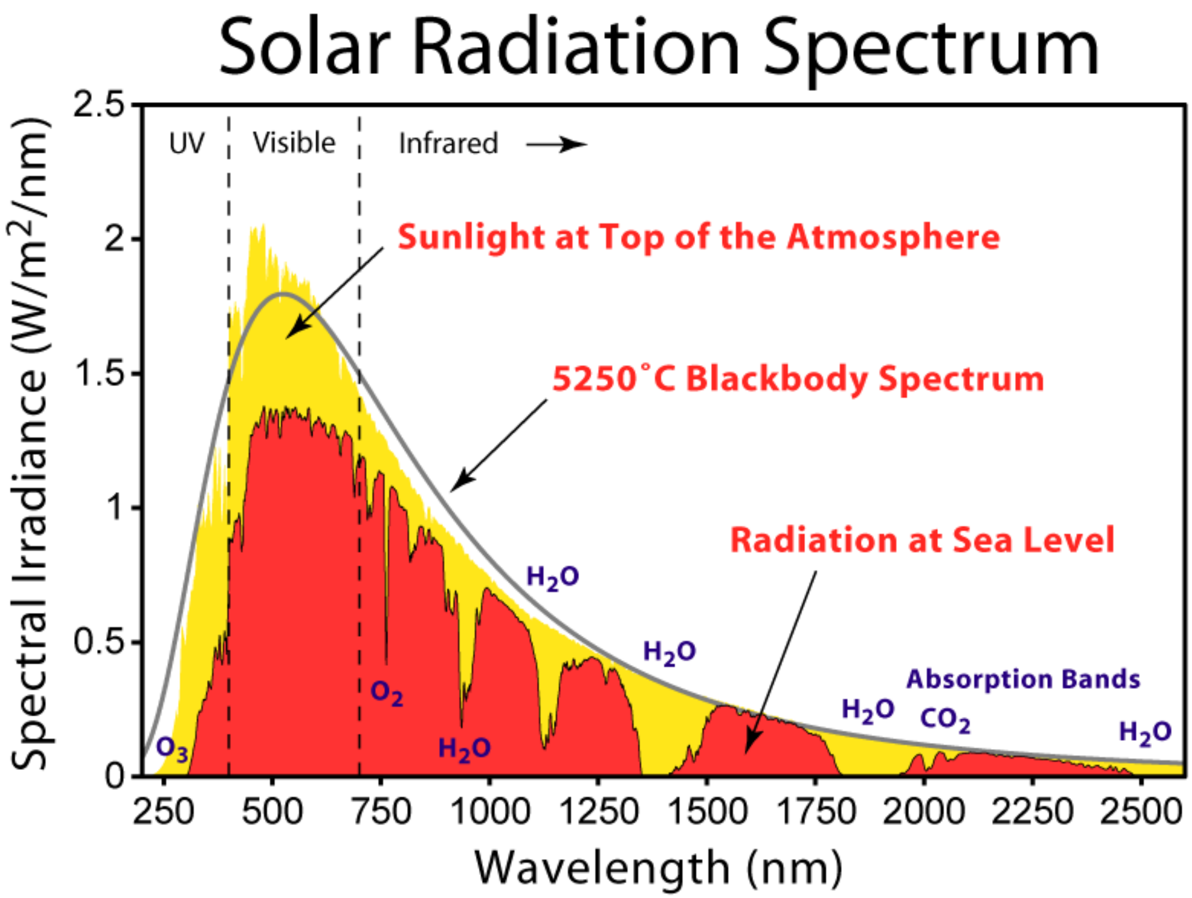
AST 453

- Some more basics on determining physical parameters of stars
- Photometry
- Luminosities
- Binaries, and relations between mass, radius, temperature for normal stars



Astrophysically Useful Numbers

For fundamental physical constants, see NIST CODATA page:

http://physics.nist.gov/cuu/Constants/index.html

Constants for Sun:

http://www.pas.rochester.edu/~emamajek/sun.txt

Solar radius $R_\odot$ = 695,660 km Solar Mass $M_\odot$ = 1.989e30 kg

Solar Luminosity $L_\odot$ = 3.827e33 erg/s = 3.827e26 W

Solar Effective Temperature $T_{eff\odot}$ = 5,772 K

Astronomical Unit = 149,597,870,700 m

Jupiter radius R_J = 71,492 km Jupiter mass M_J = 1.8986e27 kg

Earth radius R_E = 6,378 km Earth mass M_E = 5.9736e24 kg

A perusal of the astrophysics literature shows a mix of units:

SI, cgs, solar units, eV, Angstroms. Get used to converting units!

Apparent magnitudes: stellar photometry

$m - m_0 = -2.5 \log_{10}(f/f_0)$

$m = -2.5 \log_{10}(f) + \text{zeropoint}$

f = observed flux, m = magnitude

Usually this measured at some effective wavelength λ and measured with respect to some reference object (the star Vega has often been used).

Units of flux "f" are usually either quoted in either

erg/s/cm^2/Angstrom

erg/s/cm^2/μm

erg/s/cm^2/Hz

Jansky = $1 \text{ Jy} = 10^{-26} \frac{\text{W}}{\text{m}^2 \cdot \text{Hz}}$ (usually used in radio and IR)

http://www.astro.utoronto.ca/~patton/astro/mags.html

Absolute Magnitudes

Absolute magnitude M is the star's brightness at 10 pc

Distance modulus (m – M) $= -2.5 \log((L/d^2)/(L/(10pc)^2))$

$= 5\log(d_{pc}) - 5$

For Sun at "V" band (λ=0.55μm), m_V= -26.75, M_V= 4.82

On this system m_V(Vega) = 0.03 (don't ask why not zero…)

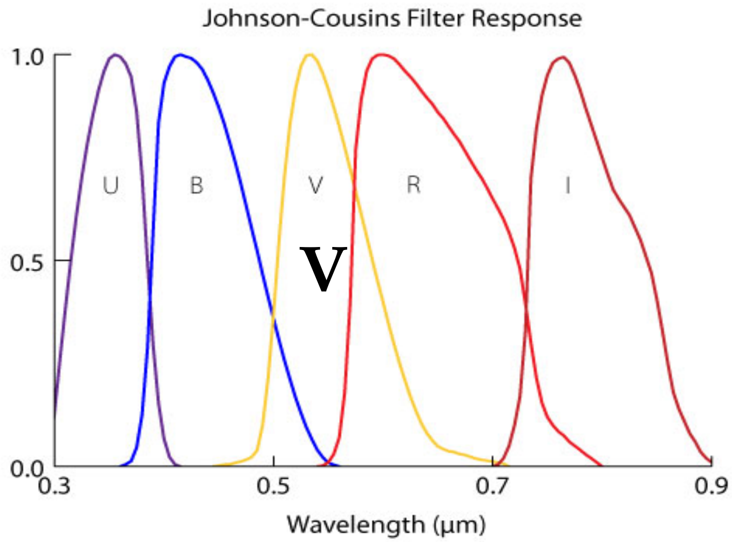
Example: Vega has apparent V-band mag: m_V(Vega) = 0.03

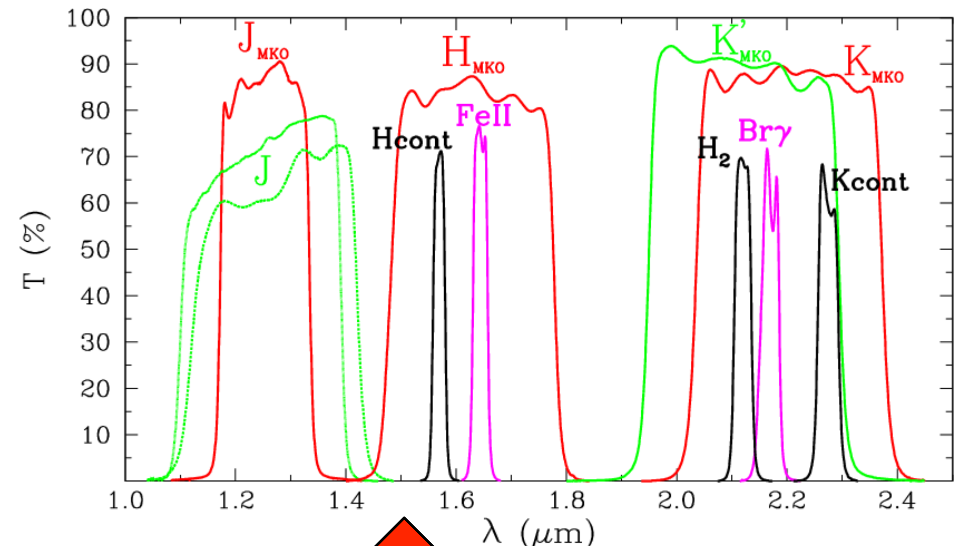
And parallax ϖ = 0.129 arcsec => Distance = 1/ϖ = 7.75 pc

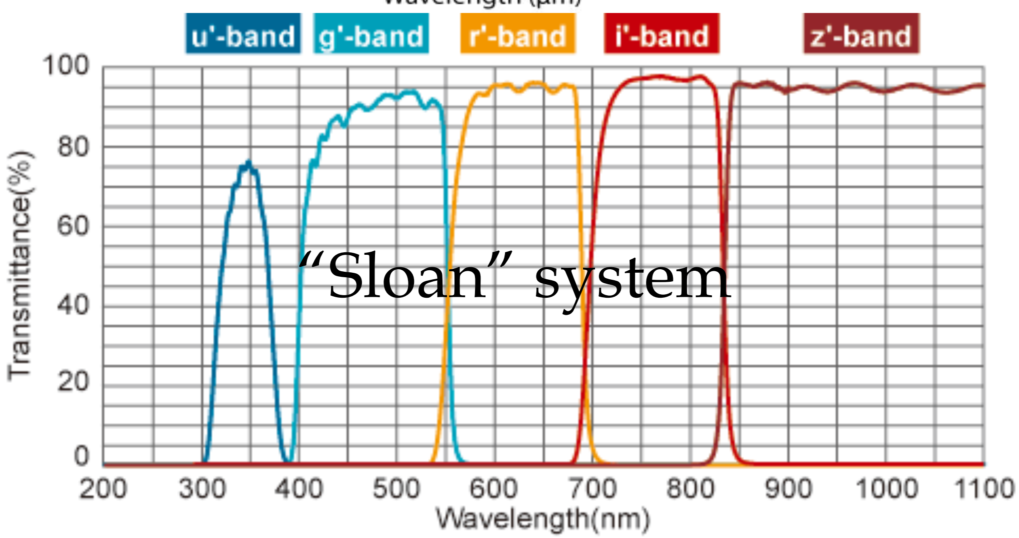
so absolute magnitude of Vega in V-band is: M_V = 0.58

Databases on magnitudes, parallaxes (distances) for stars: SIMBAD, VizieR, NStED

Filters for measuring brightnesses at various λ





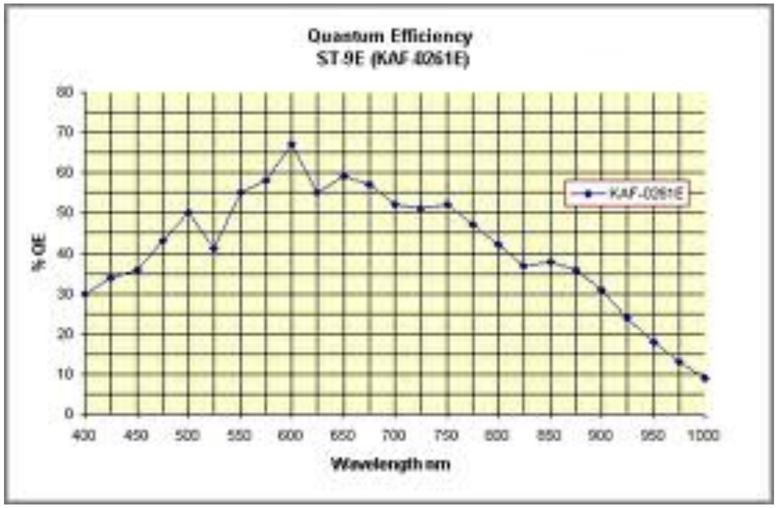


Infrared (λ > 1 μm) Bandpasses are optimized to avoid where Earth's atmosphere is opaque

e.g. http://www.asahi-spectra.com/opticalfilters/astronomical_filter.html

Ghinassi et al. 2002

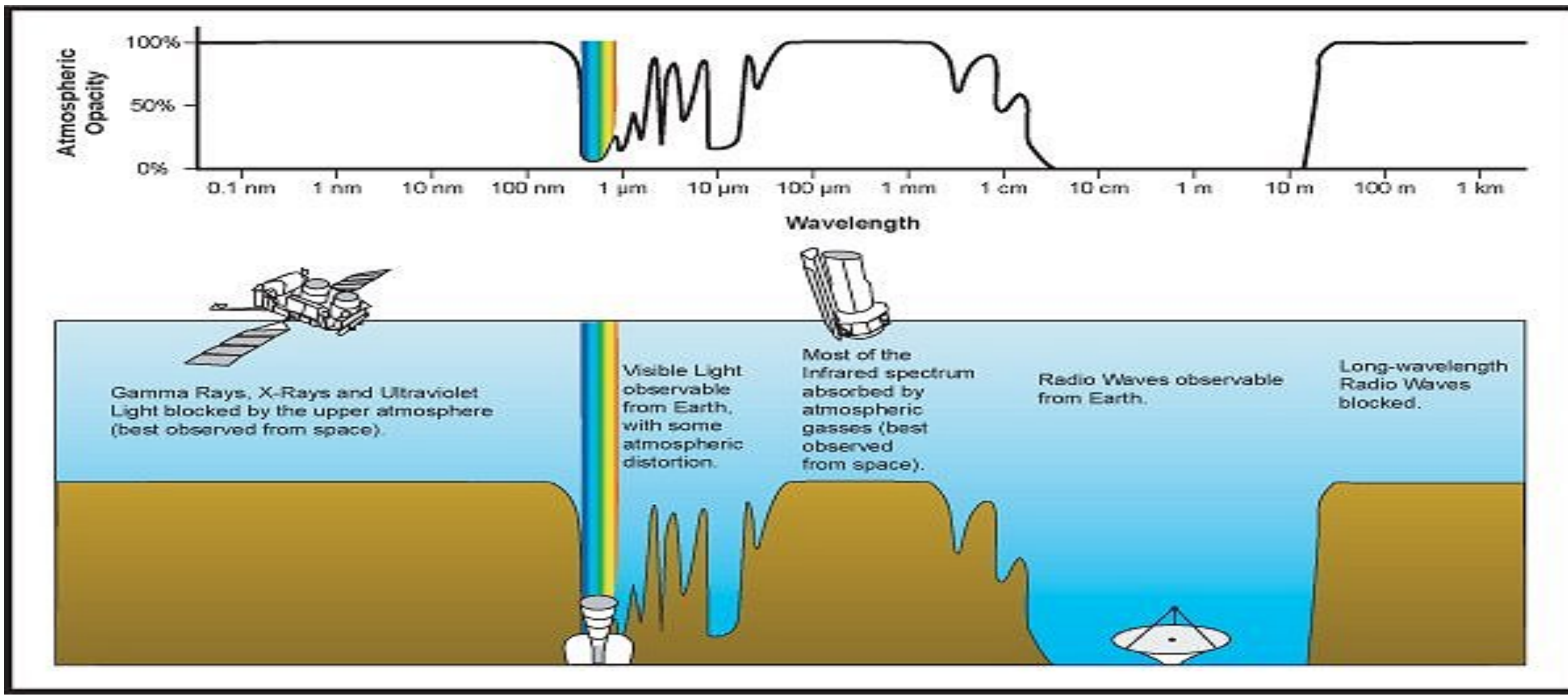
Other transmission profiles to keep in mind



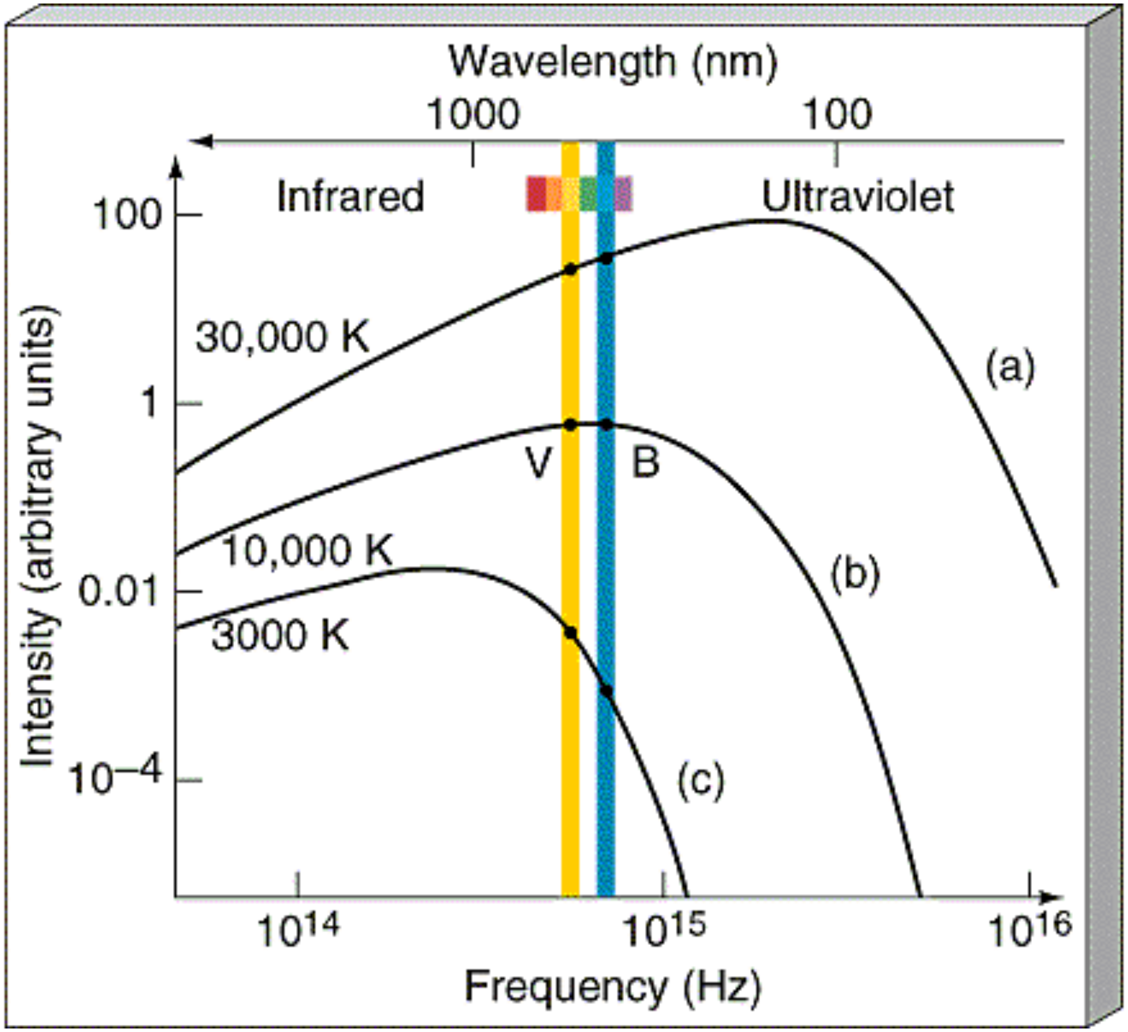
Typical CCD QE curve

[Santa Barbara Instrument Group]

Earth's atmospheric "windows"



Brightness/magnitude at two λ s => Colors



$m_B - m_V = B - V$
$= -2.5 \log(f_B/f_V)$

Where B-V = 0.00 mag
For Vega
($T_{eff} \sim 9500$ K)

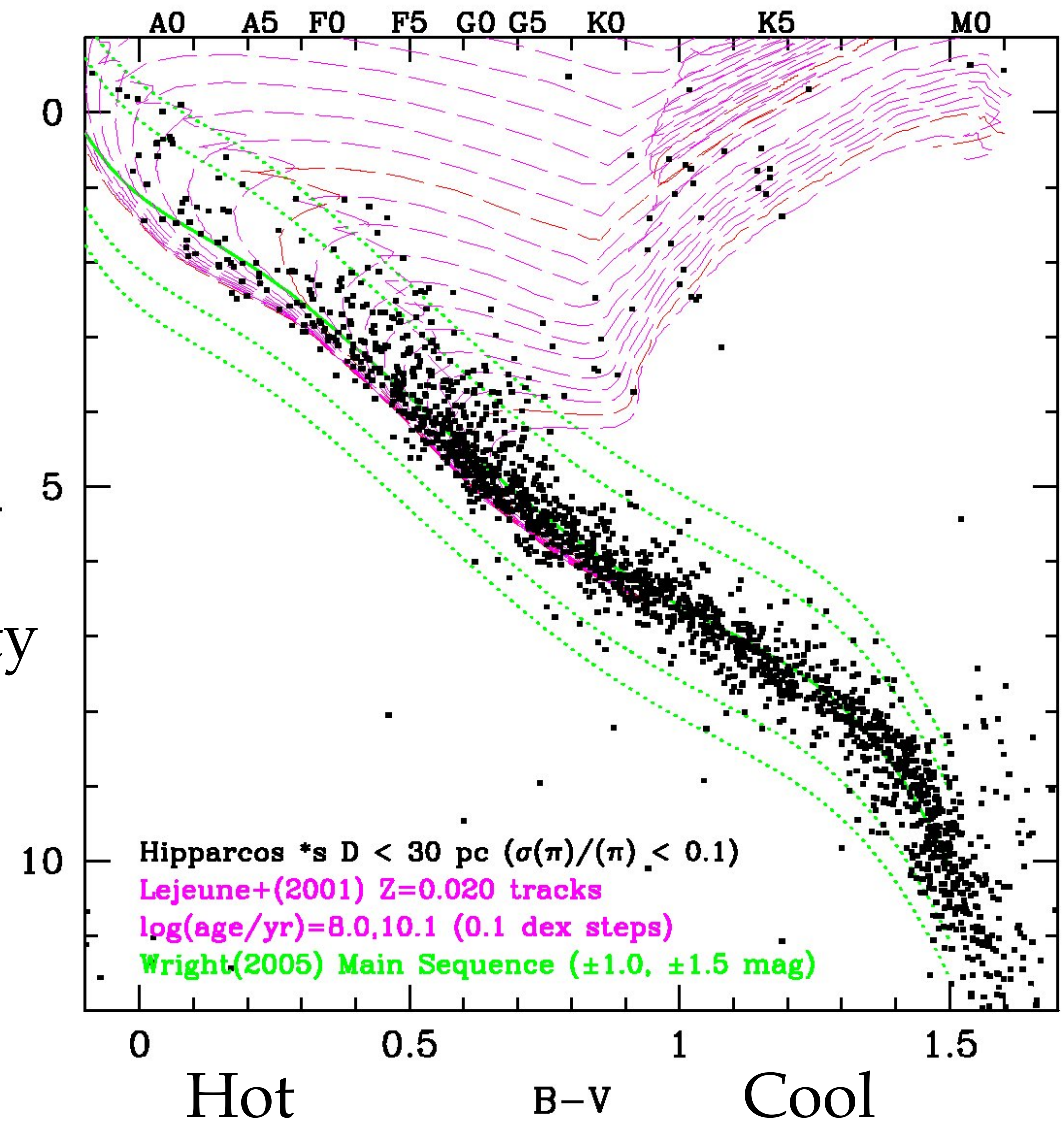
B-V(Sun, $T_{eff} = 5778$K)
= 0.65 mag
B-V($T_{eff} = 30000$K)
= -0.32 mag
B-V($T_{eff} = 3000$K)
= 1.8 mag

Combining colors and absolute magnitudes => HR diagram

Bright

Intrinsic
Brightness
~ Luminosity

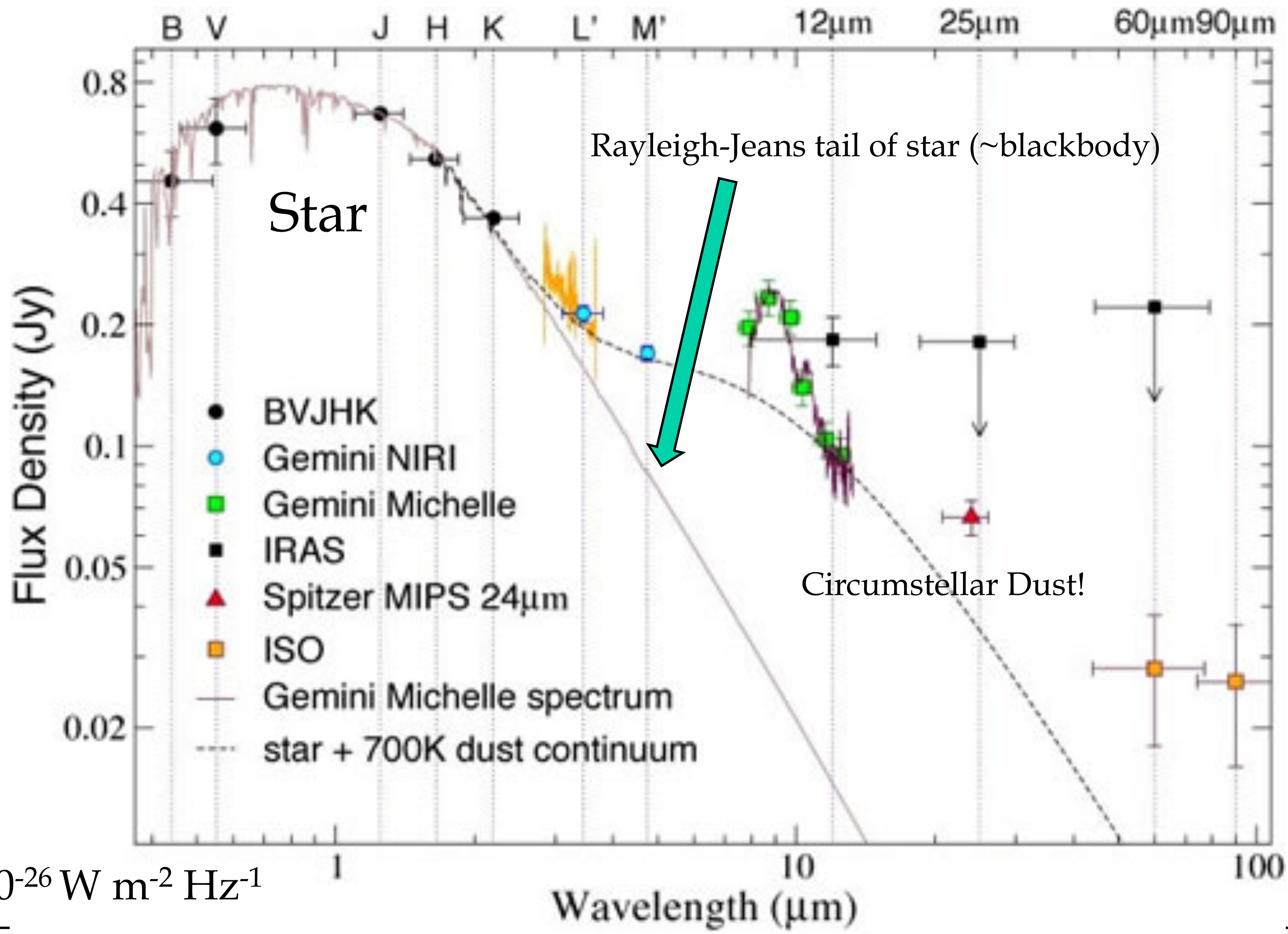
Dim



Hot Cool

Stars
Within
30 parsecs
in Hipparcos
catalog

How do we calculate luminosity with magnitudes (at some λ) and distances?



1 Jy = 10^{-26} W m^{-2} Hz^{-1}

Rhee et al. 2007

How do we calculate luminosity with magnitudes (at some λ) and distances?

We can work with "bolometric magnitudes" (m_{bol}) –
i.e. accounting for a star's light at (ostenisbly) all wavelengths.

$m_{bol} = m_V$ (V-band magnitude) + BC ("bolometric correction")

The "BC" accounts for the light not being emitted in the band whose magnitude you've measured (in this case all the light blueward and redward of the V-band ~0.55μm filter).

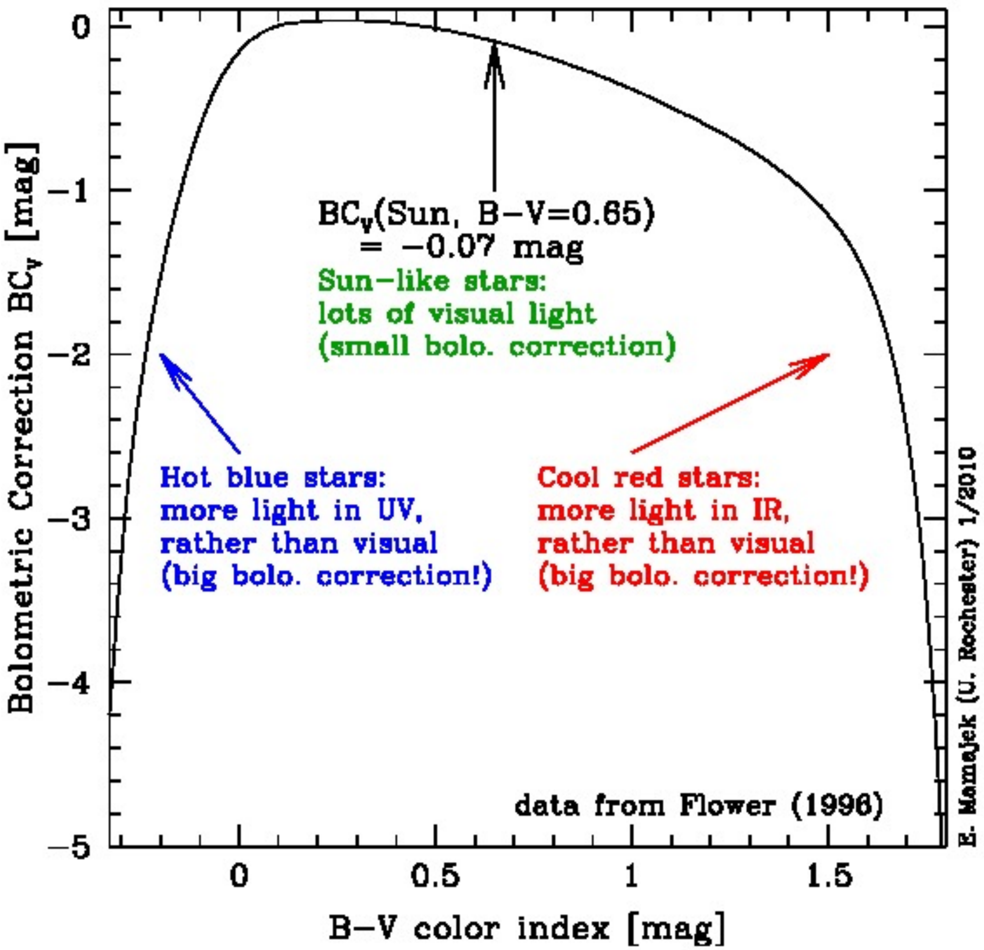
Absolute bolometric magnitude: $M_{bol} = m_{bol} - 5\log(d_{pc}) + 5$

m_V(Sun) = −26.74 ; M_{bol}(Sun) = 4.75 mag (by convention)

M_V(Sun) = 4.83 ; BC_V(Sun) = −0.08 mag

Bolometric corrections (getting luminosities from magnitude at one band!)

Bolometric correction at V-band
for main sequence stars



Shape of spectrum, and this correction factor, can be determined if one knows the color of the star (difference between apparent magnitudes at two λ s).

A scaling factor for flux is the same as an offset in magnitude. This offset is called the bolometric correction, *BC*, and is determined **empirically** from observed stellar spectra.

$m_{bol} = m_V + BC$ $\qquad B - V = m_B - m_V$

Luminosity… finally!

$\text{Log}_{10}(L/L_{sun}) = -0.4(M_{bol} - M_{bol}(\text{Sun})) = -0.4M_{bol} + 1.90$

Where $L_{sun} = 3.827 \times 10^{33}$ erg/s = 3.827×10^{26} W

Origin: spacecraft measurements measure "**solar constant"**

to be 1361 W/m^2 at 1 AU distance from Sun: and $L = f * 4\pi R^2$

Stefan-Boltzmann law: surface flux = $f_{bol} = \sigma\, T_{eff}^{\ 4}$

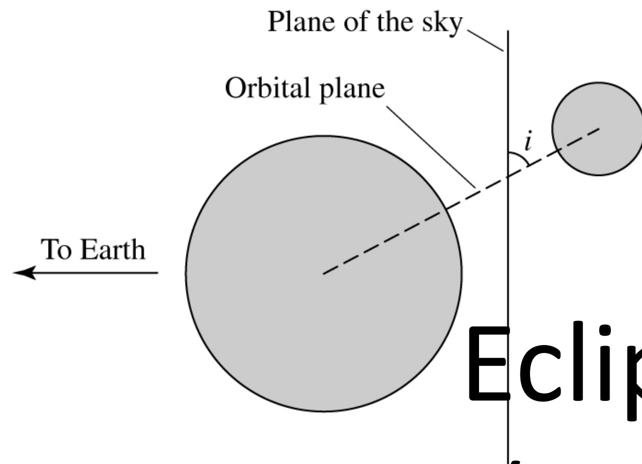
σ = Stefan-Boltzmann Constant = 5.67×10^{-5} $erg/cm^2/s/K^4$

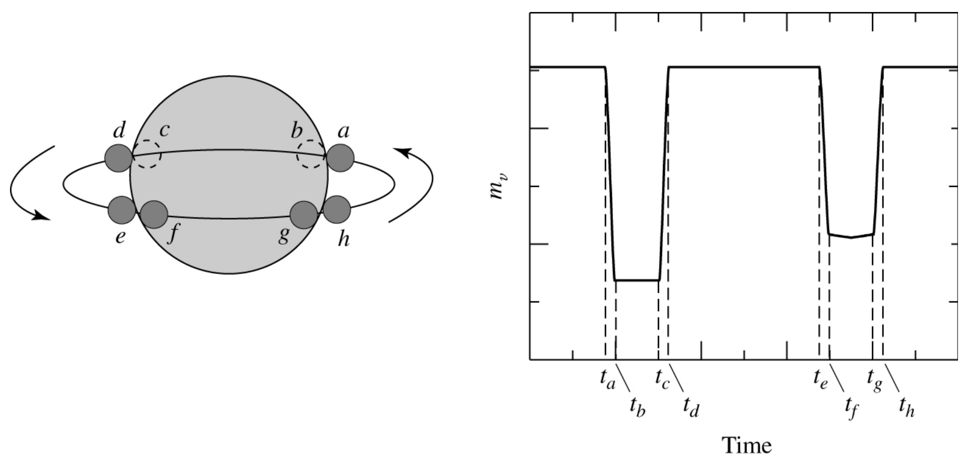
Luminosity $L = 4\pi R^2\ (\sigma T^4)$

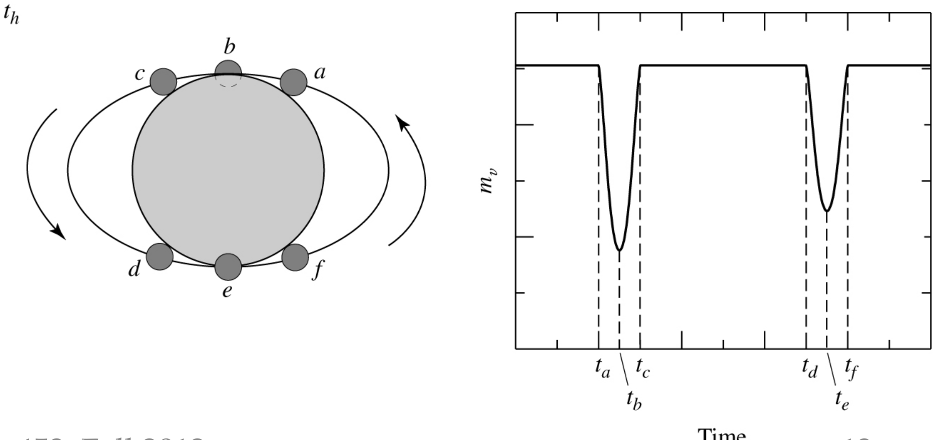
Sun's radius is opaque to radiation at R_{sun} = 695, 600 km

We define the star's **effective temperature** T_{eff} to be the temperature of a blackbody that would emit the same luminosity (power) as a star of a given radius

Eclipsing Binaries (primary source of accurate stellar masses)





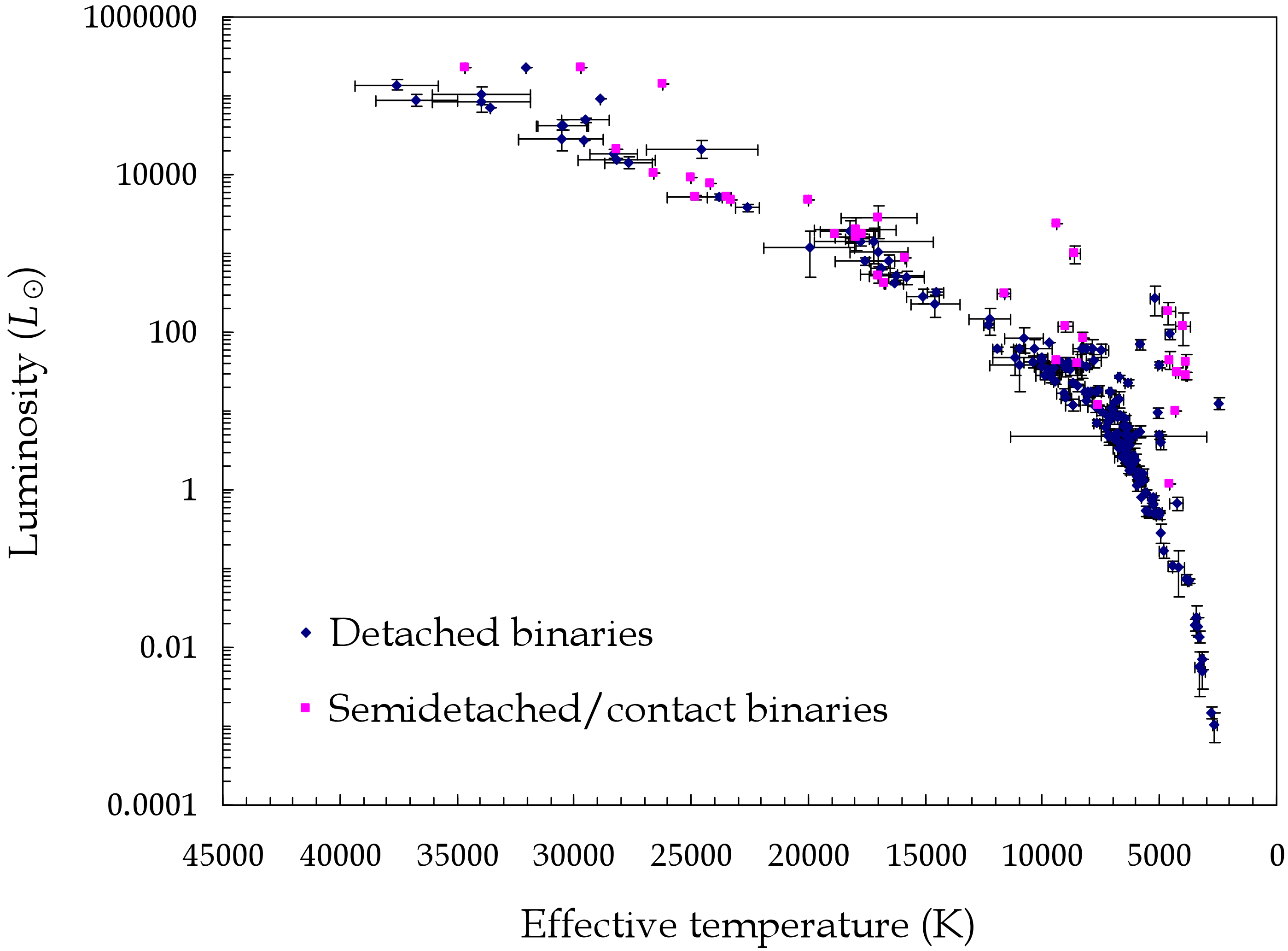


Binaries from which one gets useful mass measurements

Most normal stars turn out to be members of binary systems.

- Resolved **visual binaries**: see stars separately, measure orbital axes and speeds directly. Few demonstrate "useful" orbital motion (i.e. period ~ τ_{human})
- **Astrometric binaries**: only brighter member seen, with periodic wobble in the track of its proper motion.
- **Spectroscopic binaries**: unresolved (relatively close) binaries told apart by periodically oscillating Doppler shifts in spectral lines. Periods = days to years.
    - Spectrum binaries: orbital periods longer than period of known observations.
    - **Eclipsing binaries**: orbits seen nearly edge on, so that the stars actually eclipse one another. (Most useful.)

Luminosity-temperature relation for binary stars (mostly eclipsing) with well-determined orbits



Compiled by Oleg Malkov (1993), based mostly on work over many decades by Dan Popper.

Stellar masses determined for binary systems

- If orbital major axes (relative to center of mass) or radial velocity amplitudes are known, so is the ratio of masses:

$$\frac{m_1}{m_2} = \frac{a_2}{a_1} = \frac{v_{2r}}{v_{1r}}$$

- If the period, *P,* and the sum of major axis lengths, $a = a_1 + a_2$, are known, Kepler's third law can give masses separately:

$$P = \frac{4\pi^2}{G(m_1 + m_2)} a^3$$

Stellar masses determined for binary systems

- If only radial velocities are known, the sum of masses (from Kepler's third law) is:

$$m_1 + m_2 = \frac{P}{2\pi G}\left(\frac{v_{1r} + v_{2r}}{\sin i}\right)^3$$

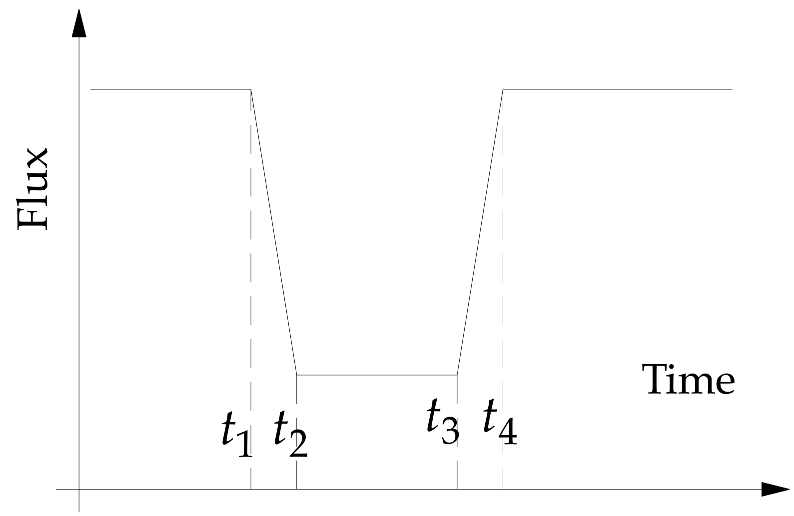
- If orientation angle of orbit, *i*, is known, this allows separate determination of the masses; that's why eclipsing binaries are so important (sin *i* must be close to unity in such cases).

Other uses for totally-eclipsing binary systems

Duration of eclipses and shape of light curve can be used to determine **radii** of stars:

$$R_s = \frac{v_1 + v_2}{2}\left(t_2 - t_1\right)$$

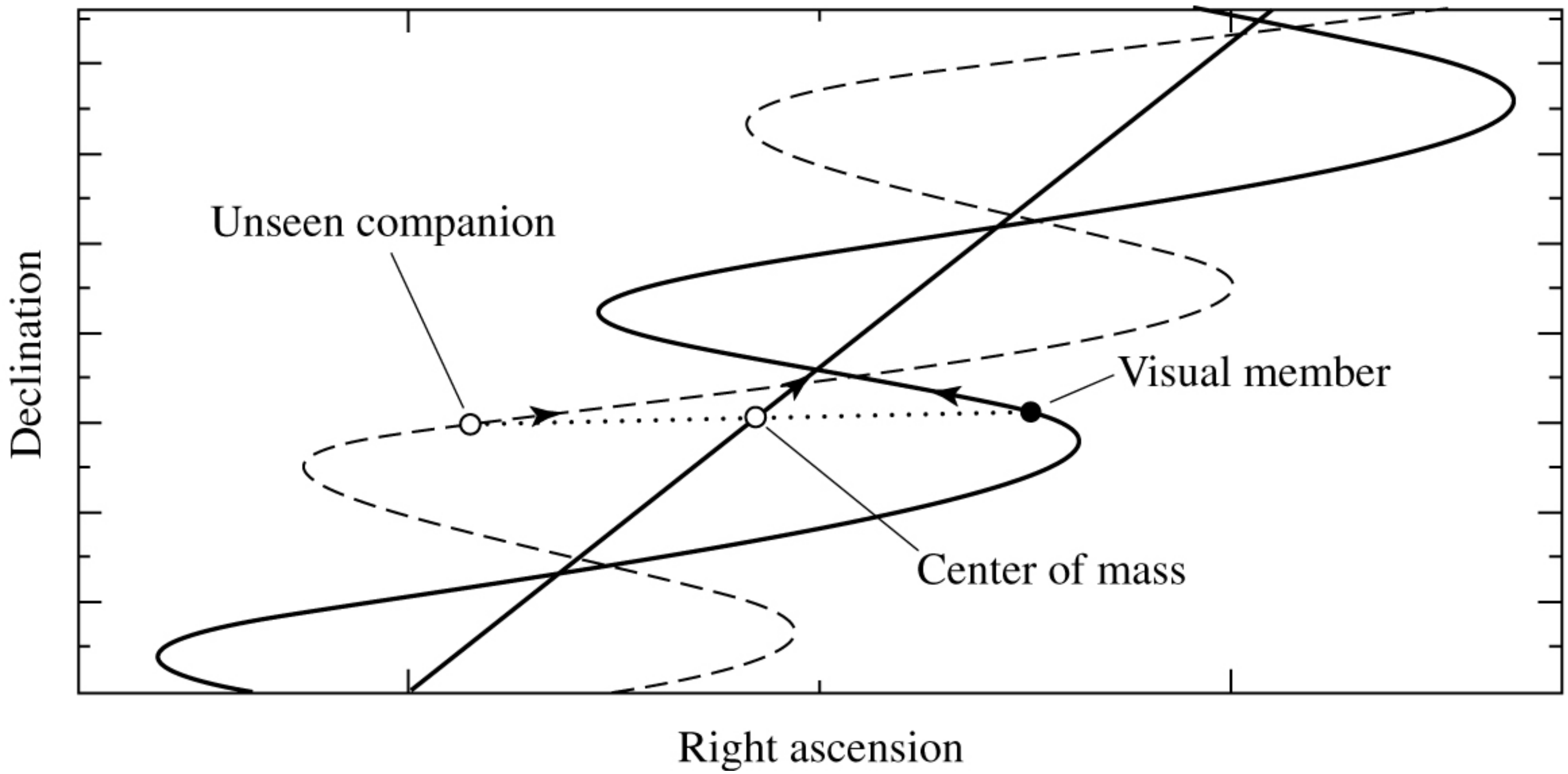
$$R_\ell = \frac{v_1 + v_2}{2}\left(t_3 - t_1\right)$$



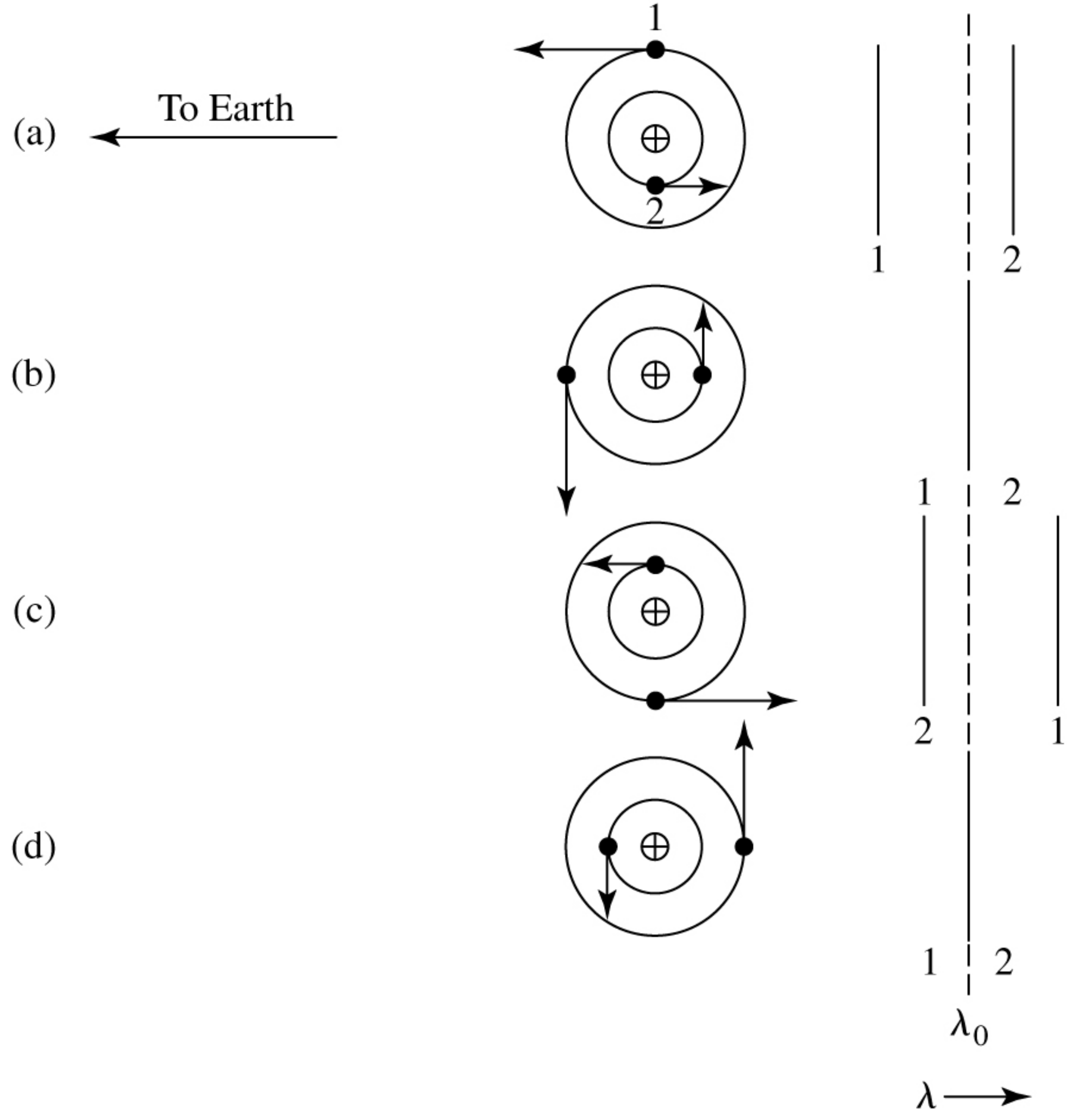
Relative depth of primary (deepest) and secondary brightness minima of eclipses can be used to determine the **ratio of effective temperatures of the stars**:

$$\frac{F_0 - F_{\mathrm{primary}}}{F_0 - F_{\mathrm{secondary}}} = \left(\frac{T_{e,s}}{T_{e,\ell}}\right)^4 \quad .$$

Astrometric Binary

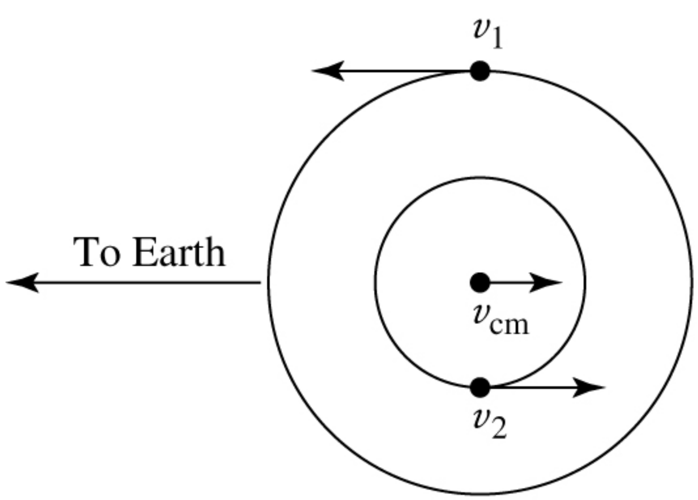


Spectroscopic Binary

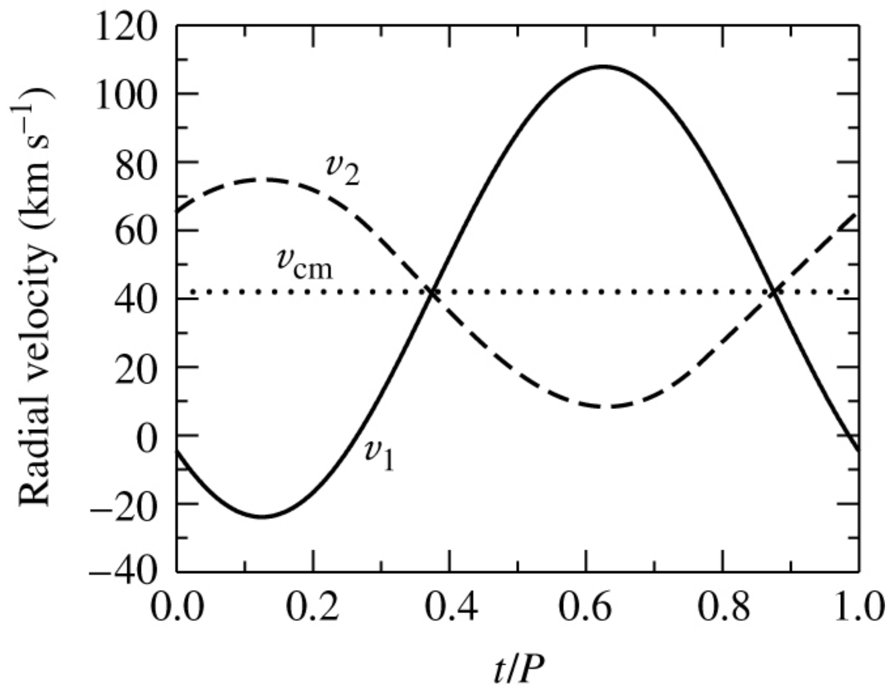


<"blue" "red">

Radial Velocity vs. Time for Double-lined SB in Circular Orbit

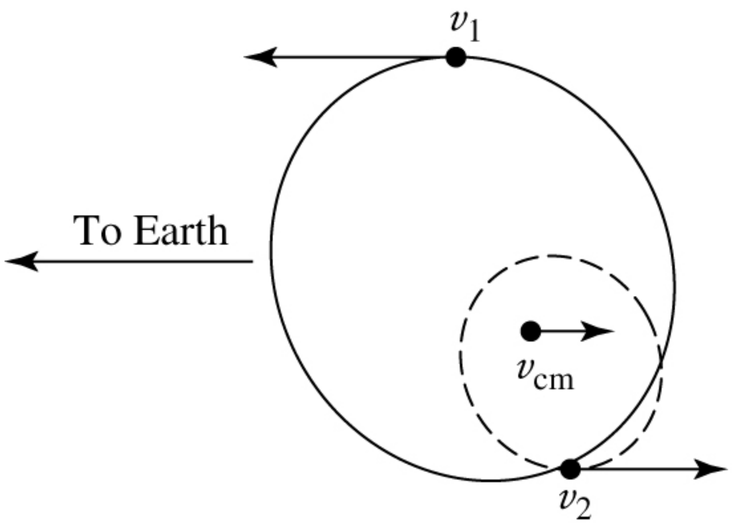


(a)

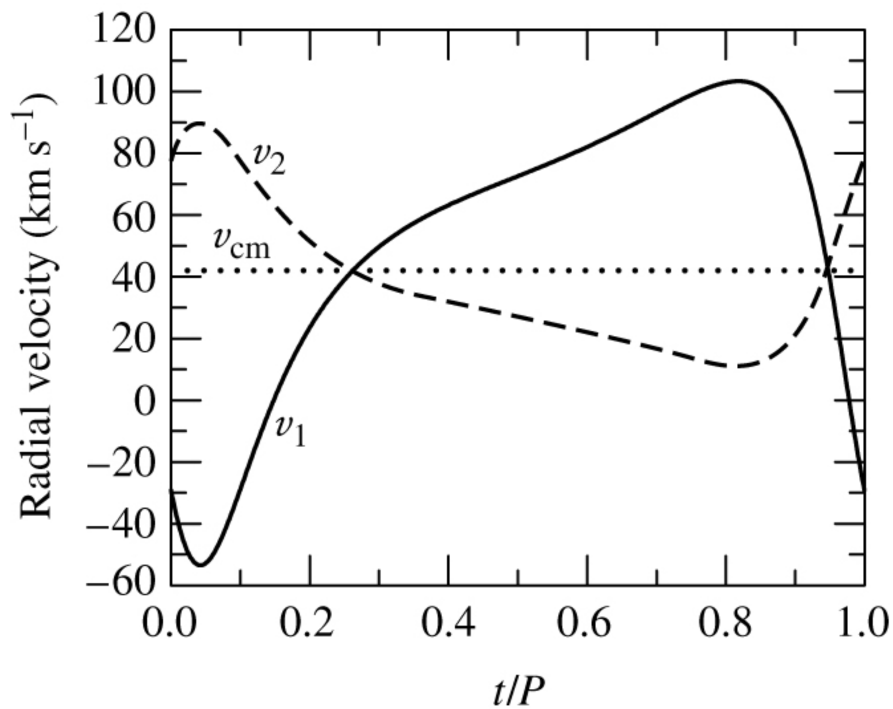


(b)

Radial Velocity vs. Time for Double-lined SB in Elliptical orbit (e=0.4)

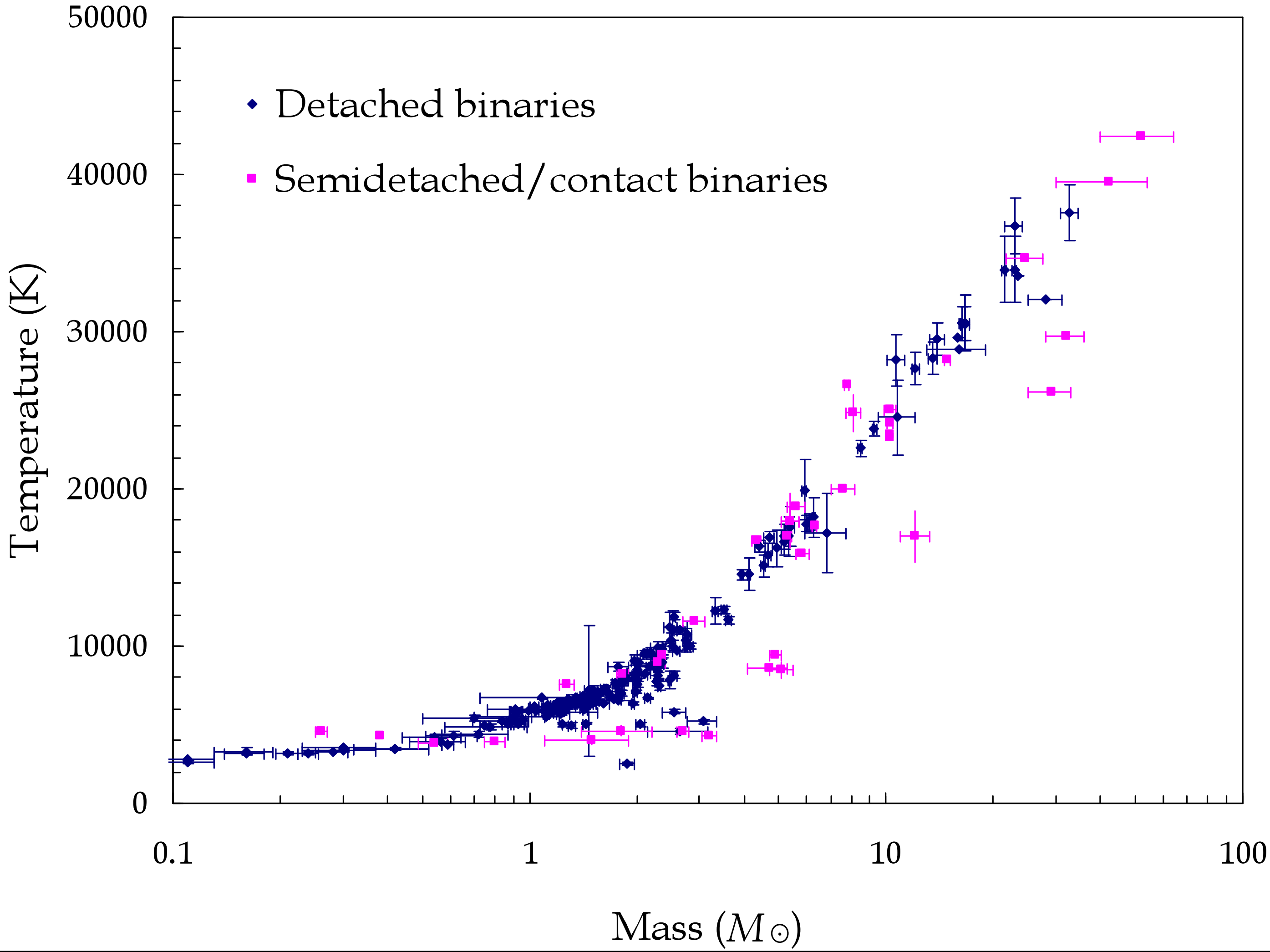


(a)



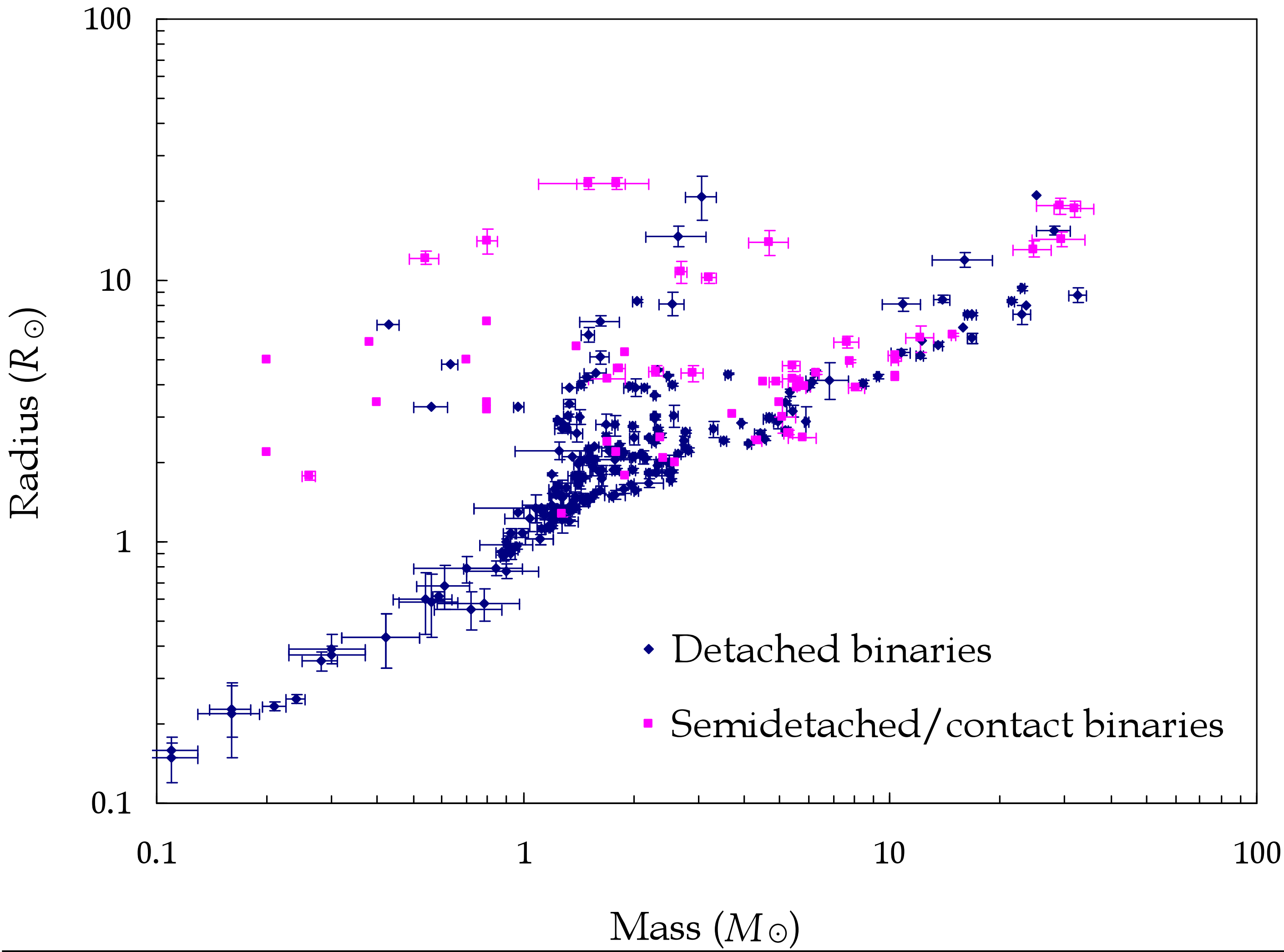
(b)

Temperature-mass relation for binary stars with well-determined orbits



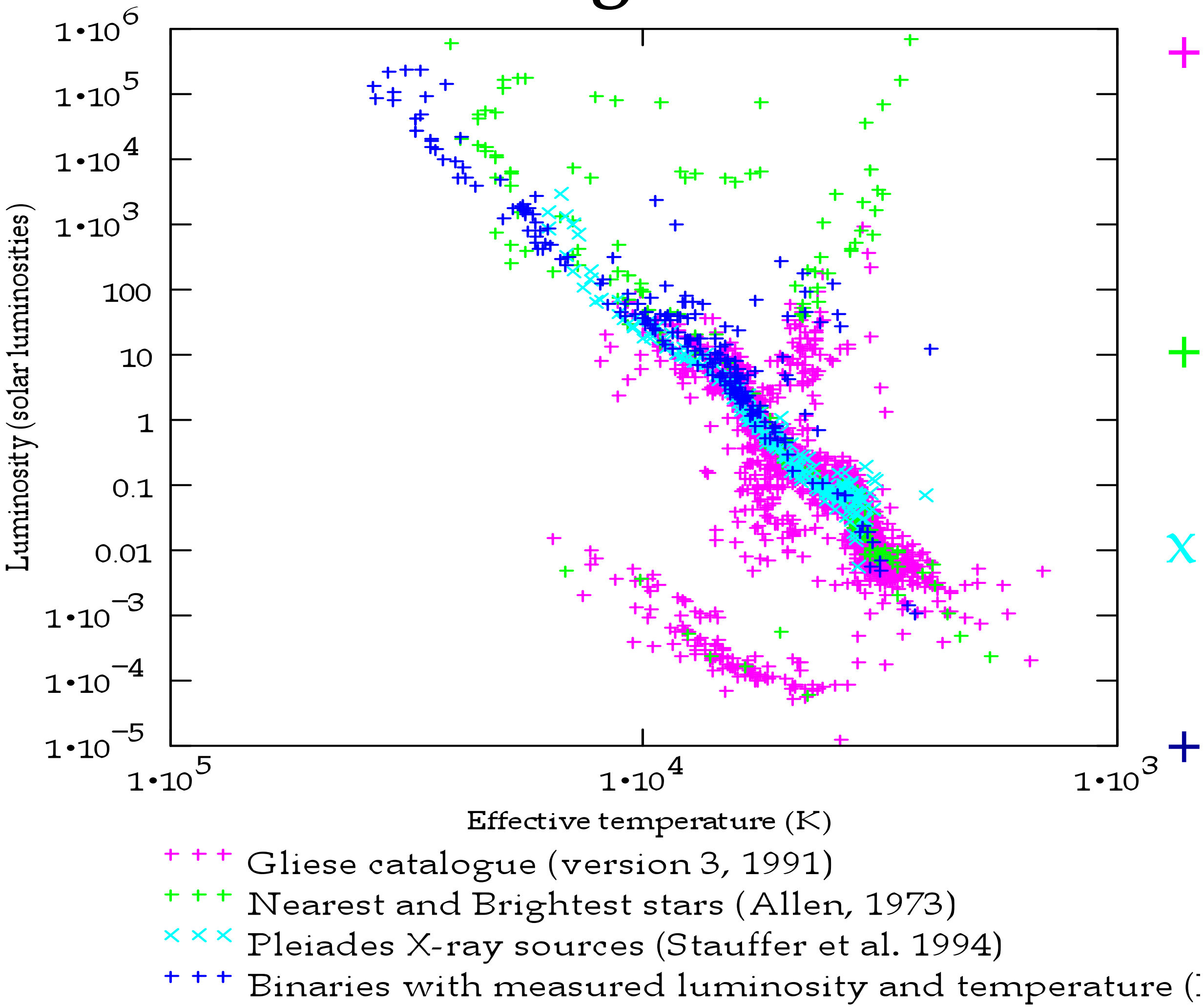
Compiled by Malkov (1993), based mostly on work over many decades by Popper.

Radius-mass relation for binary stars with well-determined orbits



Compiled by Malkov (1993), based mostly on work over many decades by Popper.

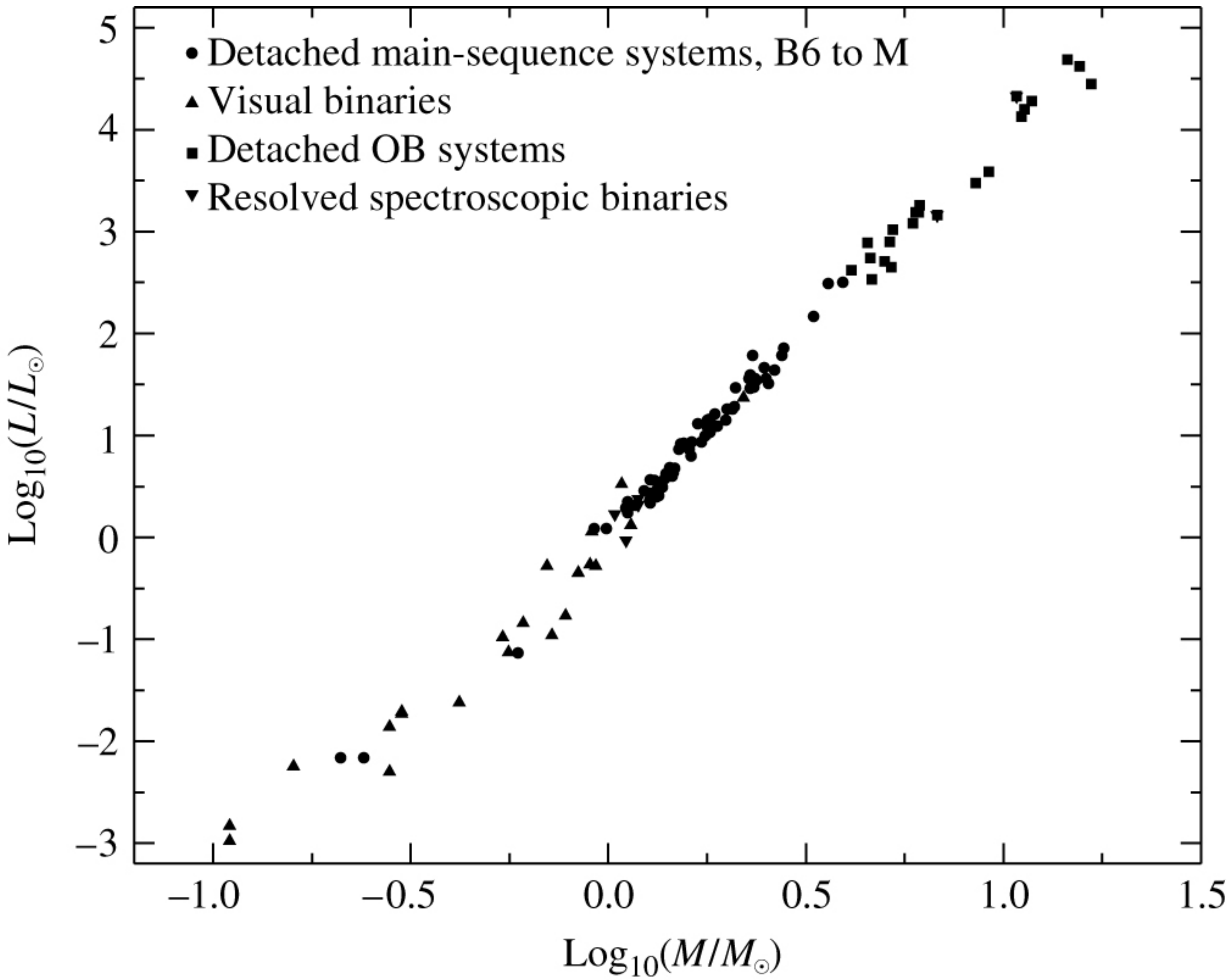
Why do we think these results apply to stars in general? Well …



- + Stars within 25 parsecs of the Sun (Gliese and Jahreiss 1991)
- + Nearest and Brightest stars (Allen 1973)
- x Pleiades X-ray sources (Stauffer *et al.* 1994)
- + Binary components with measured temperature and luminosity (Malkov 1993)

Mass-Luminosity Relation

(our stellar models need to reproduce this!)



Data from Popper (1980; ARA&A 18, 115)