Today in Astronomy 142: stellar clusters and stellar evolution

- Observations of stellar evolution: the Hertzsprung-Russell diagrams of open and globular stellar clusters
- Extinction of starlight by interstellar dust, and its correction in clusters



Open cluster M 44 in Cancer (Giuseppe Donatiello).

Observation of stellar evolution: star clusters

Stars tend to form in clusters, essentially **coevally**: all members within 1-2 My of having the same age.

- **Open clusters** (young): low density, irregular, lots of blue stars, low random velocities (few km/sec), hundreds to thousands of stars, not always gravitationally bound.

  Archetypes: Pleiades (M 45), Hyades, h and χ Persei.

- **Globular clusters** (old): high density, spherically symmetrical, few blue stars, higher random velocities (tens of km/sec), millions of stars, gravitationally bound.

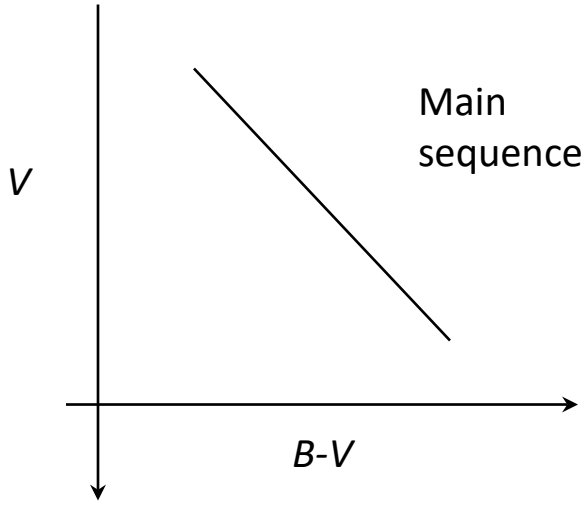
  Archetypes: ω Centauri, M3, M13, 47 Tucanae.

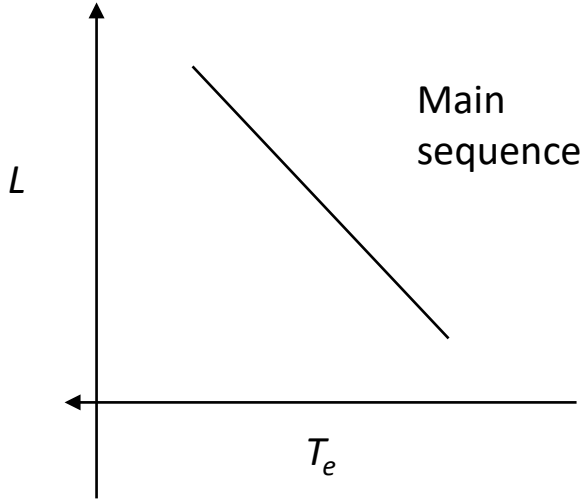
- Star clusters are useful for studying stellar evolution and for determination of distance scales in the universe.

The (observer's) H-R diagram for clusters

The classical Hertzsprung-Russell diagram is a plot of apparent magnitude in the *V* band – backwards – against the color index *B*-*V*.

- Or, with *Gaia* data: *G* backwards against $G_{BP} - G_{RP}$, where the wavelengths of G, G_{BP} and G_{RP} are respectively λ = 673 nm, 532 nm and 797 nm.





Stellar nomenclature: spectral type

The “Harvard” spectral type of a star is a classification invented by Annie Cannon (1901) based upon the strength of absorption lines of several molecules, atoms and ions in its spectrum.

- Generally the types A-M correspond to steady decreases in the strength of hydrogen lines; type O “weaker” still (emission lines instead of absorption), P for planetary nebulae, Q for miscellany. N was not used.

- Years later Cecilia Payne (1925) showed that **the spectral-type sequence OBAFGKM is a sequence of decreasing temperature**, roughly 35000 – 3500 K. More recently types L, T and Y have been added for brown dwarfs.

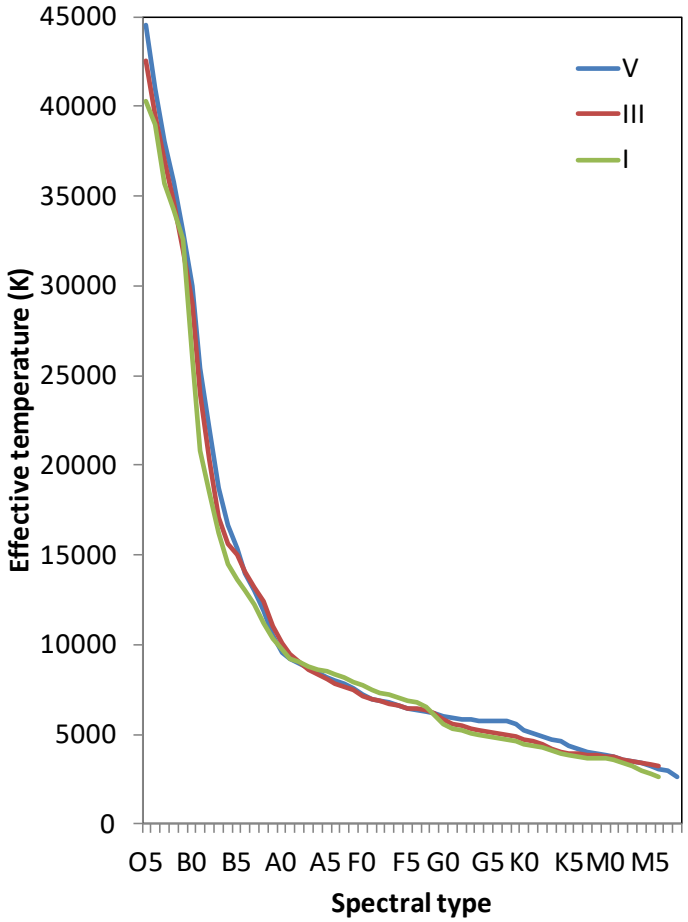
- Examples: Vega is an A0 star, the Sun a G2 star, Pollux a K2 star, and Betelgeuse an M2 star.

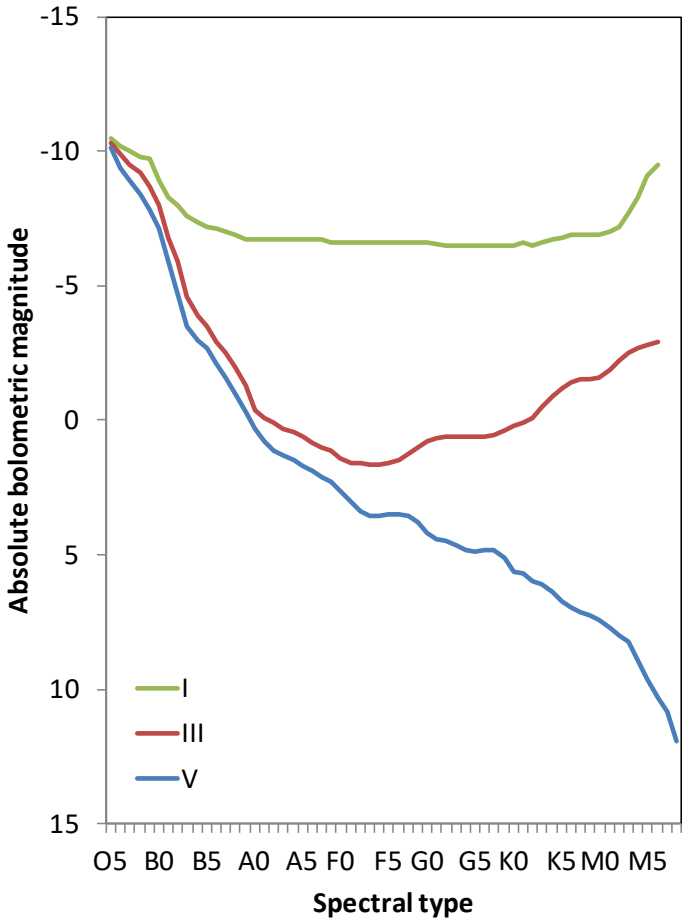
Stellar nomenclature: luminosity class

At Yerkes Observatory in the 1940s, Morgan, Keenan and Kellman (1943; MKK) added another dimension to classification by introduction of **luminosity classes**.

- V: main sequence, or dwarf, stars.
- IV: subgiants, brighter than V by a magnitude or two for the same spectral type.
- III: normal giants, another few magnitudes brighter
- II,I: bright giants and supergiants, yet another few magnitudes brighter.
- VI, VII: subdwarfs and white dwarfs.
- Examples: Vega is an A0V star, the Sun is G2V, Pollux is K2III, and Betelgeuse is M2I.

Spectral type, T_e, and luminosity class





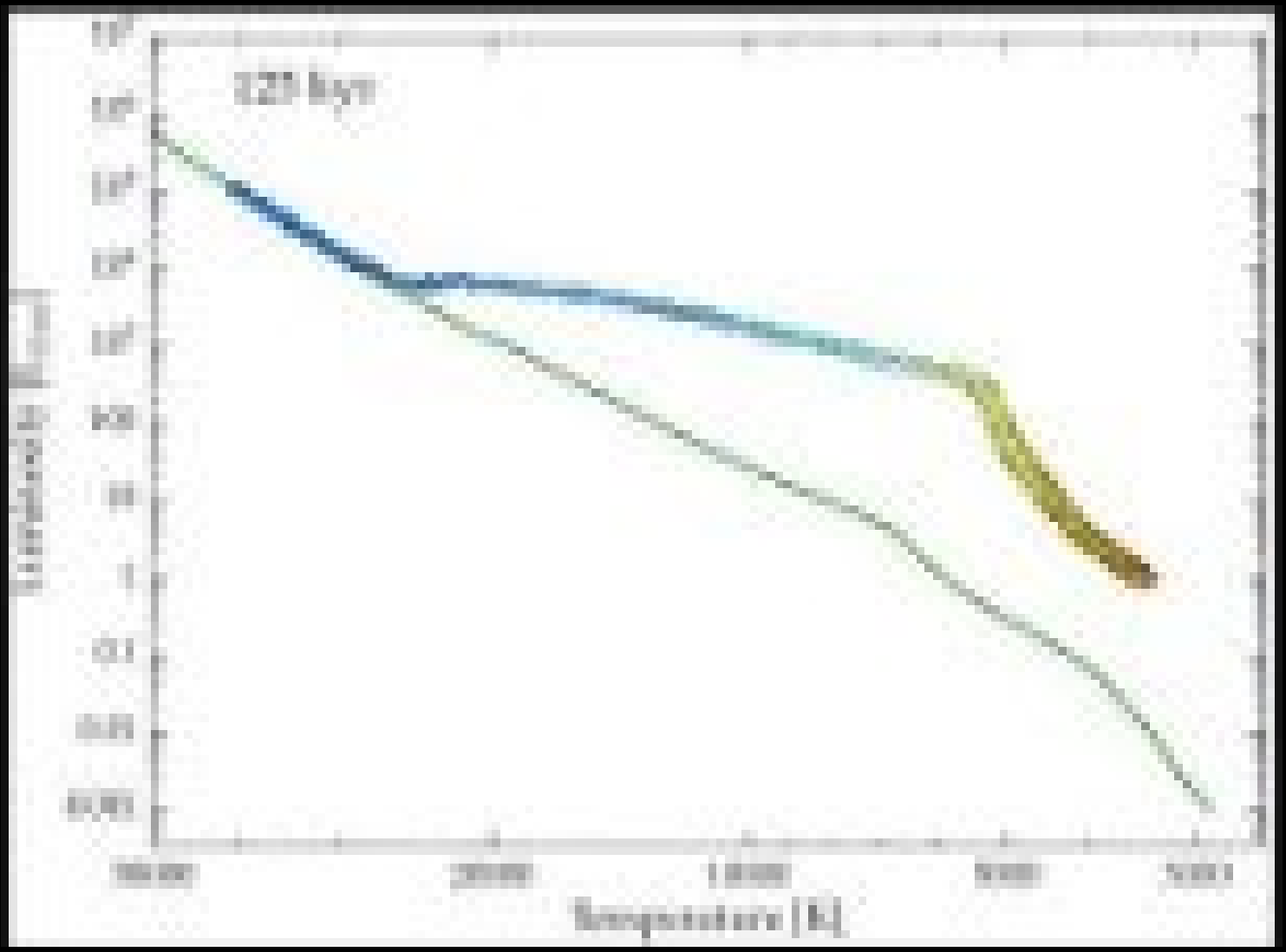
Data from Schmidt-Kaler 1982

Evolution of stars in a cluster

Because the measurement of an HR diagram is a snapshot in stellar age terms – made in an instant – the HR diagram of a cluster does not resemble the tracks in L-T_e space followed by individual stars as they age.

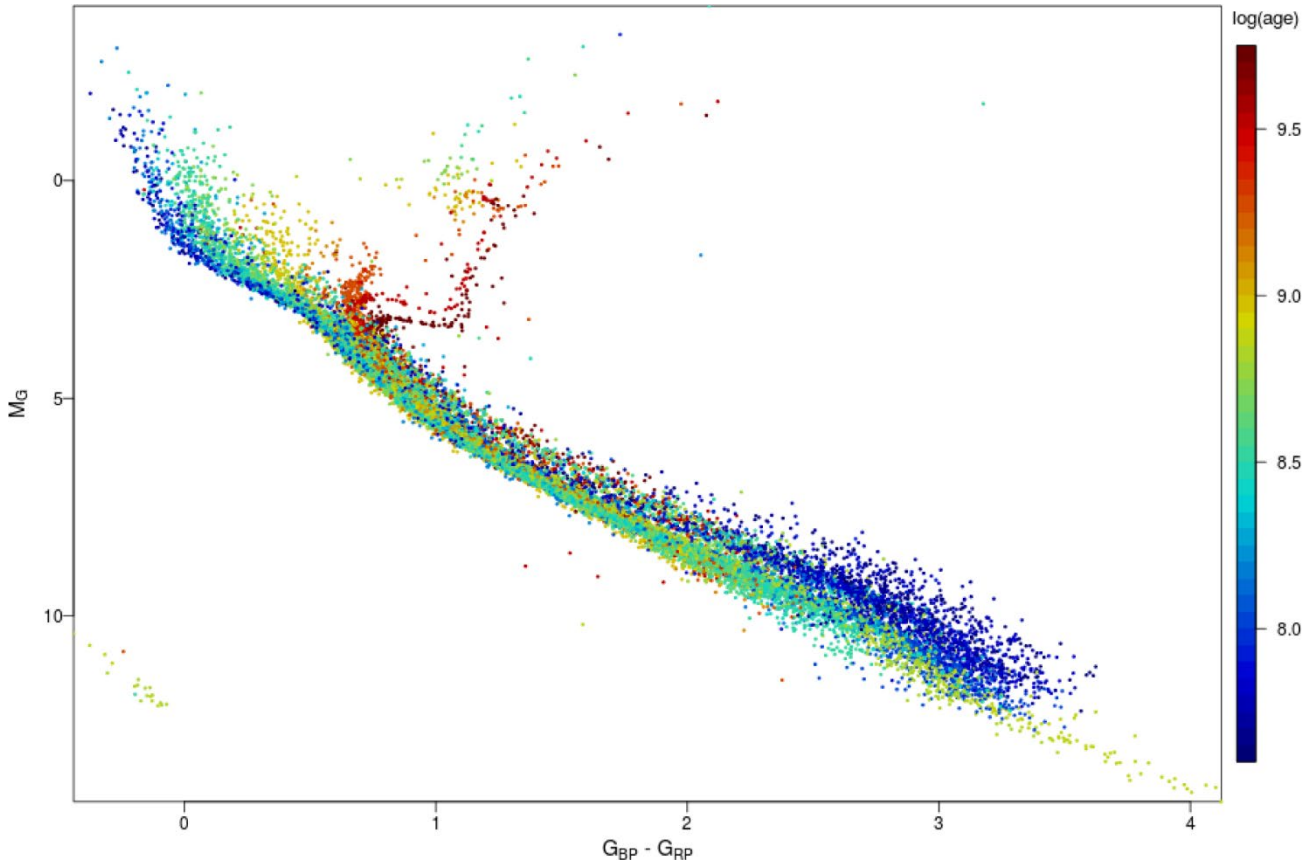
- Instead there is a **turnoff** at some point on the main sequence, above which there are no main sequence stars left.
    - All the stars originally on the upper main sequence have moved elsewhere in the HR diagram.
    - Identifiable collections only in the longer-lived stages like the RGB and the horizontal branch.
- Next page: animation of the HR diagram of a 30,000-star cluster from age 10^5 years to 2×10^{10} years, by Richard Pogge (OSU).

Evolution of stars in a cluster (continued)



Open clusters

Composite H-R diagram of 32 open clusters, color coded by age. From *Gaia* DR2, Babusiaux et al. 2018.



Open clusters: the Pleiades (M 45)

The Pleiades lie about 136 pc away and are about 110 Myr old.



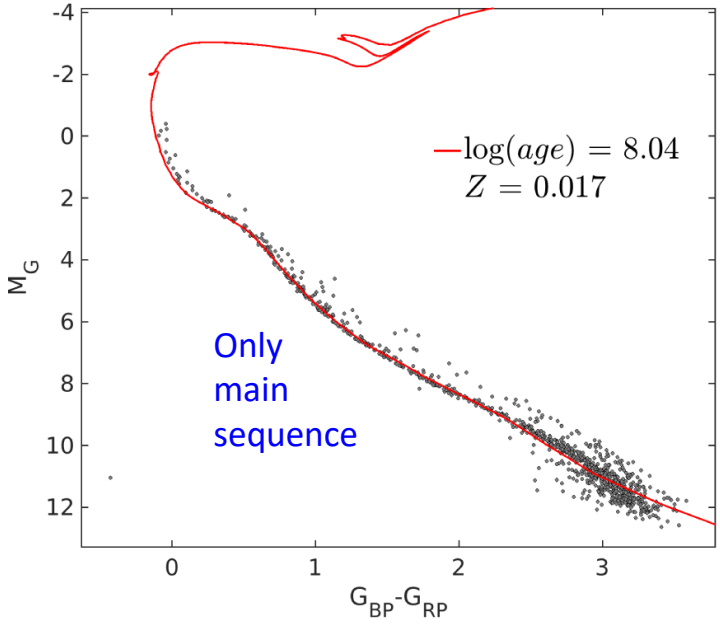
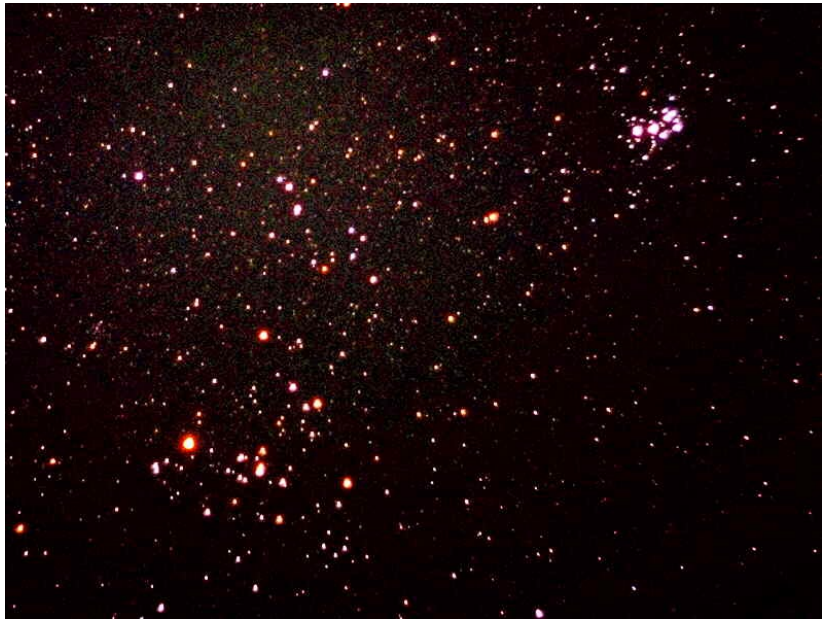


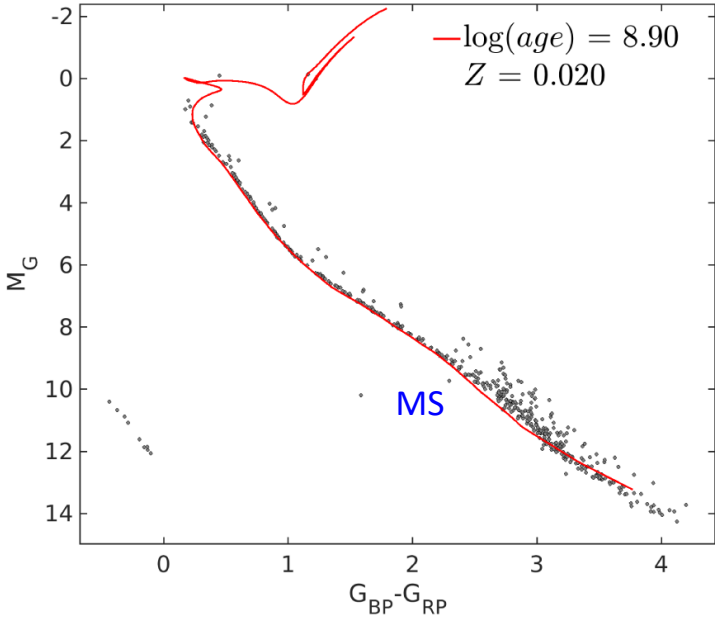
Image: David Malin, Anglo-Australian Observatory. HR diagram and isochrone: Babusiaux et al. 2018.

Open clusters: the Hyades

The Hyades are the closest open cluster (46 pc) and are about 790 Myr old. Most of the stars comprising the zodiac constellation Taurus are Hyades.



Hyades



Pleiades

Image: Hermann Gumpp; HR diagram and isochrone: Babusiaux et al. 2018.

Open clusters: M 67

M 67 is about 900 pc away and is about 4×10^9 years old; it's the oldest known open cluster. It's not a globular cluster, though: too young and metal-rich.



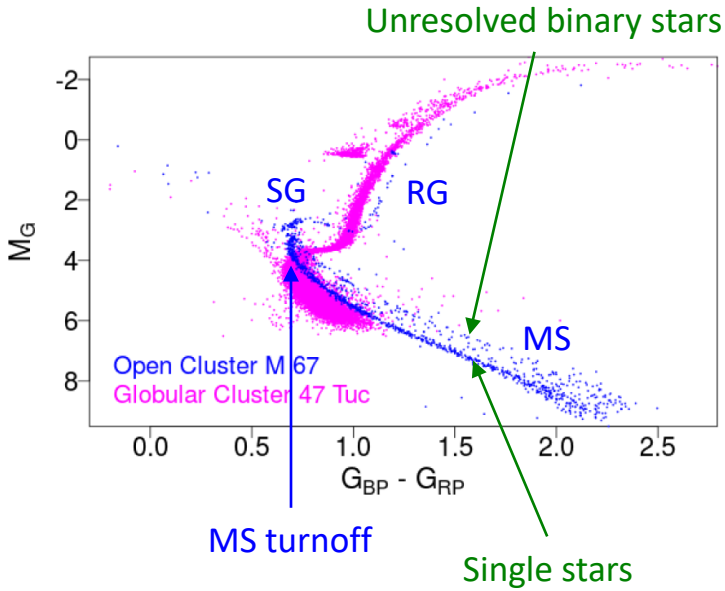
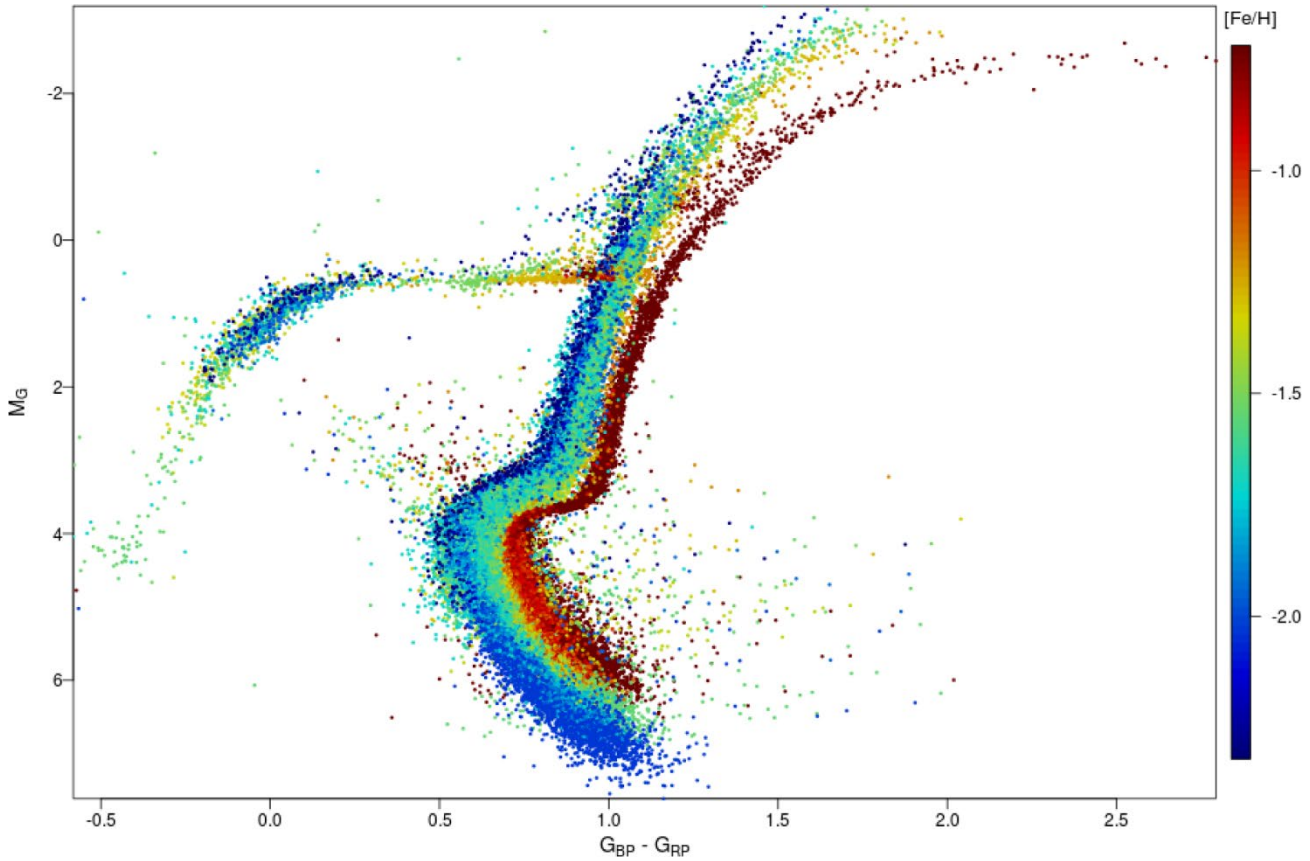


Image: Sharp & Hanna (NOAO/AURA/NSF); HR diagram: Babusiaux et al. 2018.

Globular clusters

Composite H-R diagram for 14 relatively-nearby globular clusters, color coded by metallicity. From *Gaia* DR2, Babusiaux et al. 2018.



Globular clusters: M 3

Like all the Milky Way's globular clusters, M 3 is about 1.3×10^{10} yr (13 **Gyr**) old. It lies about 10400 pc away. RR Lyrae stars are not plotted – note the gap in the horizontal branch.



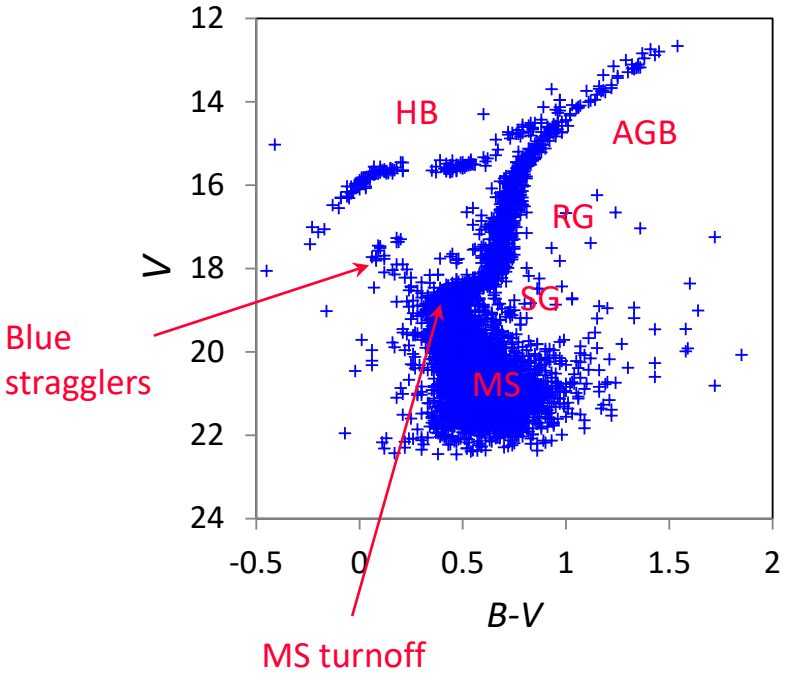
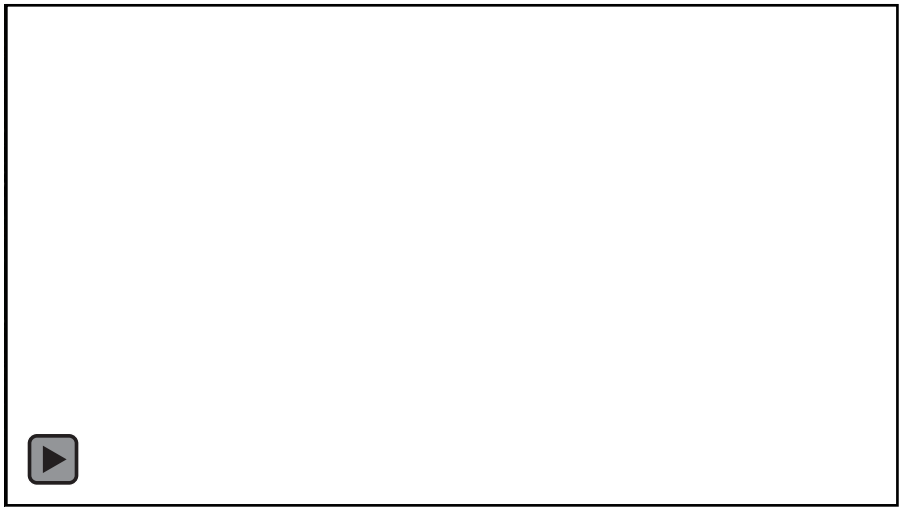
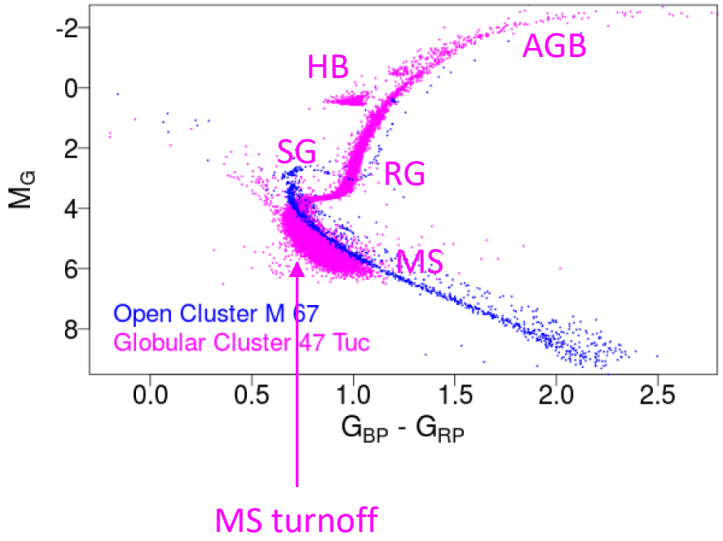


Image: Peter Challis (Harvard-Smithsonian CfA); HR diagram: Ferarro et al. (1997).

Globular clusters: 47 Tuc

- Two globular clusters can be seen with naked eye and are named like stars are.
- GC shapes, numbers of members, and metallicities (*Z*) are different from open clusters. We will learn to regard the difference as a major one in the Galactic population of stars: Population II and Population I, respectively.





Animation: NASA/ESA/HST; HR diagrams: Babusiaux et al. 2018.

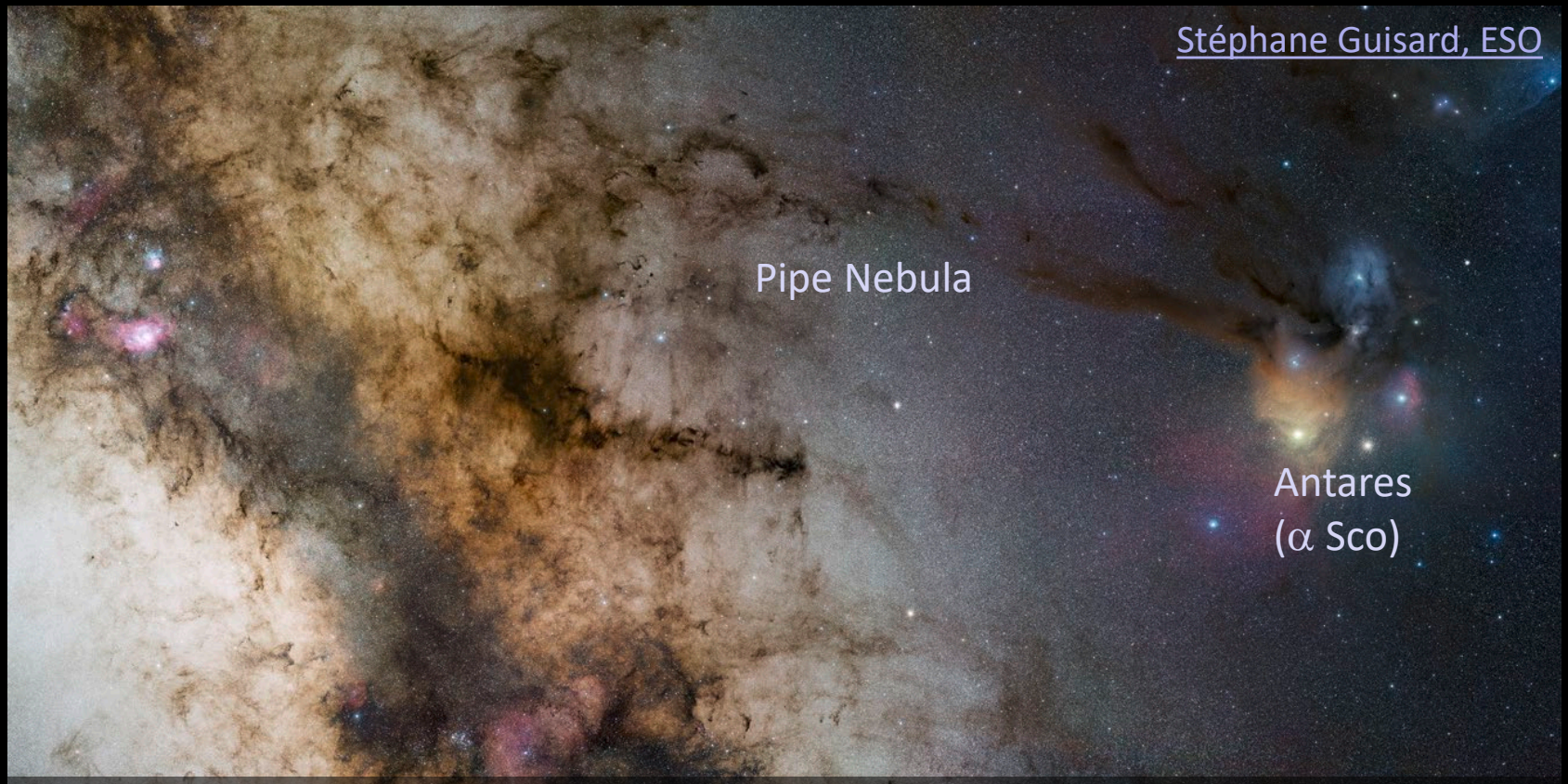
Extinction and stellar clusters

Light from stellar clusters, especially the younger open clusters, often suffers **extinction** as it propagates to us, which must be corrected before interpreting observations.

Extinction is manifest as

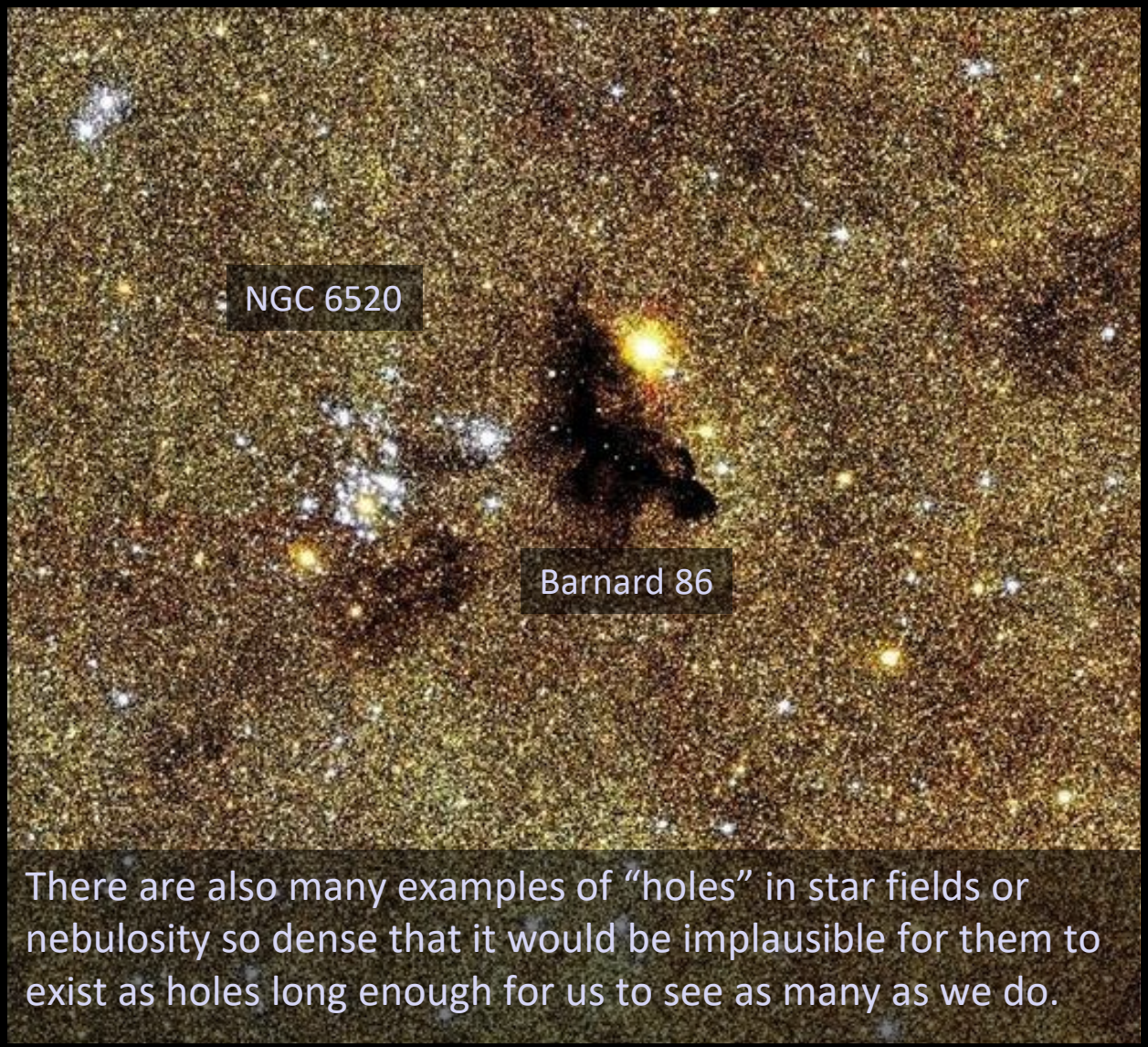
- **dark clouds:** dark markings on the Milky Way are generally absorption and/or scattering of background starlight by submicron solid particles. Or as
- **reddening:** stars and clusters associated with dark markings are often much redder in color (in their continuum) than would be inferred from their spectral type (classified by their line spectra). This **selective extinction** is naturally explained by the wavelength dependence of scattering and absorption by submicron-size solid particles. Or as
- **polarization** of (originally unpolarized) starlight: naturally explained by selective absorption by nonspherical, aligned, submicron-size solid particles.

Dark clouds



Like much else in astronomy, dark clouds were first seen by William Herschel. According to his sister and collaborator Caroline, he first saw these, in Scorpio and Sagittarius (1774), saying to her, "hier ist wahrhaftig ein Loch im Himmel" (surely here is a hole in the sky). As modern images show, though, they're not holes.

Dark clouds (continued)



There are also many examples of “holes” in star fields or nebulosity so dense that it would be implausible for them to exist as holes long enough for us to see as many as we do.

Visible-light image by Jean-Charles Cuillandre (CFHT).

Aber *hier* ist wahrhaftig ein Loch im Himmel.

Here is an exception which demonstrates the rule: NGC 1999 in Orion.

- Long thought to be a dark globule overlying a more diffuse cloud, and extinguishing starlight scattered from the latter.
- The star would lie further from us than the globule, nearer than the diffuse cloud.

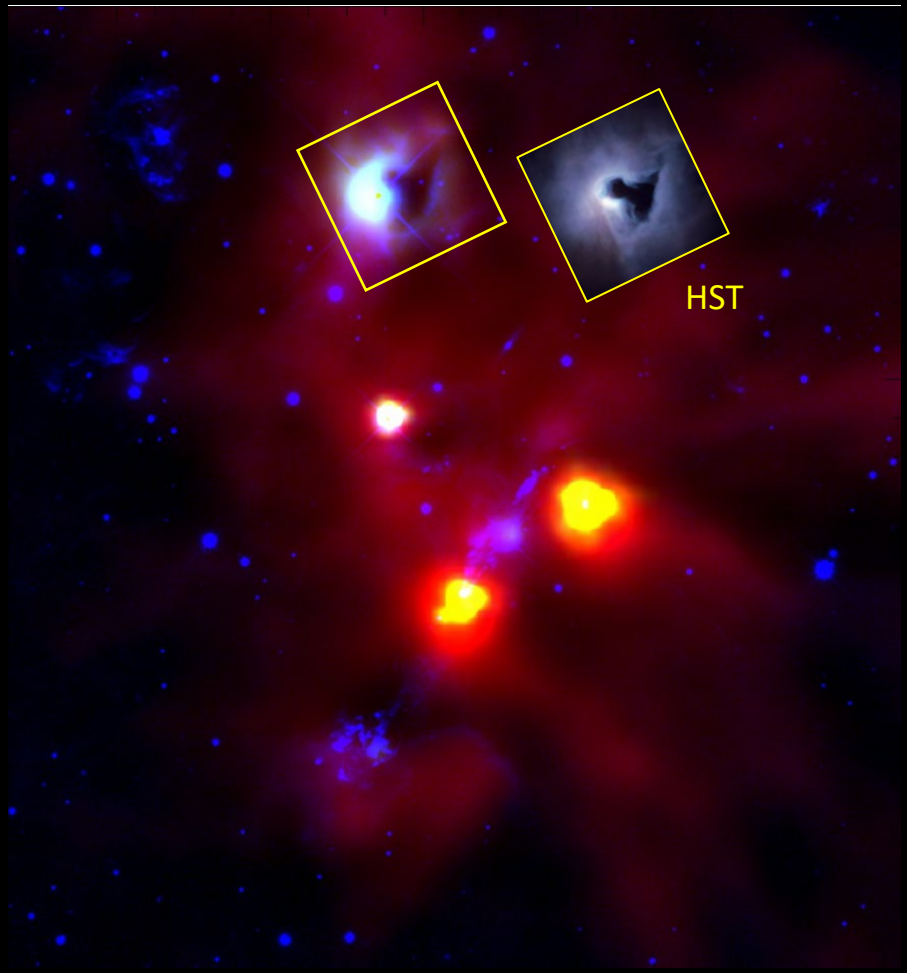


Visible light, HST/STScI/NASA

Hier ist wahrhaftig ein Loch im Himmel (continued)

- But the “globule” turns out to be dark even at very long infrared and submillimeter wavelengths.
- An ordinary globule would *emit* brightly at such long wavelengths.
- So in this case the thing that looks like a hole really is a hole.

Stanke et al. 2010. Blue = 4.5 μm (Spitzer Space Telescope); green = 70 μm, red = 160 μm (Herschel Space Observatory).



Proof that it's extinction: Trumpler's experiment on open clusters

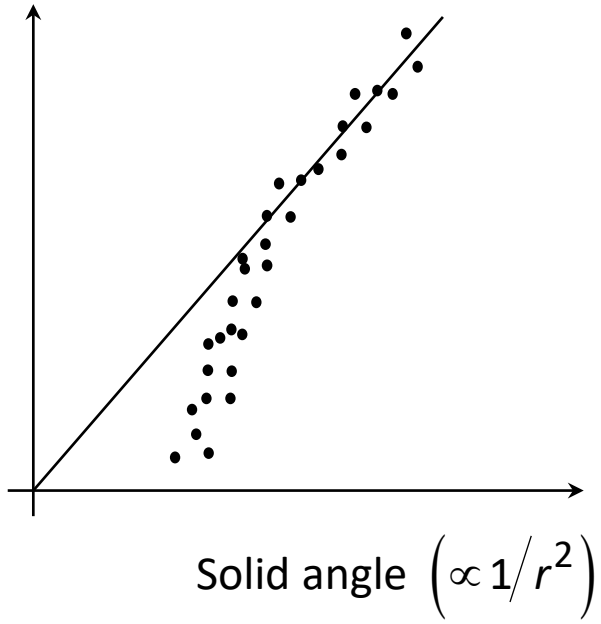
He plotted the sum of fluxes from all stars in cluster *vs*. the solid angle the cluster occupies.

- If all open clusters had the same diameter *D*, then $\Omega = \pi\left(D/2r\right)^2 \propto 1/r^2$, and since flux also scales with $1/r^2$, he should get a straight line through the origin.

- Instead he got this (Trumpler 1930):

  Scatter: they don't all have the same *D.*

  Curve doesn't pass through the origin: flux falls faster than $1/r^2$ => **extinction**.



Extinction of starlight by interstellar dust

Absorption and scattering of light by dust grains can be treated a bit like planets, familiar to most of you from ASTR 111.

- Suppose grains are all the same size and present along the line of sight with number density *n* grains per unit volume. Suppose further that each grain casts a wavelength-dependent shadow – has **cross section** – with area σ_λ.

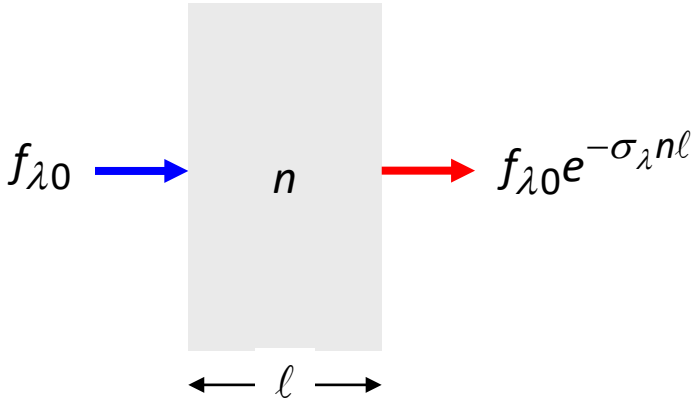
- Then starlight at wavelength λ would be attenuated exponentially, with an exponential scale length $\sigma_\lambda n \ell$:

$$f_\lambda = f_{\lambda 0} e^{-\tau_\lambda} = f_{\lambda 0} e^{-\sigma_\lambda n \ell}$$

$$m_\lambda = m_{\lambda 0} + 2.5 \log\left(\frac{f_{\lambda 0}}{f_\lambda}\right)$$

$$= m_{\lambda 0} + 2.5 \log\left(e^{\sigma_\lambda n \ell}\right)$$

$$= m_{\lambda 0} + 2.5 \sigma_\lambda n \ell \log e$$



Extinction of starlight by interstellar dust (continued)

- *A priori*, we don't know the density *n* or the cloud thickness ℓ, but we can make observations of flux *f* at many wavelengths and take ratios so that they cancel out.

- In this spirit we define **extinction**, A_λ, and **color excess**, $E_{\lambda-\lambda'}$, which can be measured and calibrated on nearby stars, and compared with physical models for σ_λ of dust grains.

- For two wavelengths λ and λ',

$$A_\lambda \equiv 2.5\sigma_\lambda n\ell \log e \qquad E_{\lambda-\lambda'} = 2.5\left(\sigma_\lambda - \sigma_{\lambda'}\right) n\ell \log e$$

  Then the corrected magnitude and color index are

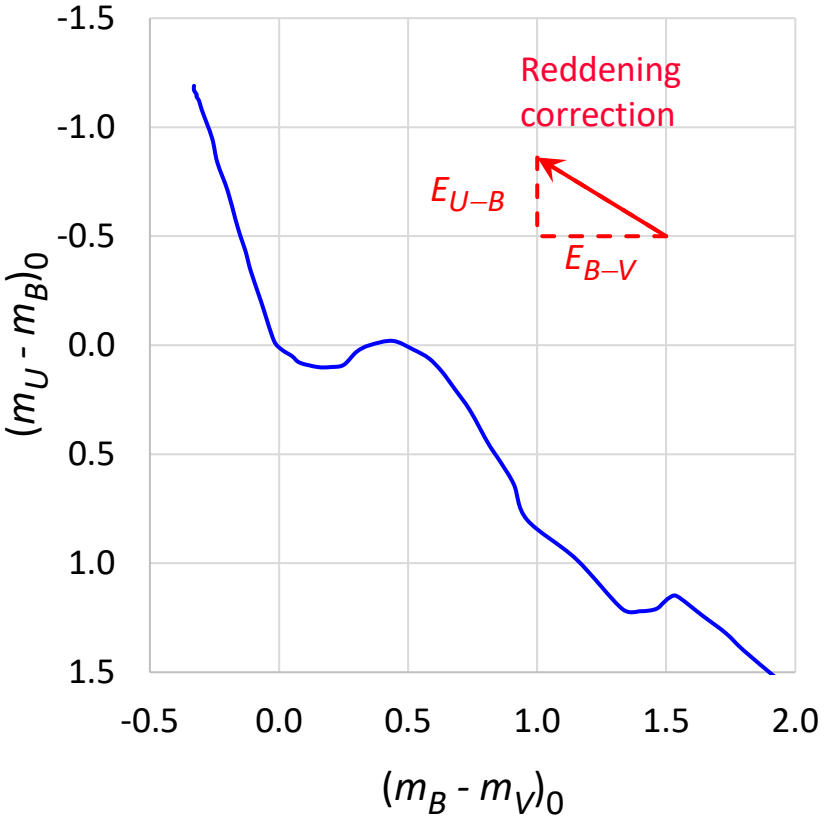
$$m_{\lambda 0} = m_\lambda - A_\lambda \qquad \left(m_{\lambda 0} - m_{\lambda' 0}\right) = \left(m_\lambda - m_{\lambda'}\right) - E_{\lambda-\lambda'}$$

Reddening correction

How do we use this? (1)

- Magnitudes and color indices have been measured for nearby **unextinguished** stars, as for the *UBV* bands at right.
- Extinction makes a star redder in all color indices, **displacing** it diagonally in color-color diagrams as at right.
- The unknowns *n* and ℓ cancel out in the slope of the displacement, leaving only measurables, as in

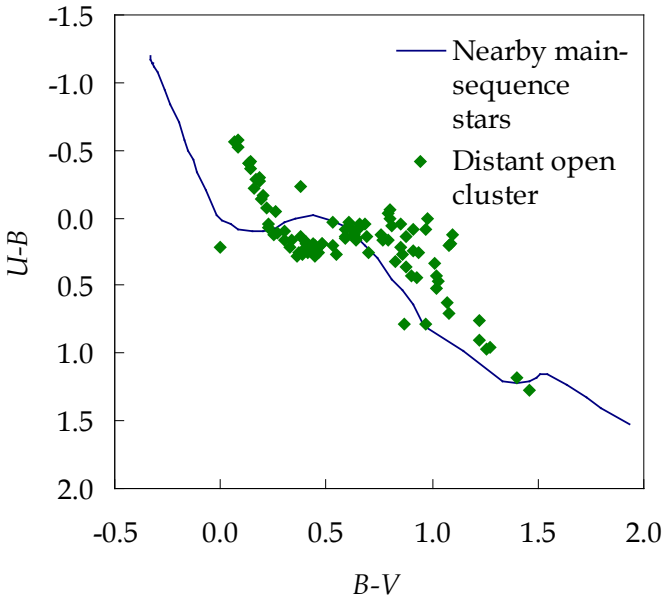
$$\frac{E_{U-B}}{E_{B-V}} = \frac{\sigma_U - \sigma_B}{\sigma_B - \sigma_V} \quad .$$



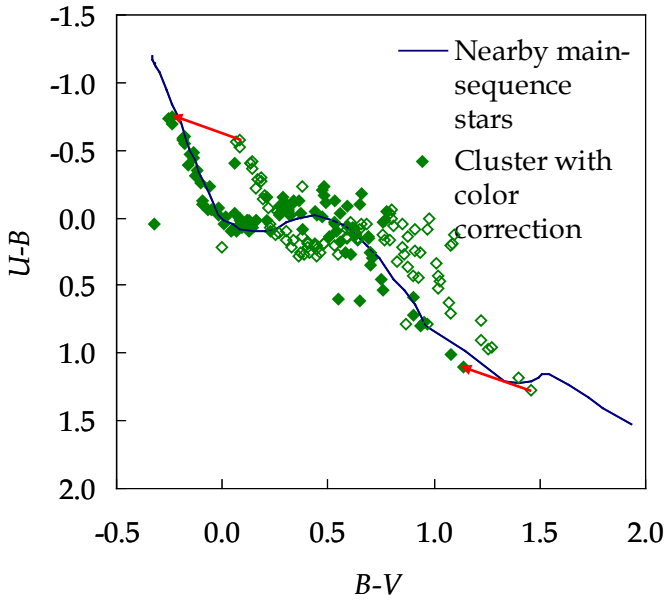
Empirical *UBV* **color-color** relation for nearby unextinguished zero-age main sequence stars

Reddening correction for a stellar cluster

Note the abbreviations: *V* for m_V, *B* for m_B, etc.



Take observations at three wavelengths (e.g. *U, B, V*); compare the color-color plot to unextinguished stars.



Shift the plots until they fit; the amounts by which the cluster shifts are E_{B-V} and E_{U-B}: values 0.32 and 0.18, here.

Extinction correction

How do we use this? (2)

- $n\ell$ also drops out from $R_\lambda \equiv A_\lambda / E_{\lambda-\lambda'}$, which is called the **total-to-selective extinction** ratio.

$$R_\lambda = \frac{A_\lambda}{E_{\lambda-\lambda'}} = \frac{2.5\sigma_\lambda n\ell \log e}{2.5\sigma_\lambda n\ell \log e - 2.5\sigma_{\lambda'} n\ell \log e}$$

$$= \frac{\sigma_\lambda}{\sigma_\lambda - \sigma_{\lambda'}}$$

- Again this can be measured, and the measurements used to constrain models for σ_λ based on the physics of dust-grain materials, with the typical result

$$R_V = \frac{\sigma_V}{\sigma_B - \sigma_V} = 3.1 \text{ for typical diffuse dark clouds,}$$

$$= 5.5 \text{ for typical dense molecular clouds.}$$

Extinction correction for a stellar cluster

- So after determining E_{B-V} for a cluster as above, one knows the total extinction, $A_V = R_V E_{B-V}$.
- Then correct the HR diagram as follows:
  - Reduce every *B-V* for every point by the same amount, E_{B-V}.
  - Reduce every *V* by the total extinction, A_V.
- The whole HR diagram shifts to bluer and brighter values.

