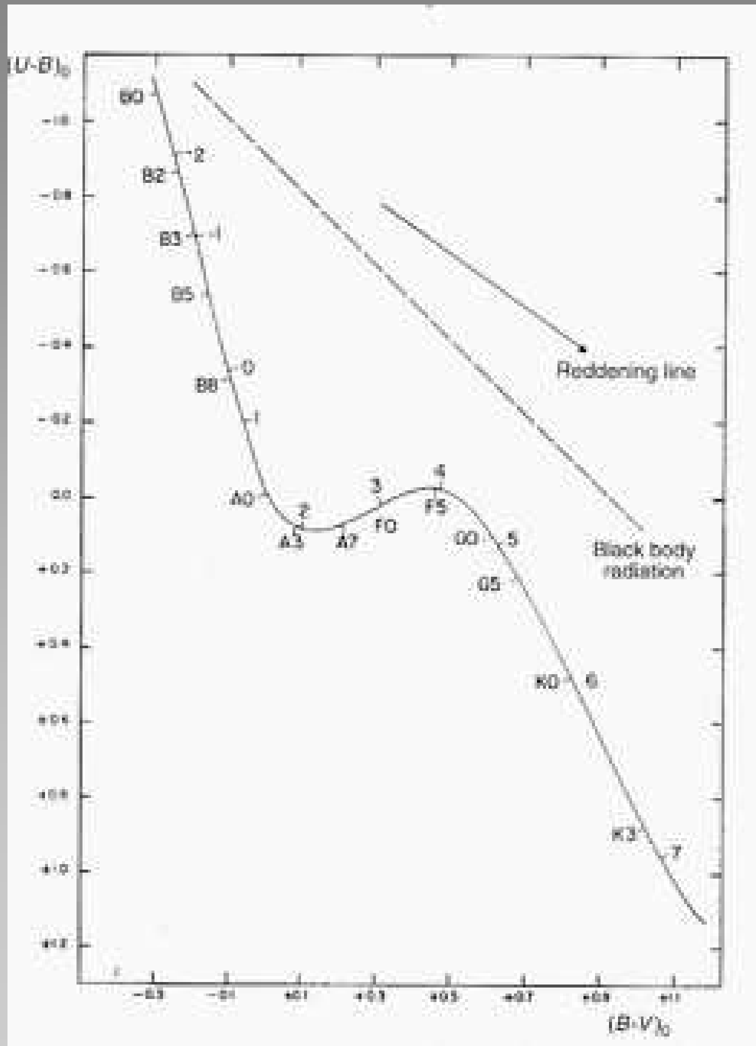


[useful for X-ray obs]

Reddening Effects on Two-Colour diagrams

- **Due to reddening, positions of stars are displaced along a *reddening line***
- **Amount of displacement dependent on degree of reddening**





The Strömgren System

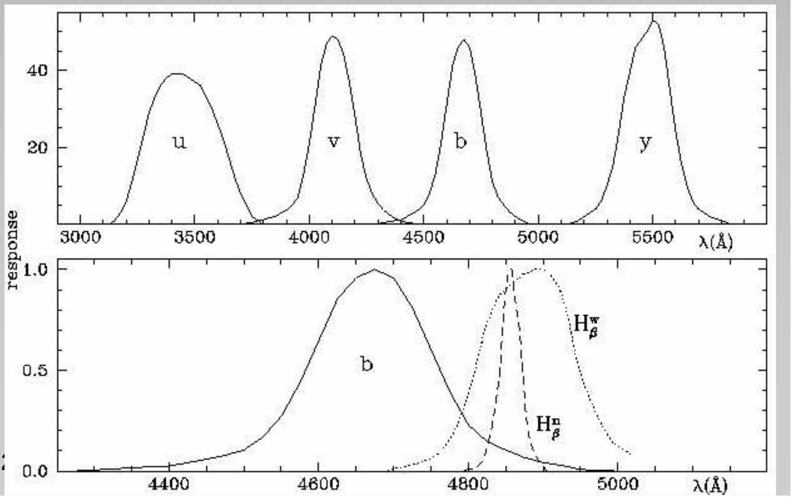
- **Used mostly for hotter star (spectral type G and hotter) and uses "Intermediate" band filters**
  - **Few hundred Å wide (narrower than UBV)**
- ***Define specific colour indices:***

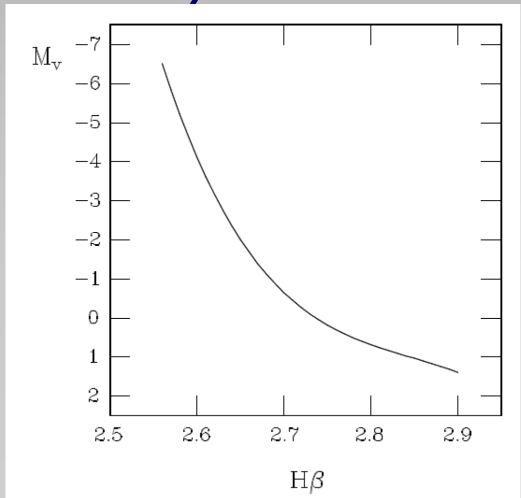
(b – y) **is a *temperature indicator* (like *B-V*)**

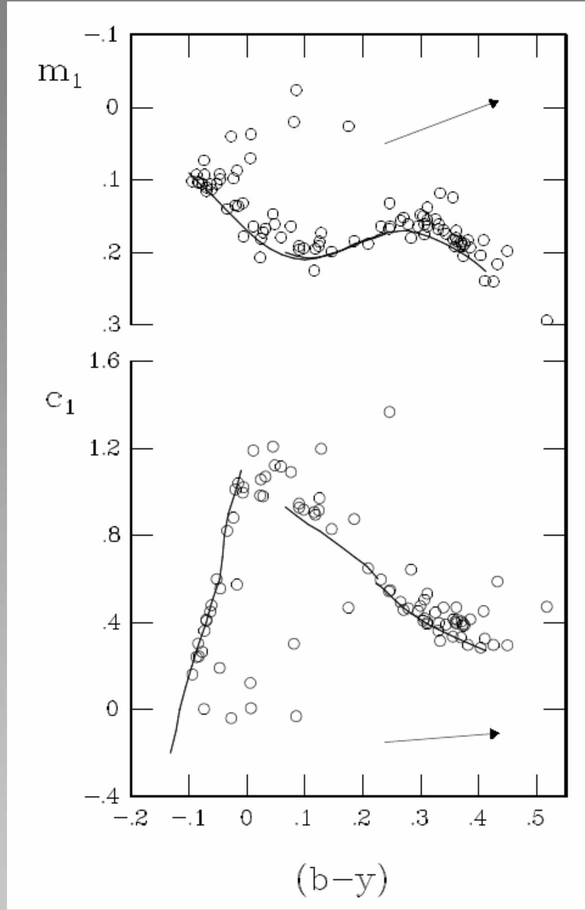
m1 = (v – b) – (b – y) **is a *metallicity index***

c1 = (u – v) – (v – b) **measures the strength of the Balmer jump and is a *luminosity indicator* for A, F & G stars and a *temperature indicator* for O-B stars**

β-index **= ratio of flux in wide & narrow Hβ filter, and is a *temperature indicator* in A, F & G stars and a *luminosity indicator* in O-B stars (compliments C1 index)**

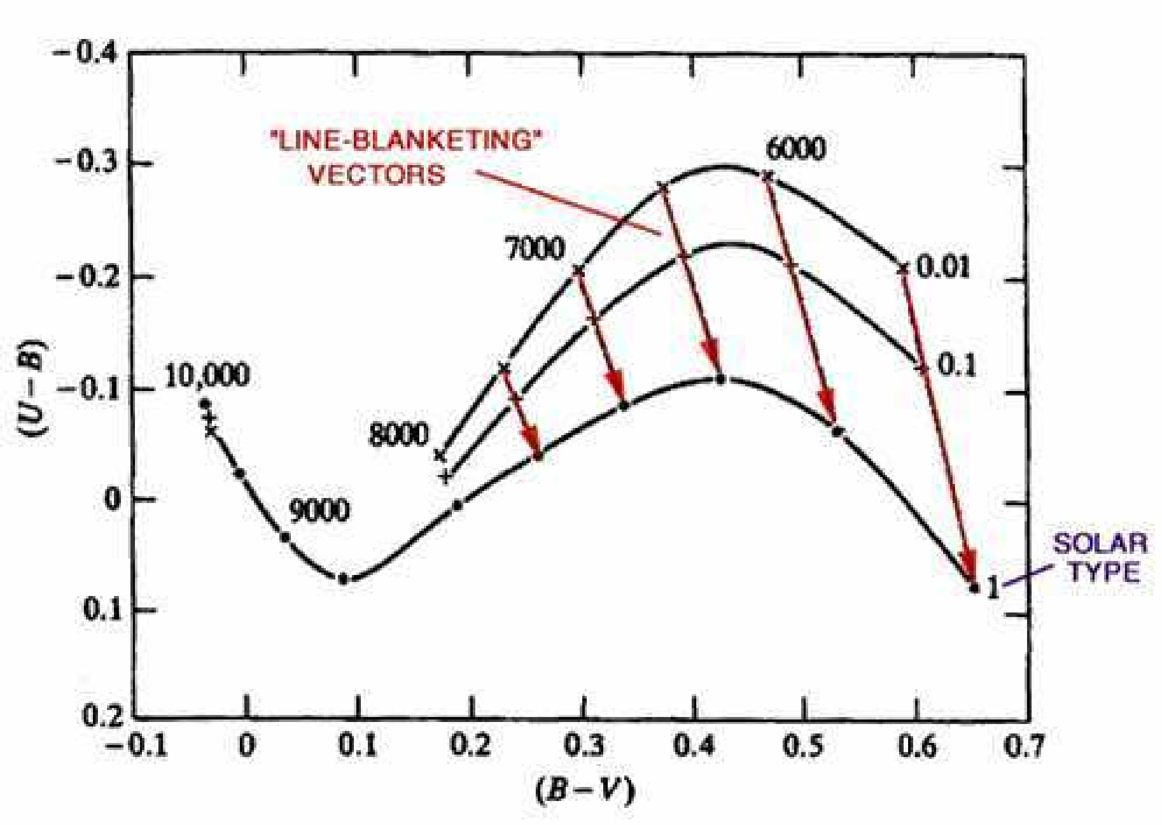






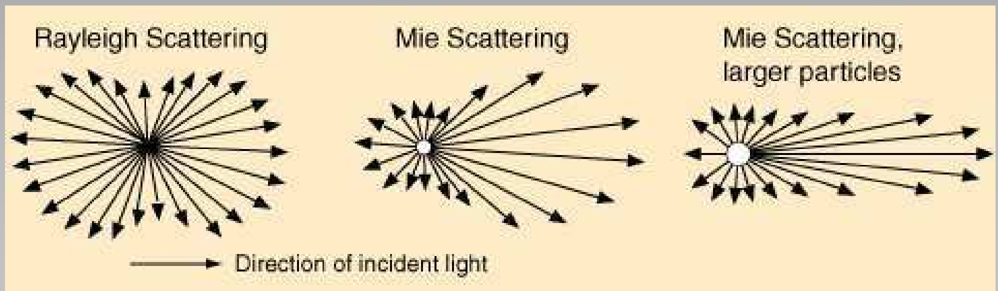
Line Blanketing

- **Akin to reddening lines, but due to the effects of metallic absorption lines in the star's atmosphere**
- **Most prevalent in the UV**
- **Decreases the UV flux, therefore *U – B* gets <u>*redder,*</u> more so than *B – V***



Effects of the Earth's Atmosphere: Extinction

- Light is ***absorbed, extinguished*** or ***extincted*** as it passes through the Earth's atmosphere
- Two primary causes:
  - Scattering
    - » Rayleigh scattering by air molecules ($\propto 1 / \lambda^{4}$)
    - » Mie scattering by aerosols e.g. man made pollutants, pollens, terrestrial, meteoric & volcanic dust, sea salt on the coast, etc. ($\propto 1 / \lambda$)



  - Molecular absorption
    - » Ozone (O_3) in the UV & Vis
    - » Water vapour in the red & IR

Atmospheric Extinction

- **Amount of extinction determined by path length through atmosphere**
- **This is dependent upon the *zenith distance (z)***
- **Define *airmass (X)* to be the path length through the atmosphere at the *zenith***
- **For a plane-parallel atmosphere (i.e. flat-Earth):**

$$X = \sec z = [\sin\phi\,\sin\delta + \cos\phi\,\cos\delta\,\cos h]^{-1}$$

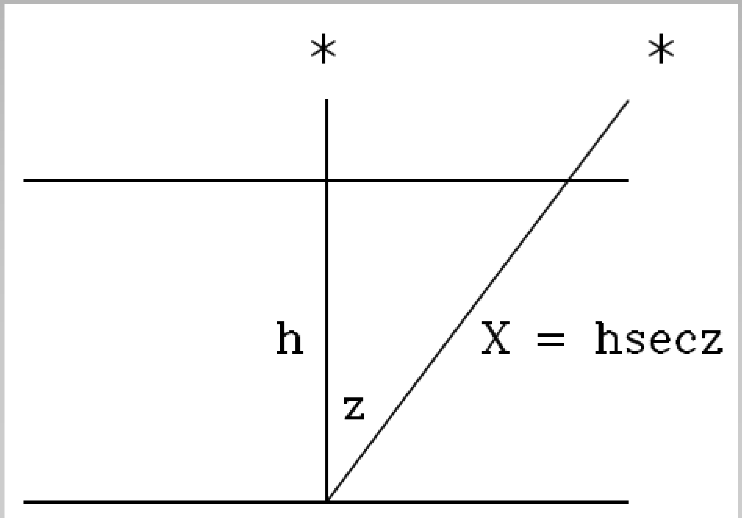
ϕ = latitude
δ = declination
h = Hour Angle

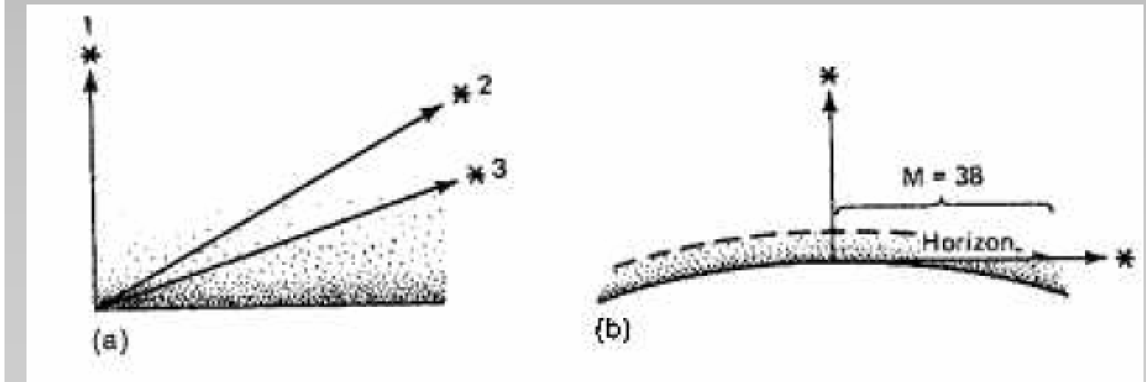
- **For the true spherical atmosphere, need to correct as follows:**

$$X = \sec z\,(1 - 0.0012(\sec^2 z - 1))$$

[*works for z < 87º*]

Stars appear dimmer (& redder) nearer the horizon. For real (curved) atmosphere, objects on horizon have X ~38! Generally astronomers avoid observing at X > 2 (z > 60º), unless really necessary.





Atmospheric Extinction

- **Define extinction in terms of *opacity*, *optical depth* and *airmass***
- **A beam of light of intensity I_0 at the top of the atmosphere passes through the atmosphere of *optical depth*, τ, and is dimmed by an amount *dI*, so it now has a reduced intensity, *I*, where:**

$$I = I_0 - dI \quad \text{and} \quad I/I_0 = e^{-\tau X}$$

- **The degree of dimming is determined by the *airmass (path length)* and *optical depth*, thus:**

$$dI = -I\,\tau\,dX \quad \text{or,} \quad \frac{dI}{I} = -\tau\,dX \qquad \text{Integrating path} \Rightarrow \quad \ln I - \ln I_0 = -\tau X$$

- **Optical depth is related to the *opacity*, κ, and *density*, ρ:**

$$\tau = \kappa\rho \quad \text{so,} \quad dI_\lambda = -\kappa\rho I_\lambda\,dX$$

- **In terms of magnitudes:**

$$m - m_0 = -2.5\log_{10}(I/I_0) = -2.5\log_{10}(e^{-\tau X}) = -2.5 \times 0.4343\ln(e^{-\tau X}) = 1.086\,\tau X$$

$$\Rightarrow \quad m = m_0 + k\,X$$

[where k is the extinction coefficient, k = 1.086 τ, measured in mags]

Extinction

- **Extinction changes the observed brightness of stars:**

$$m_{obs} = m_{true} + k(\lambda) \sec Z$$

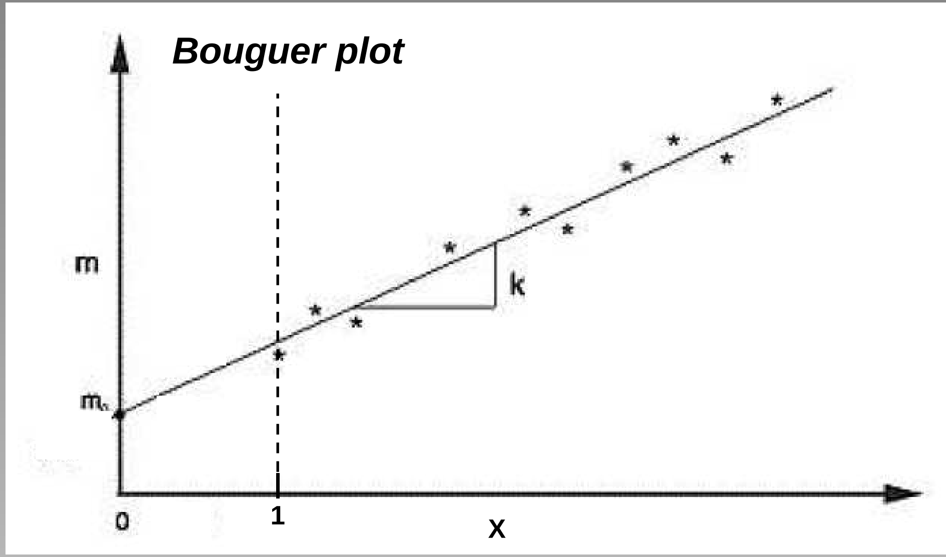
- **The extinction coefficient, *k*, is strongly wavelength dependent**
- **It is solely dependent on the nature of the atmosphere**
  - **i.e. the processes causing the absorption & scattering**
- **Because filters are not *monochromatic* (i.e. they have some bandwidth), the effective wavelength depends on the object's *colour index (e.g. B – V)***

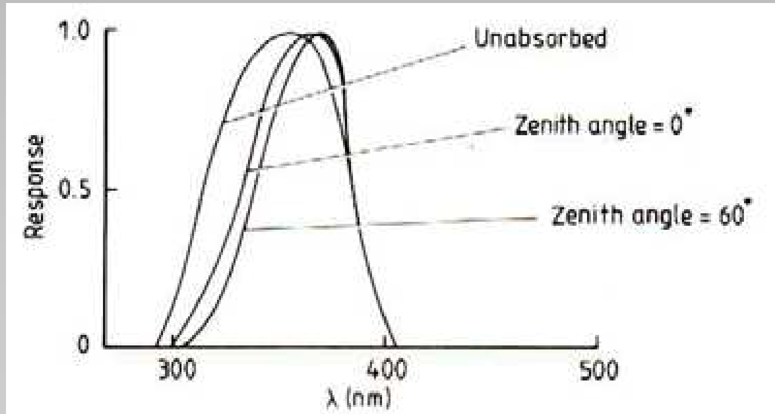
$\Rightarrow$ *k* has a colour dependency:

$$k_\lambda = k_\lambda' + k_\lambda'' (B - V)$$

k_λ': Primary extinction coefficient

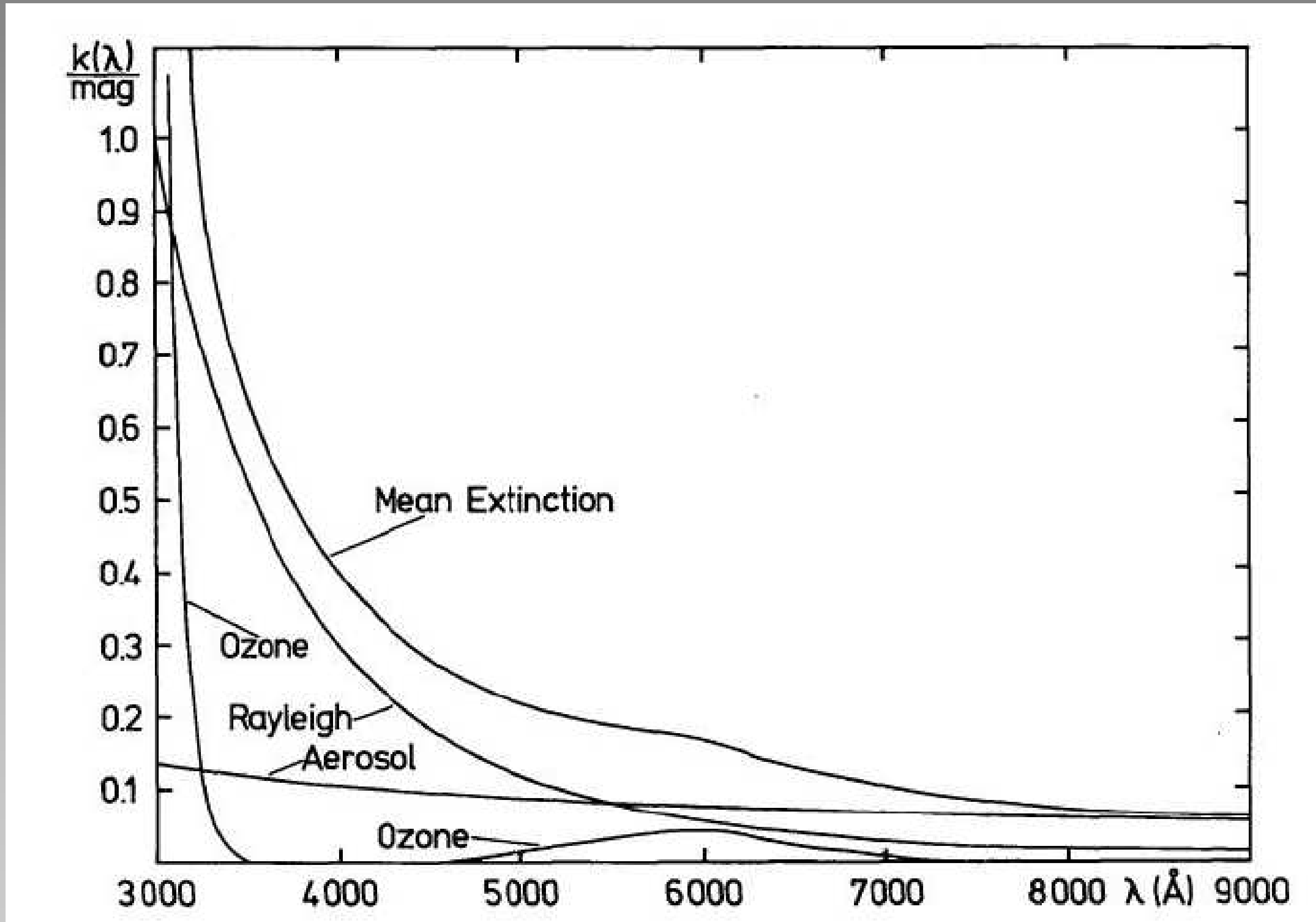
k_λ'': secondary extinction coefficient





Extinction Coefficient

- **Increases *exponentially* to short λ**
- **Correct magnitudes to out-of-atmosphere values**
- **Use stars of known (and constant) magnitudes and colours to determine extinction coefficients**



Extinction Coefficient

- **Ideally extinction coefficient is constant and just a function of the observing site**
  - **Dependent on altitude (e.g. can be above inversion layers of atmosphere)**
  - **Dependent on the aerosol content**
  - **In the IR dependent upon the water vapour content**
- **In reality extinction can change**
  - **Dust can be more prevalent in certain seasons (e.g. late spring in Sutherland sometimes suffers from Kalahari dust)**
  - **Pollutants can vary during the year (e.g. pyrogenic aerosols from veld fires; volcanic dust from eruptions; pollens from plants; dust during windy episodes)**

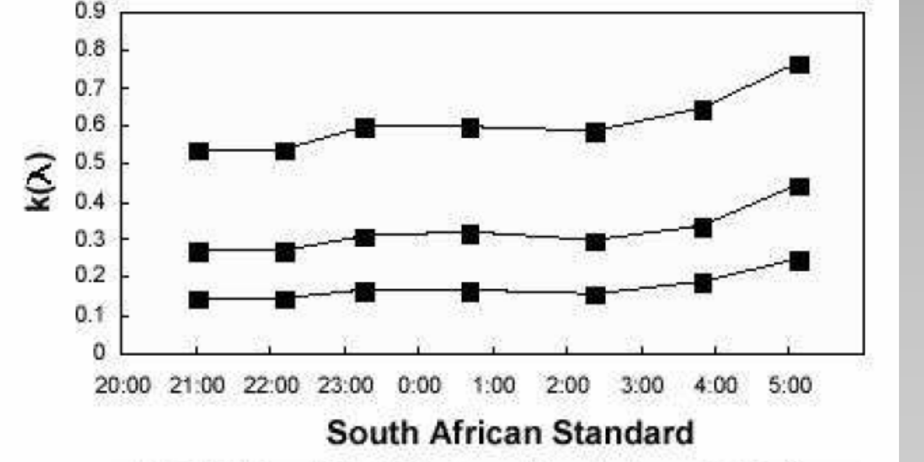
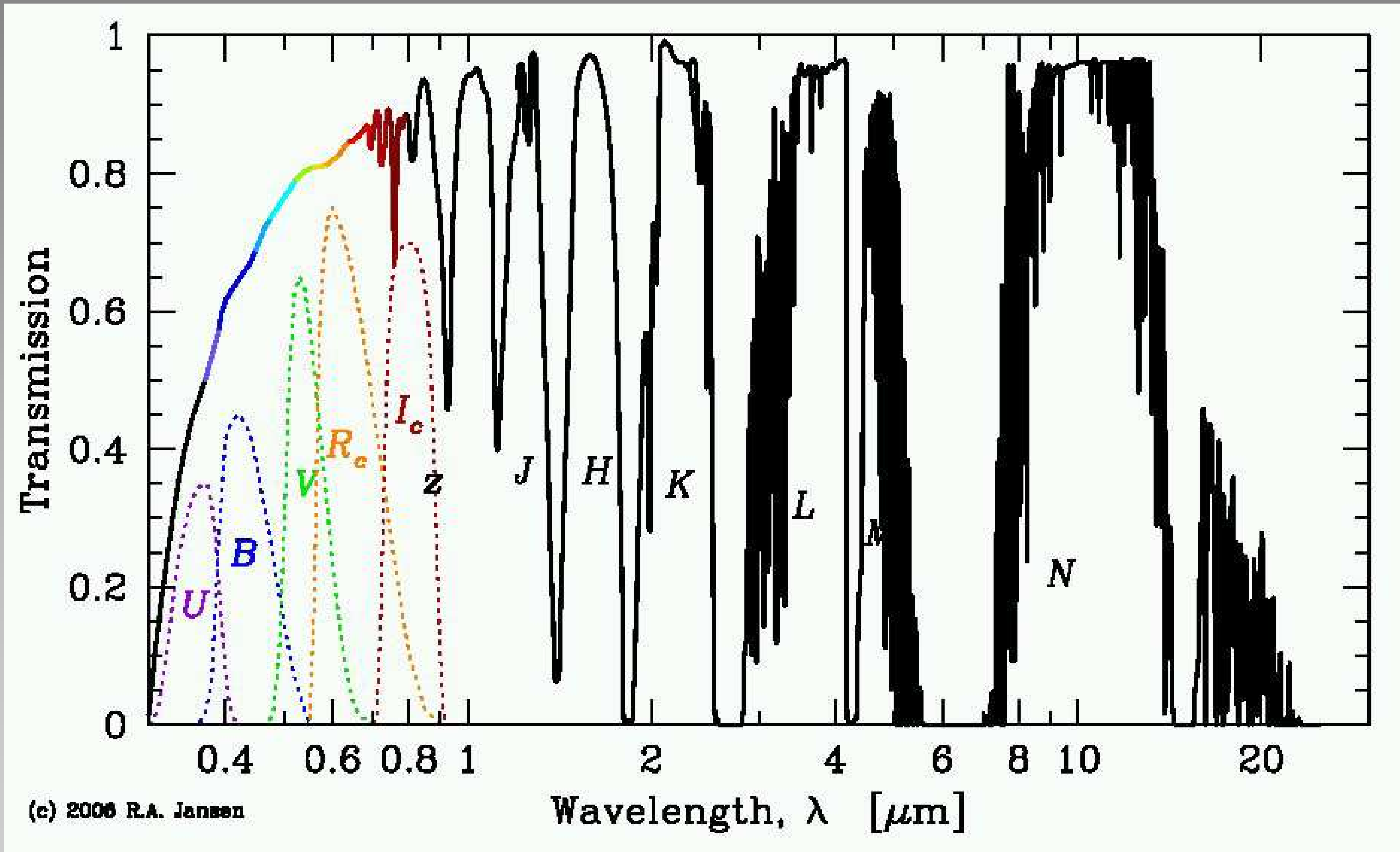


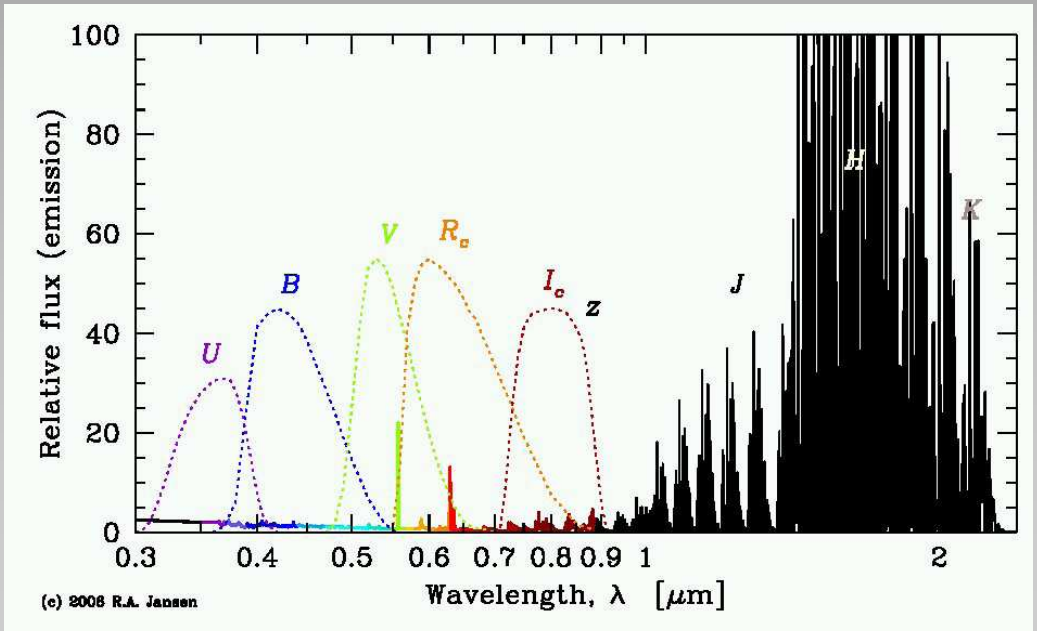
Fig. 2. Variations in the total k_U, k_B and k_V extinction coefficients (from top to bottom) during the night 29–30 September 1997.

Atmospheric Transmission

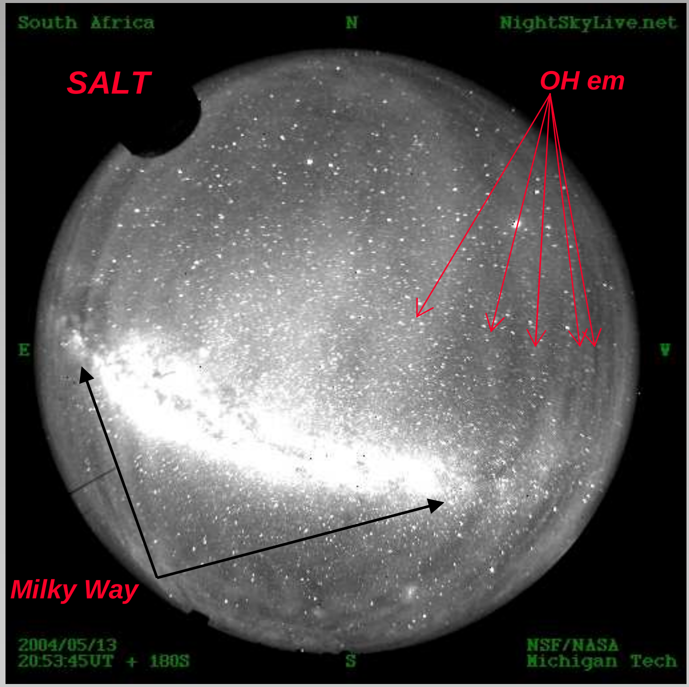


Atmospheric Emission

- Caused by emission from atoms and molecules in atmosphere, at night
  - "Airglow" lines from excited O, N & Na (e.g. 5577, 6300, 6363Å of O some of the strongest)
  - OH^- emission in the IR (gravity waves in atmosphere)
- Additional source of background emission (plus "sky" from lots of unresolved stars & galaxies)
- Need to subtract background to obtain object brightness
  - Aperture photometry uses some "blank" region of sky
  - 2-D imaging median filter to remove stars & fit sky

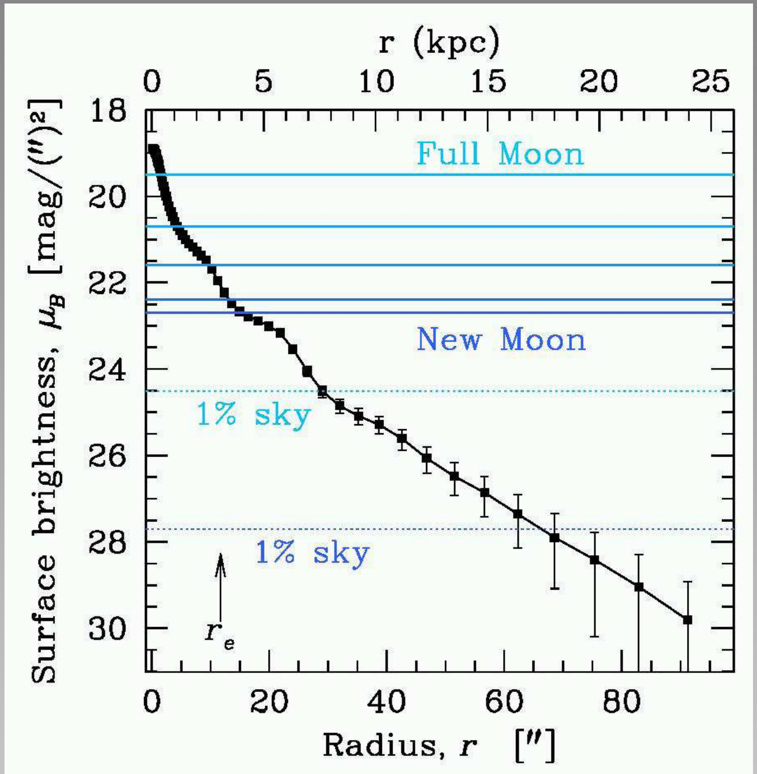


Sutherland CONCAM all-sky image



Contributors to Sky Background

- **Moonlight adds to sky background**
  - **Essentially a Rayleigh scattered Solar spectrum**
  - **See Solar absorption features in spectra**
- **Fainter objects harder to observe when Moon is around**
  - **Contrast is less**
- **Light from the dust in the Solar System**
  - **Zodaical glow of dust scattering sunlight***



***Brian May (*Queen*) obtained his PhD on Zodaical dust in 2007, ~30 years after he suspended his studies in favour of a non-astronomical career!**

Optical/IR Observational Astronomy

Photometry I

Photometric Observations

- Measure brightness with a photometric ***system***
- Correct for background
  - Subtract off "sky"
- Correct for extinction
  - Apply airmass correction
  - Determine extinction coefficients from observations of standard stars over range of airmass
  - Alternatively, use canonical (default) coefficients and make small "zero point" corrections using observations of standard stars
- Determine the standard magnitudes & colours
  - "Transform" magnitude and colour measurements from the *system* or *instrumental* magnitudes to the standard magnitudes
    - » *Absolute or "all sky" photometry*
  - Achieved using observations of standard starts of known magnitudes in the photometric system being used (e.g. UBVRI)
  - Needs *"photometric"* conditions, i.e. completely clear and stable extinction, also called good atmospheric "transparency"

Differential Photometric Observations

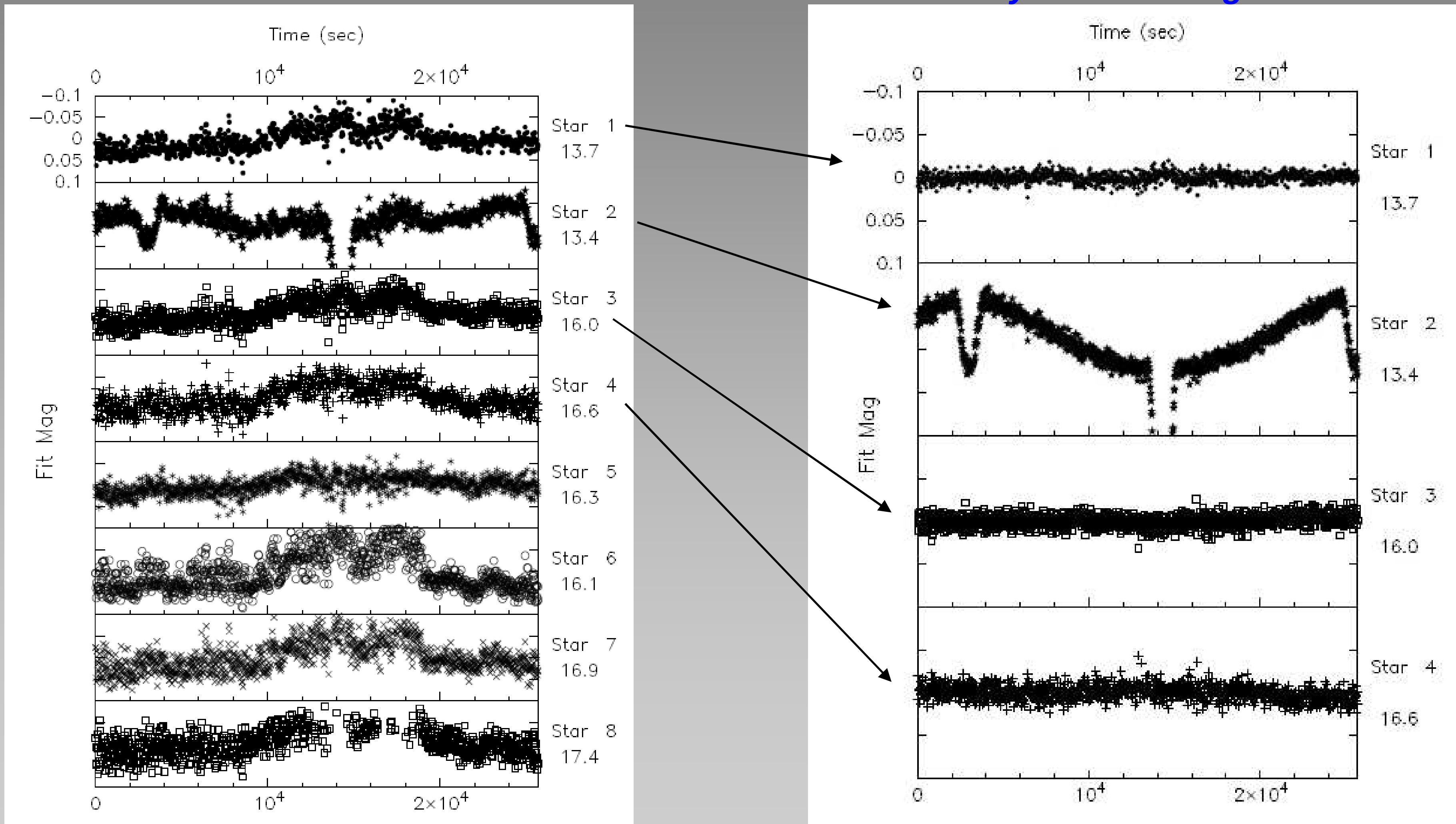
- Alternatively conduct ***differential*** photometry
  - Compare relative magnitudes between object of interest and a "comparison" star nearby
  - For single channel systems (e.g. photomultiplier-based photometers), need to flip back & forth between object & comparison star
  - Single channel devices use *aperture photometry*
  - Two channel devices can measure two stars simultaneously
    - » Sometime possible to observe in non-photometric conditions

      e.g. thin uniform cirrus cloud cover
  - 2D imaging devices (e.g. CCDs) can measure ***many*** stars simultaneously
    - » Able use several stars as "comparisons"
    - » Statistically better (average brightness over many stars)
    - » Can use profile fitting to PSFs as well as aperture photometry
  - On SALT can ***only*** do differential photometry, due to varying effective collecting area of the telescope

Differential Photometry

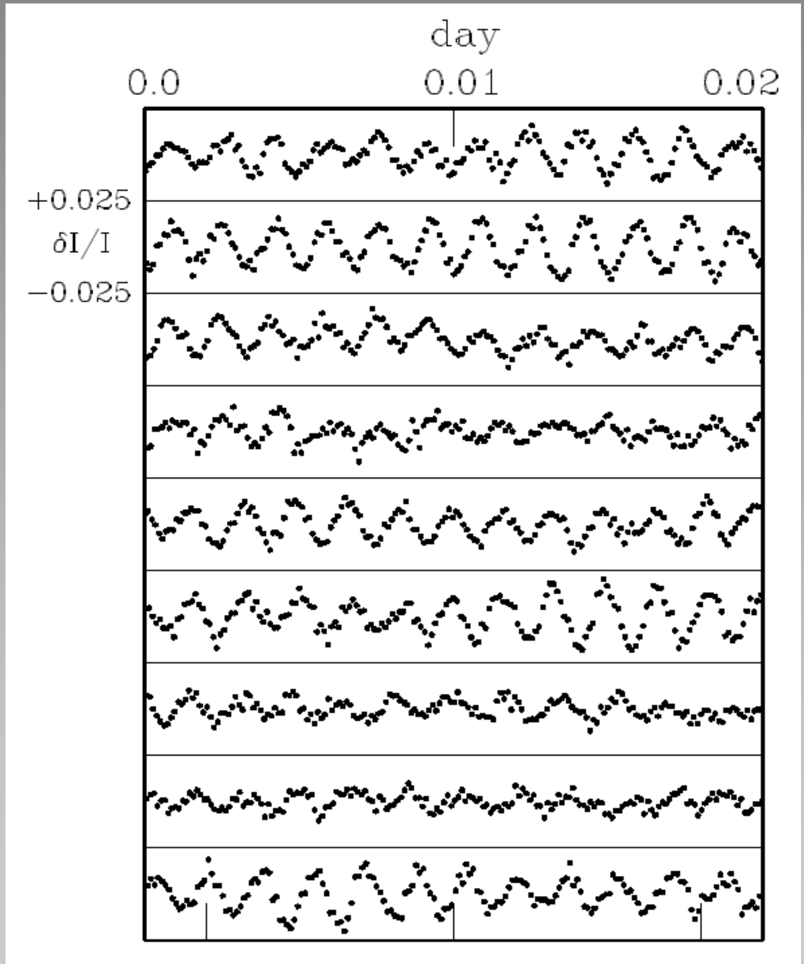
Uncorrected light-curves

Differentially corrected light-curves



Time Resolved Photometry

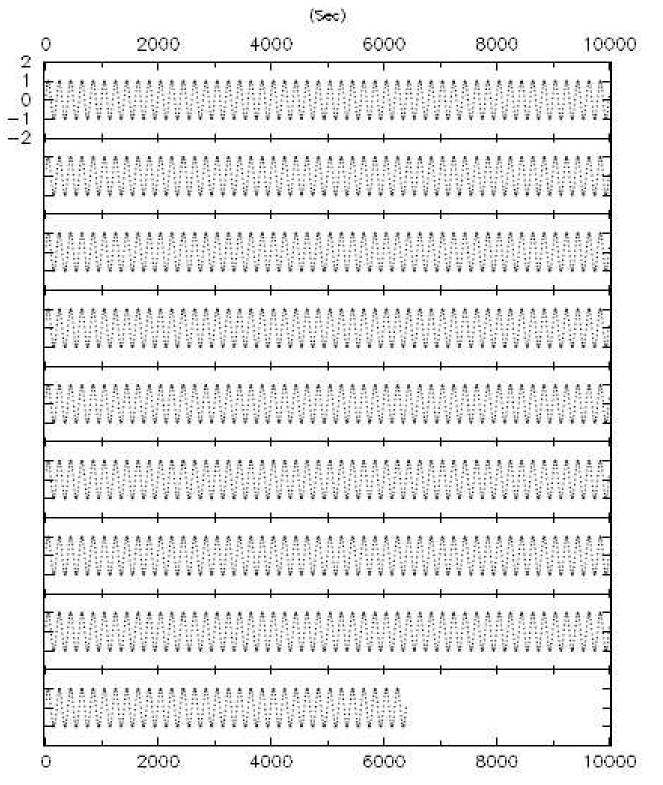
- **Important for *<u>any</u>* time varying sources**
- **Long observing spans (hours, all-night) sometimes important for detecting *<u>multi-periodic</u>* light variations**
  - **From stellar pulsations**
  - **Spin, orbital & beat period variations**
- **Analysis of light variations usually done by Fourier analysis, or similar techniques**
  - **e.g. attempt to match data with a series of sinusoidal variations**
  - **Varying amplitude, frequency & phase**
- **Produce a *<u>power spectrum</u>* (∝ amplitude^2)**
  - **Shows the likely *<u>periodic</u>* frequencies that, combined together, can explain the observed light curves**

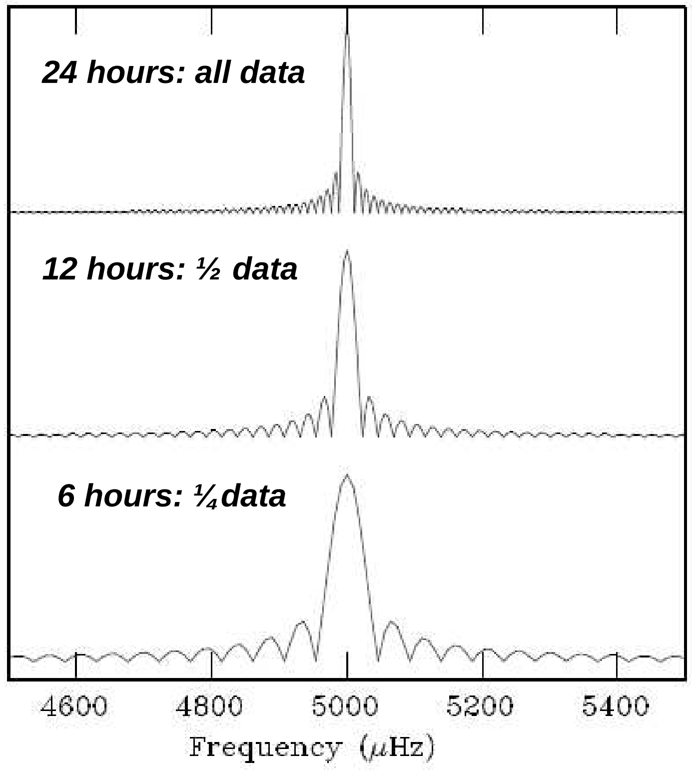


Fourier Theory

- **Power spectrum (= periodogram) of an *infinitely long* single periodic sinusoid will be a *delta function* (i.e. a “spike”)**
- **Actual data is *finite* and the corresponding periodogram will have single peak of a *sinc function***

24 hour light curve for a single periodic cariation at *P = 200 sec* (ν = 5 milli Hz)

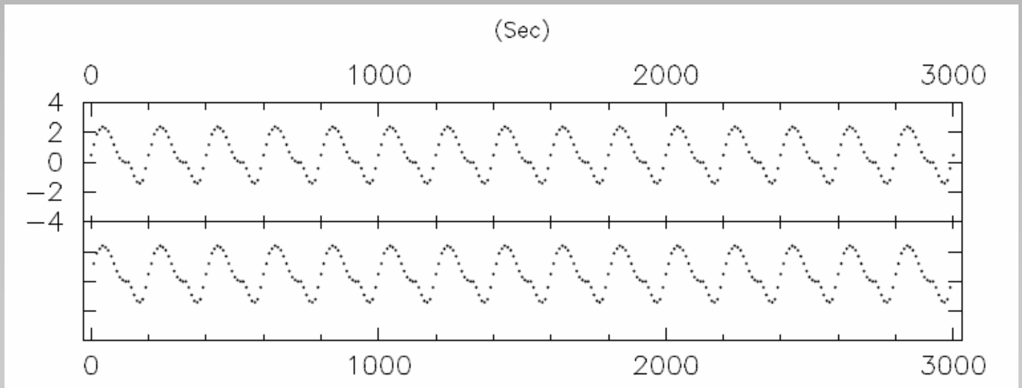




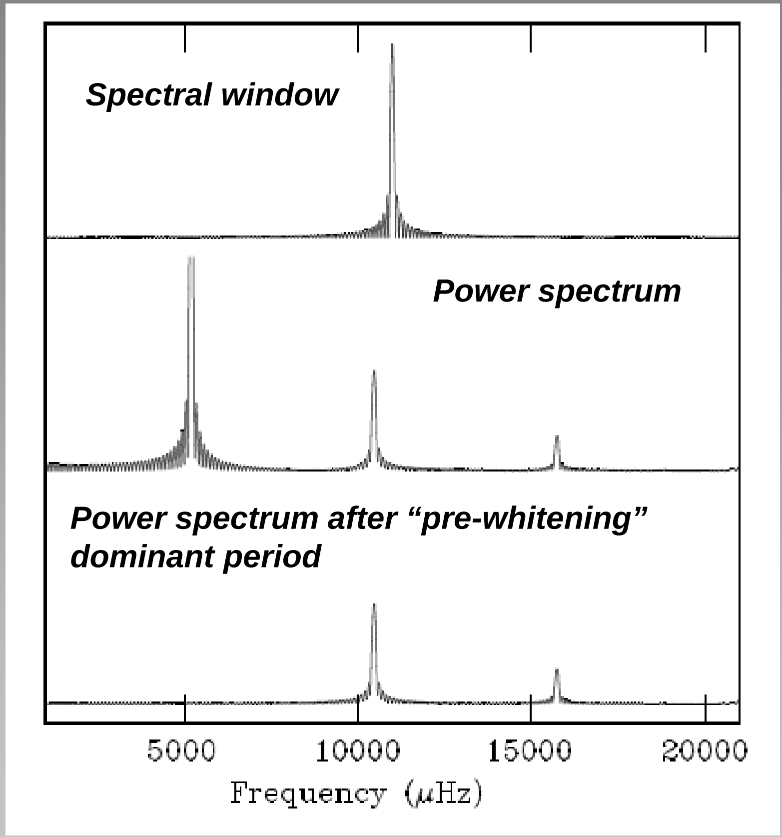
Fourier amplitude spectrum for various segments of the light curve at left

Harmonics

- **Sometimes light variations are *non-sinusoidal***
  - **e,g, in pulsating stars like RR Lyr**
- **Can still simulate the non-sinusoidal shape by combining higher order *harmonics***
  - **Fundamental frequency (period), ν, has harmonics 2ν, 3ν, 4ν … nν**
  - **Attempt to fit data with combination of harmonics, varying their *amplitudes* and *phases***



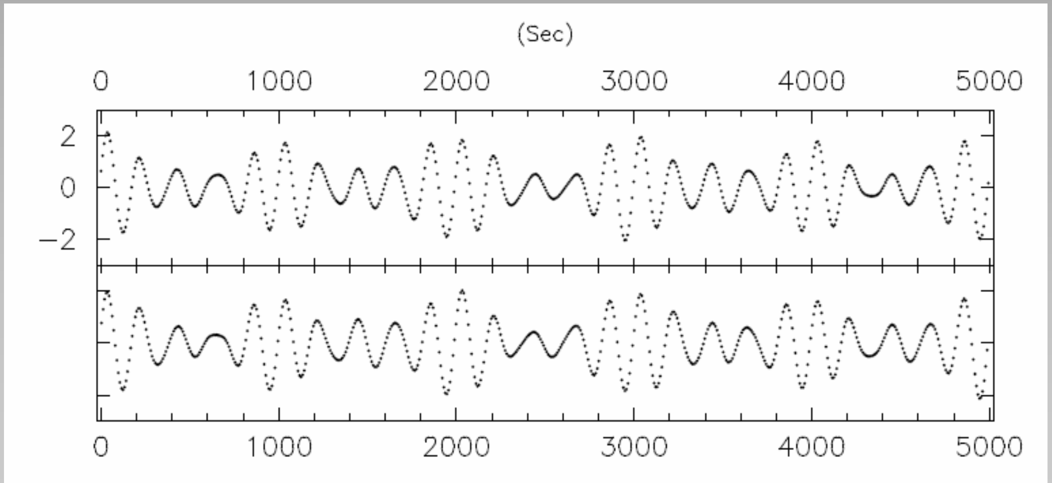
Simulation of non-sinusoidal variations

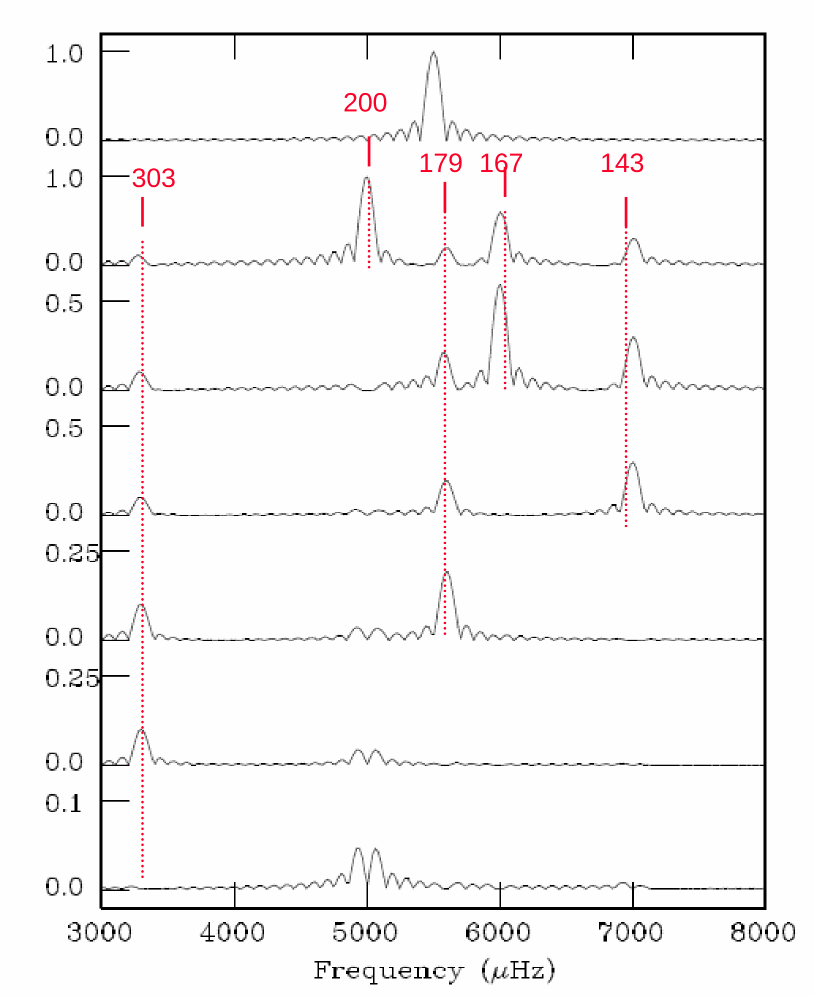


Power spectrum for the light curve at left shopwing the harmonic peaks

Multi-Periodic Variability

- Multiple periods show power spectra with ***multiple peaks***
- Simulation below is for 5 period (200, 167, 143, 179 and 303 sec)
  - See how periods interact and 'beat' together
  - Can see all 5 frequencies in periodogram
  - By doing best-fit of each period, can subtract each periodic signal ("pre-whiten") to enhance visibility of weaker periods





Determining Periodicities

- The resolution of peaks in a periodogram depends on ***data length***

  – The longer the observation span the narrower the period peak and the more precise is the period determination

  – Typically observing are < 8 hours or so (night length, hour angle range for object0

  – Interrupted by DAYLIGHT

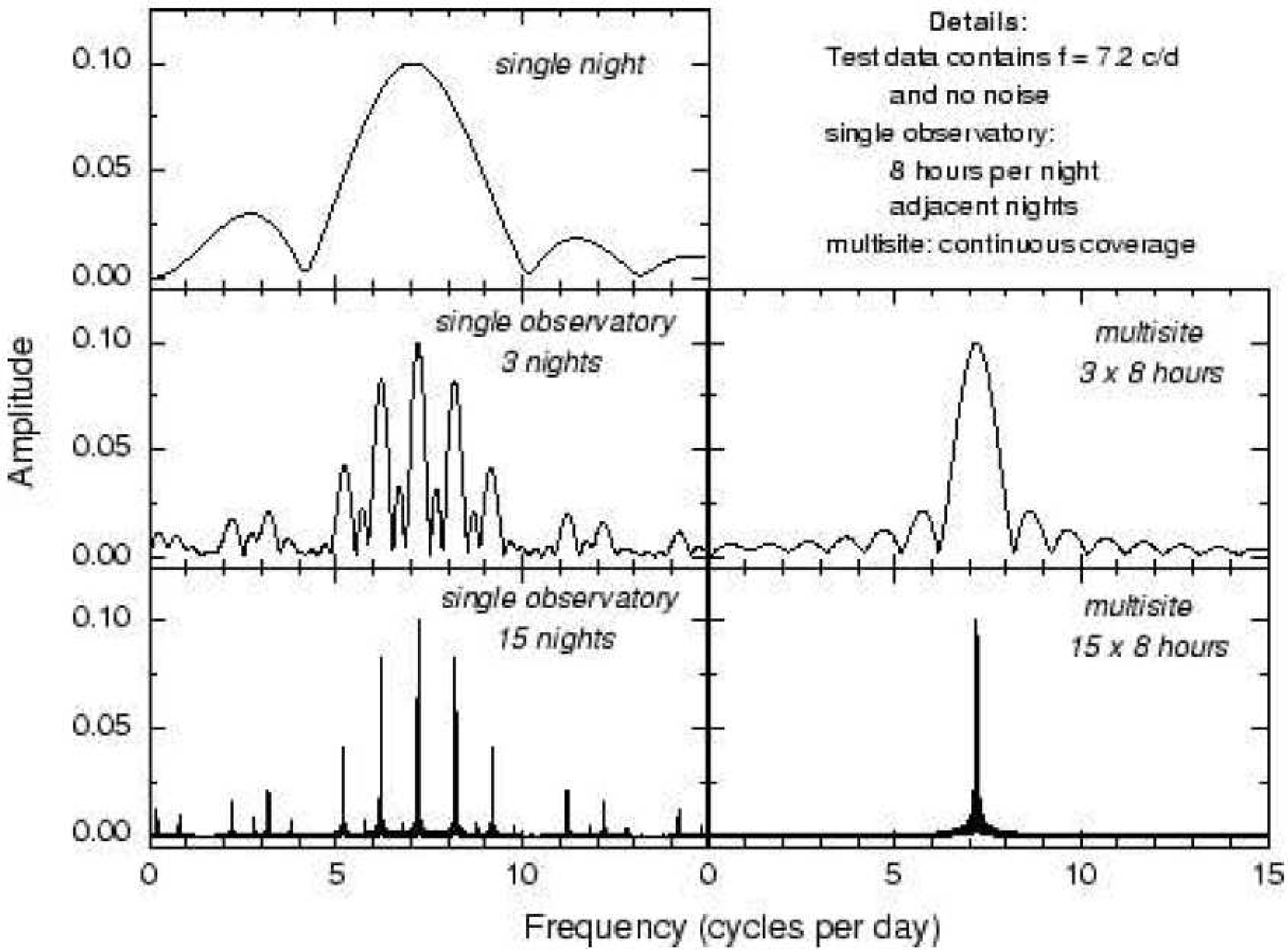
  – Causes “aliasing” of signals

    » Can fit data equally well with signals that differ by only 1 cycle per day

    » Ambiguous periods (typically 3-5)

    » Only way to reduce the ambiguity is to observe at other longitudes to fiull in the ‘gap’

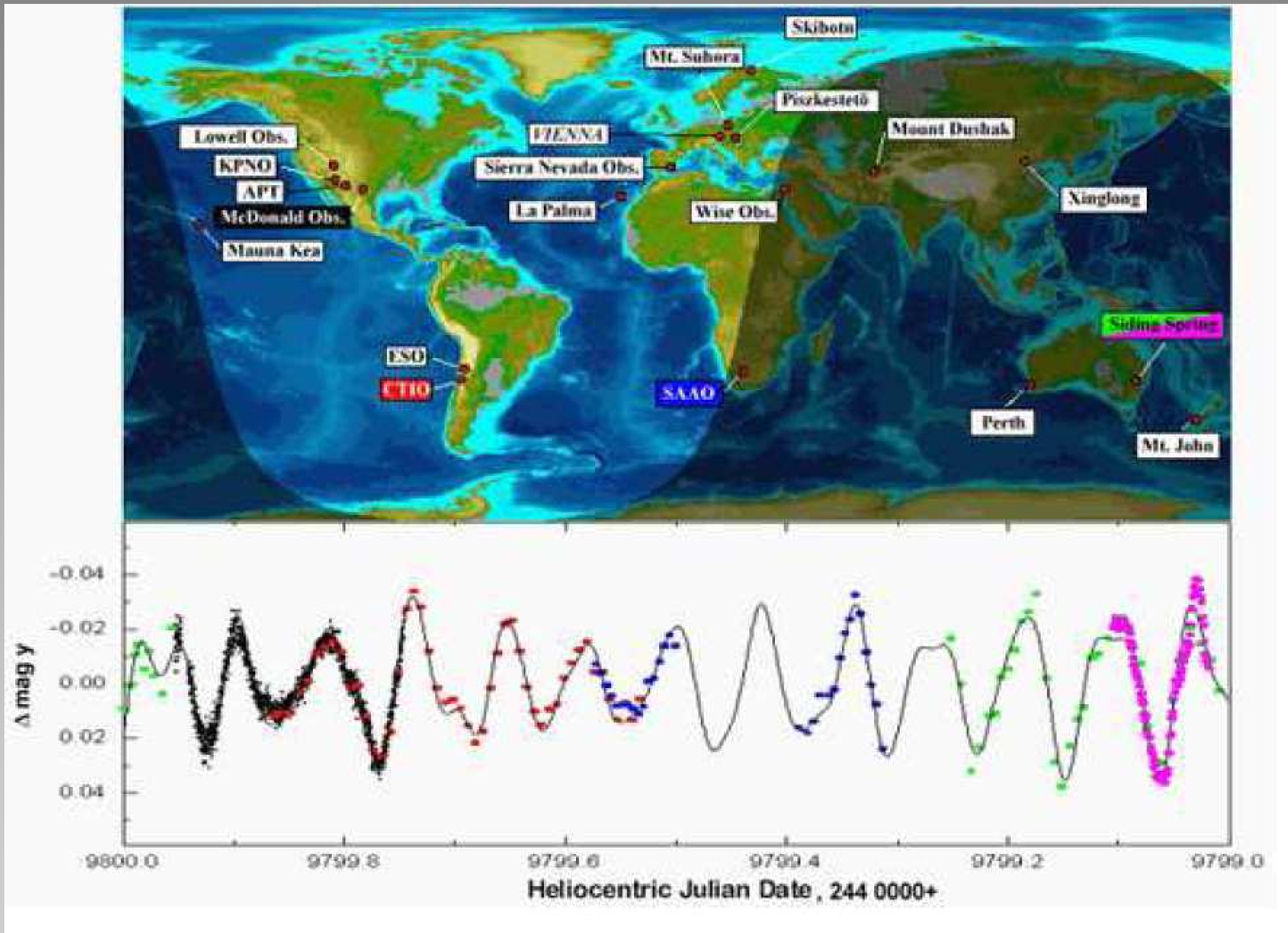
Determining Periodicities



Optical/IR Observational Astronomy

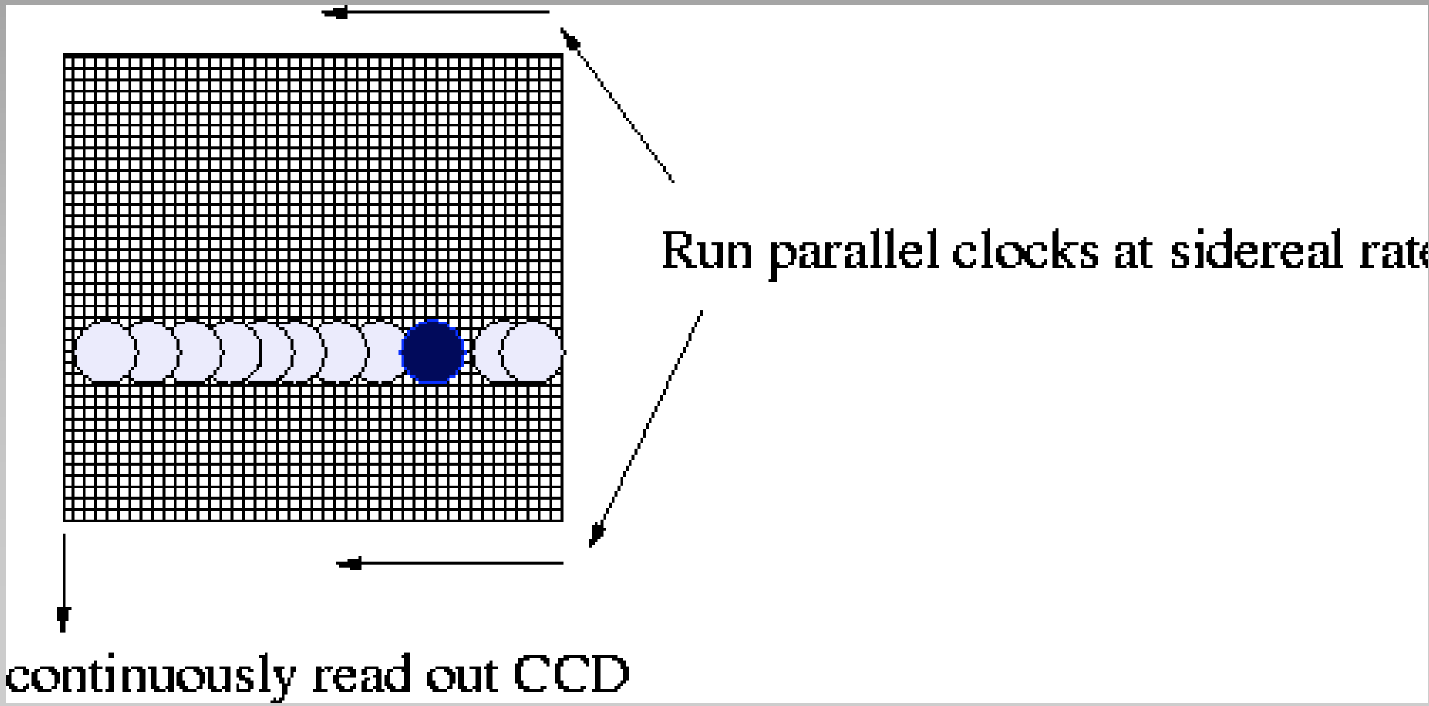
Photometry I

The *Whole Earth Telescope* (WET)



Drift Scanning: A Novel Photometry Method

- **Instead of letting the telescope *track* an object across the sky, let the object trail across the CCD detector**
  - **i.e. turn off the telescope drive, or drive it at a non-sidereal rate**
  - **Clock the CCD charge across the chip at the same rate the object moves**
  - **End up with a long strip image of the sky with a "height" = the CCD width and a length set by how long you let the drift run (or by how big your disk storage is).**



Drift Scanning: A Novel Photometry Method

- **The sky goes by at 15 arcseconds/second at the celestial equator and slower than this by a factor of 1/cos(δ) as you move to the poles**
  - ***With SALT, at the equator, with 4096 pixels x 0.13”/pixel, you get a total integration time per object of about 35 seconds.***

So, what’s the point?

- **Survey large strips of the sky**
  - **Good for large area surveys**
- **Superb flat-fielding (measure objects on many pixels and average out QE variations)**
- **Very efficient (don’t have CCD readout, telescope setting)**

Problem:

- **Only at the equator do objects move strictly in straight lines**
- **As you move toward the poles, the motion of stars is in an arc**
  - **So stars begin to “creep” in the direction perpendicular to star motion**
  - **Causes blurring, decreased S/N**
  - **Can’t drift-scan at high declinations**

Drift Scanning Example: Sloan Digital Survey