Stellar Clusters, Stellar Evolution, & Interstellar Dust

The final stages of stellar evolution
Open and globular clusters
Composition of dust grains
Extinction, reddening, polarization of starlight

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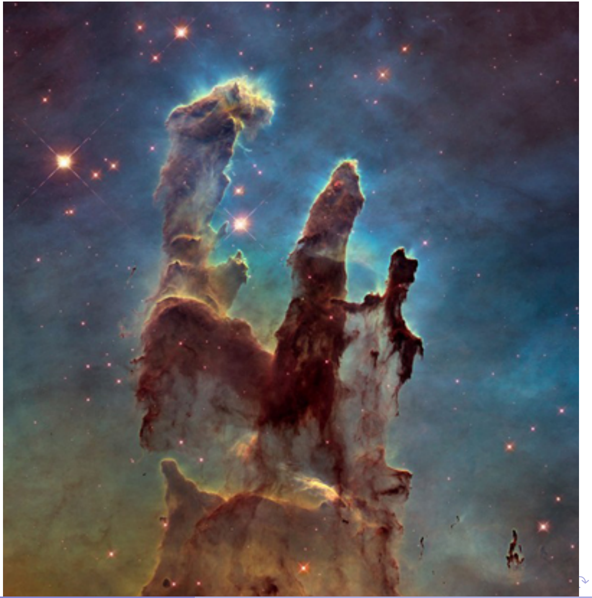
University of Rochester

Stellar Clusters, Stellar Evolution, & Interstellar Dust

- Type II (core-collapse) supernovae
- Open and globular clusters as stellar clocks
- Dust composition, size, and origin
- Extinction and reddening of starlight
- Scattering and optical depth
- Polarization of starlight

Reading: Kutner Sec. 14.2–14.3, Ryden Sec. 16.1, Shu Ch. 11



"Pillars of Creation," Eagle Nebula (M16), NASA/ESA/HST.

What happens after the nuclear fuel is exhausted?

For the most massive stars ($M \gtrsim 8M_\odot$):

- Mass loss is insufficient to keep the core in the white dwarf phase; maximum mass of Fe white dwarf is $1.26M_\odot$.
- Result: further collapse and neutronization (and creation of signicant number of neutrinos).
- When the collapsing core reaches tens of km in size, neutron degeneracy pressure sets in, which can stop or slow the collapse.
- However, since the collapse has been from white-dwarf to neutron-star dimensions, infalling material from the stellar envelope is going very fast (a large fraction of c).
- Result: envelope rebounds off the stiff neutron-degenerate material and blows up the rest of the star.

This is called a **core collapse** or Type II supernova.

Core-collapse (Type II) supernova

Nomenclature: Type II or CCSN. Remnant is a NS or more rarely a BH, depending on core mass ($M = 1.3 - 2.2M_\odot$).

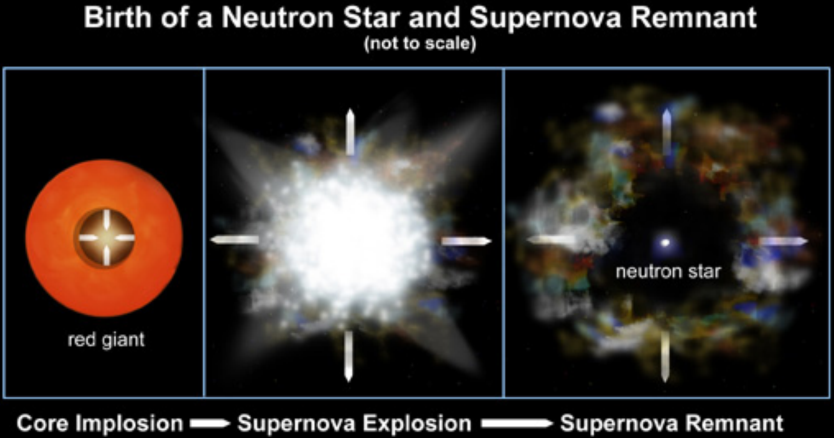
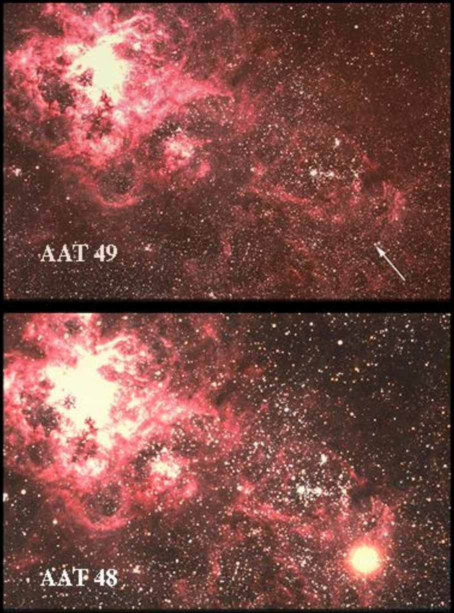


Image from NASA/CXC

SN1987A: A recent nearby supernova

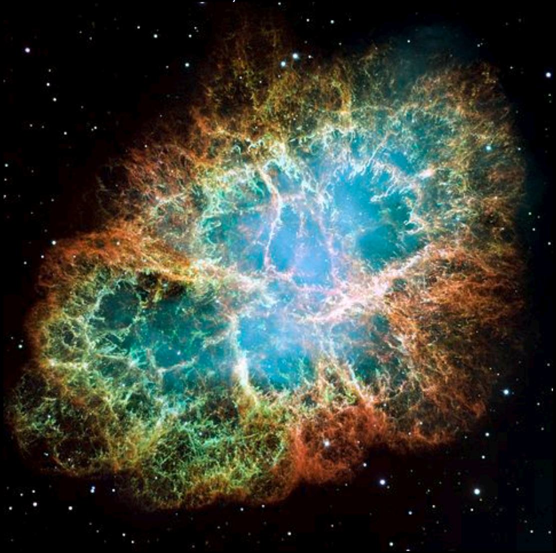
- The last “naked eye” supernova occurred in the Large Magellanic Cloud, a Milky Way satellite galaxy.
- SN1987A (Feb. 23, 1987): a Type II
- Output luminosity temporarily exceeded luminosity of the entire galaxy!
- First supernova for which we knew the progenitor star.
- Neutrino burst observed by three detectors (Kamiokande II, IMB, Baksan).



SN1987A after a few decades

X-ray: NASA/CXC/U. Colorado/S. Zhekov et al. Optical: NASA/STScI/CfA/P. Challis.

A Type II supernova after 1000 years

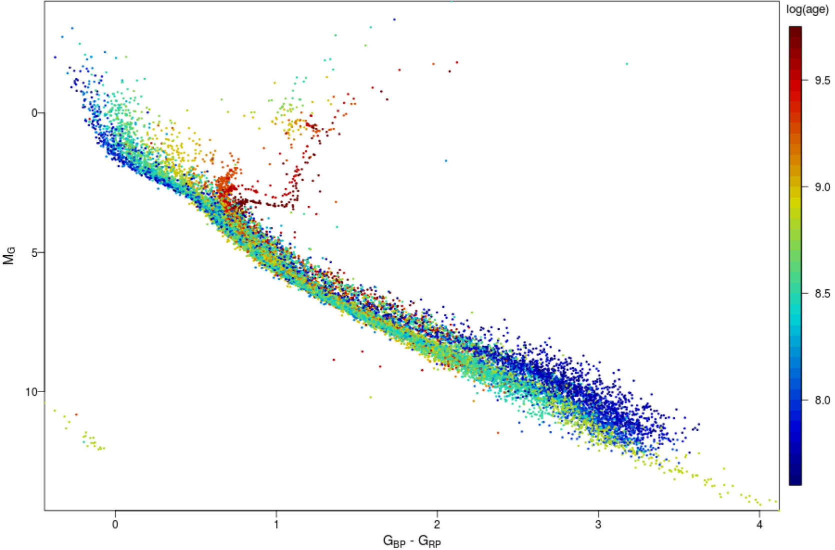


NASA/HST mosaic.

Observation of stellar evolution: Star clusters

- Stars tend to form in **clusters** at about the same age (within $1 - 2$ Myr of each other) and are nearly the same distance from us.
- H-R color-magnitude diagrams for stars in the cluster make it very easy to infer the stars' location on the main sequence.
- If we make an H-R diagram of a cluster we tend to see a turnoff point.
- The turnoff is caused by stars exhausting their H supply and moving along the horizontal branch.
- Higher-mass stars move off the MS first, so the turn off starts on the high-mass/high-T_e end of the H-R diagram (upper left) and moves down as lower-mass stars age and exit the MS.
- In other words, the turnoff point acts like a clock, telling us the age of stars in the cluster with very good accuracy.

The turnoff point



H-R diagram for 32 open clusters, colored by age (Gaia Collaboration 2018).

Open and globular clusters

Stars are classified into **open** (young) or **globular** (old) clusters.

Properties of open clusters:

- Low density, irregular, lots of blue stars
- Low random velocities (few km/s)
- Hundreds of thousands of stars, not always gravitationally bound

Archetypes: Pleiades (M45), Hyades, h and χ Persei

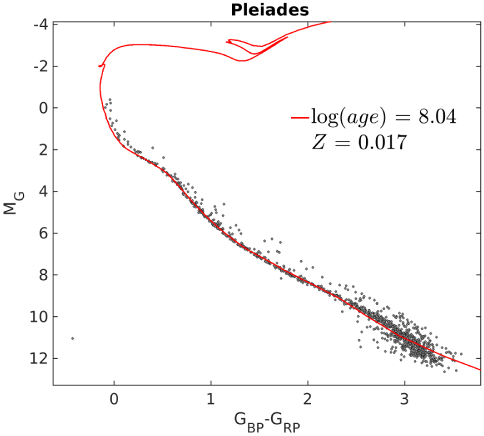
Properties of globular clusters:

- High density, spherical, few blue stars
- Higher random velocities (tens of km/s)
- Millions of stars, gravitationally bound

Archetypes: ω Centauri, M3, M13, 47 Tucanae

Open clusters: the Pleiades (M45)

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

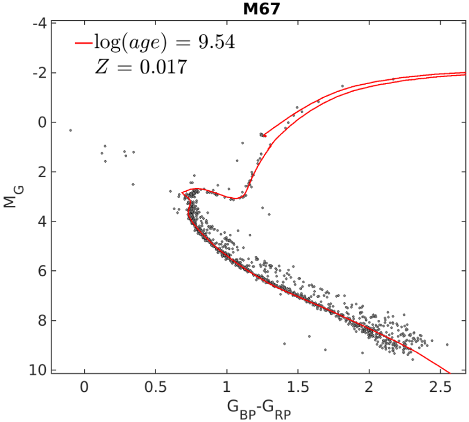


Left: Optical image of the Pleiades cluster (Palomar Observatory).

Right: H-R diagram of optical sources in the cluster (Gaia Collaboration 2018).

Open clusters: M67

M67 is 900 pc away and is the oldest known open cluster: 4 Gyr, the same age as the Sun.

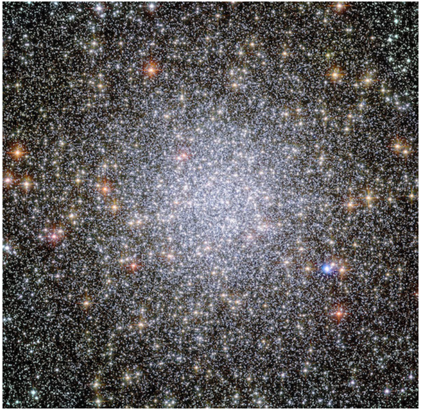


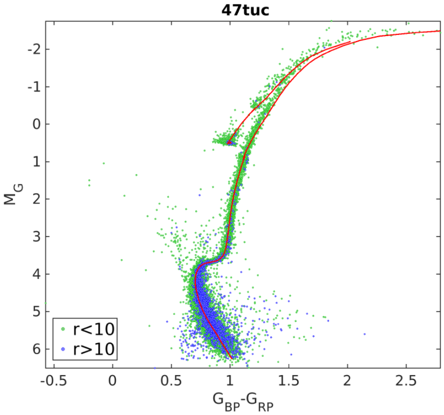
Left: M67, from N. Sharp and M. Hanna, NOAO/AURA/NSF.

Right: H-R diagram of optical sources in the cluster (Gaia Collaboration 2018).

Globular clusters: 47 Tuc

47 Tuc is about 13 Gyr old, like all Galactic globular clusters, and it is 4.0 kpc away. RR Lyrae stars are not plotted (note gap in HB).





Left: 47 Tucanae (NASA/ESA/HST).

Right: H-R diagram the Gaia Collaboration (2018).

Size and composition of interstellar dust

Size More like cigarette smoke than household dust: $< 0.1\ \mu$m in most dark clouds, ranging from 10 nm (50-100 atoms) in diffuse and UV-illuminated clouds to $\sim 1\ \mu$m in the darkest molecular clouds.

Amount About 1% by mass of the interstellar medium.

Composition Silicates (“rock”), carbon, and probably metallic iron, just like terrestrial planets.

Temperature $T = 10 - 100$ K

- Heated by UV starlight
- Cooled by blackbody emission; radiation from interstellar grains can be seen at IR wavelengths.

Origin and life of interstellar dust grains

Grains are born primarily in the winds of late type (giant, AGB) stars, condensing as the wind material cools; and perhaps secondarily in the interstellar medium (ISM), condensed from cold gas and perhaps conglomerated with other grains.

- Dust is often seen to be crystalline in giant stars, yet it is not crystalline in the interstellar medium.
- But the average dust grain lives billions of years in the ISM, enough time for originally crystalline grains to become shattered and amorphotized by UV photons and cosmic rays.
- Cold-gas condensation and conglomeration naturally produce amorphous grains.

See, e.g., Draine (2006).

Evidence for interstellar dust

How do we know that there is interstellar dust?

Evidence for interstellar dust

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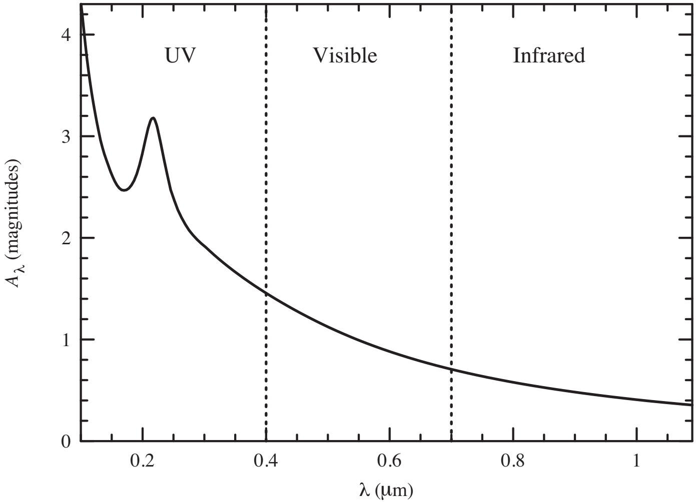
Extinction	Dark markings on the Milky Way (dark clouds) are generally caused by absorption and/or scattering of background starlight rather than holes in the stellar distribution.
Reddening	Stars associated with dark markings are much redder in color in their continuum emission than one would infer from their spectral type (classified by line emission). This selective extinction is naturally explained by the wavelength dependence of scattering and absorption of light by sub-μm particles.
Polarization	of originally unpolarized starlight is naturally explained by selective absorption by nonspherical, aligned, sub-μm solid particles.

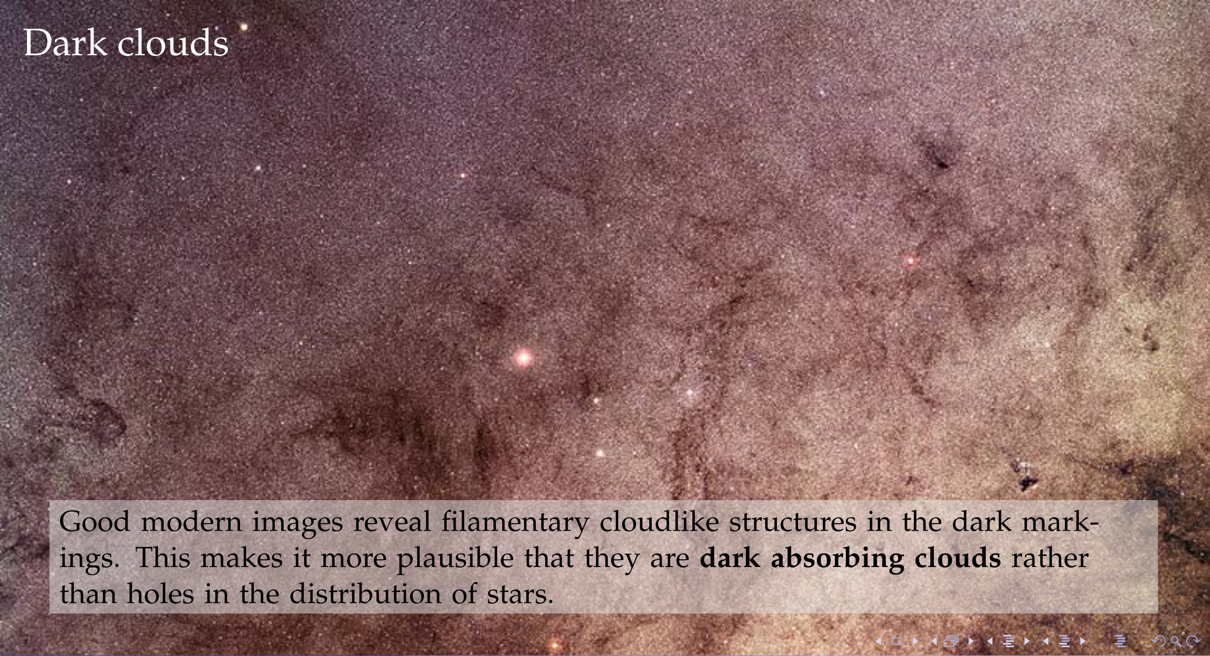
Extinction vs. wavelength

Dust extinction as a function of wavelength, normalized to $A_V = 1$. The bump at 0.22 μm is likely caused by grains of graphite (e.g., soot).



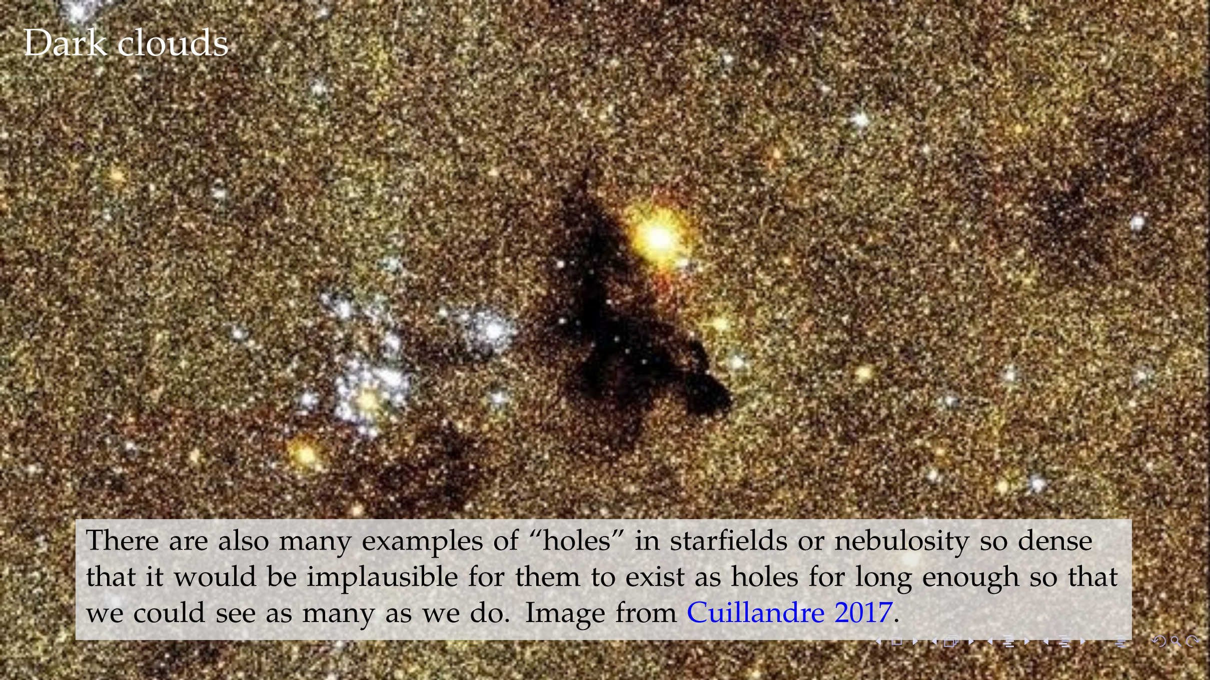
Dark clouds

Dark clouds



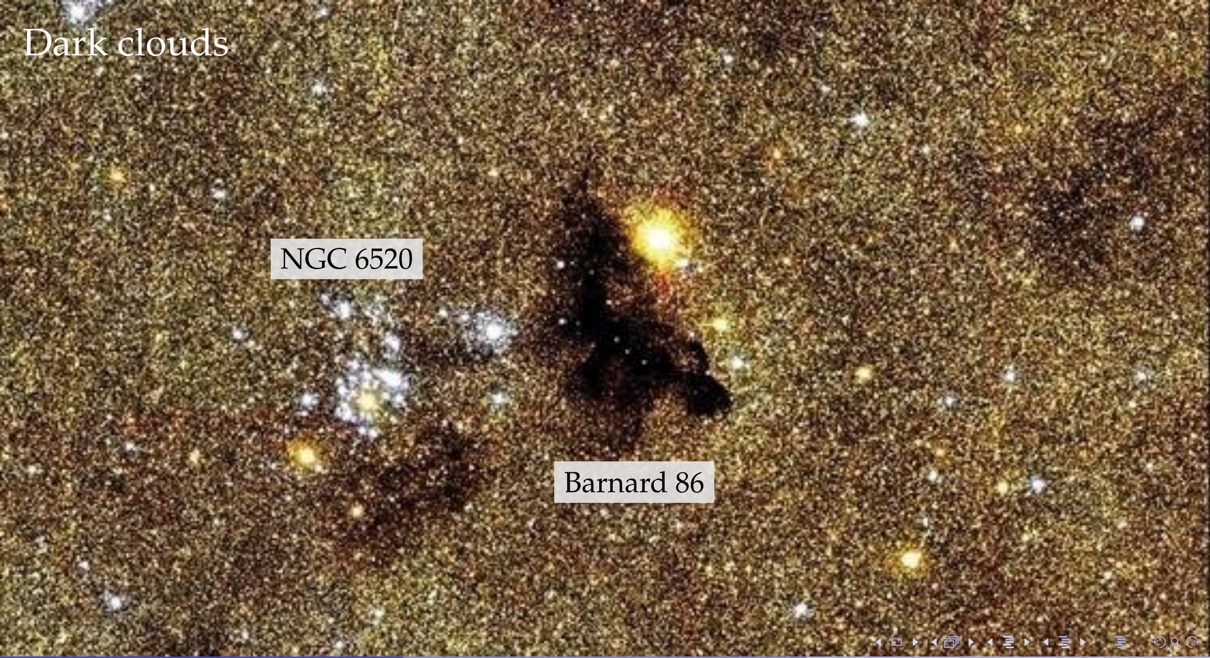
Good modern images reveal filamentary cloudlike structures in the dark markings. This makes it more plausible that they are **dark absorbing clouds** rather than holes in the distribution of stars.

Dark clouds

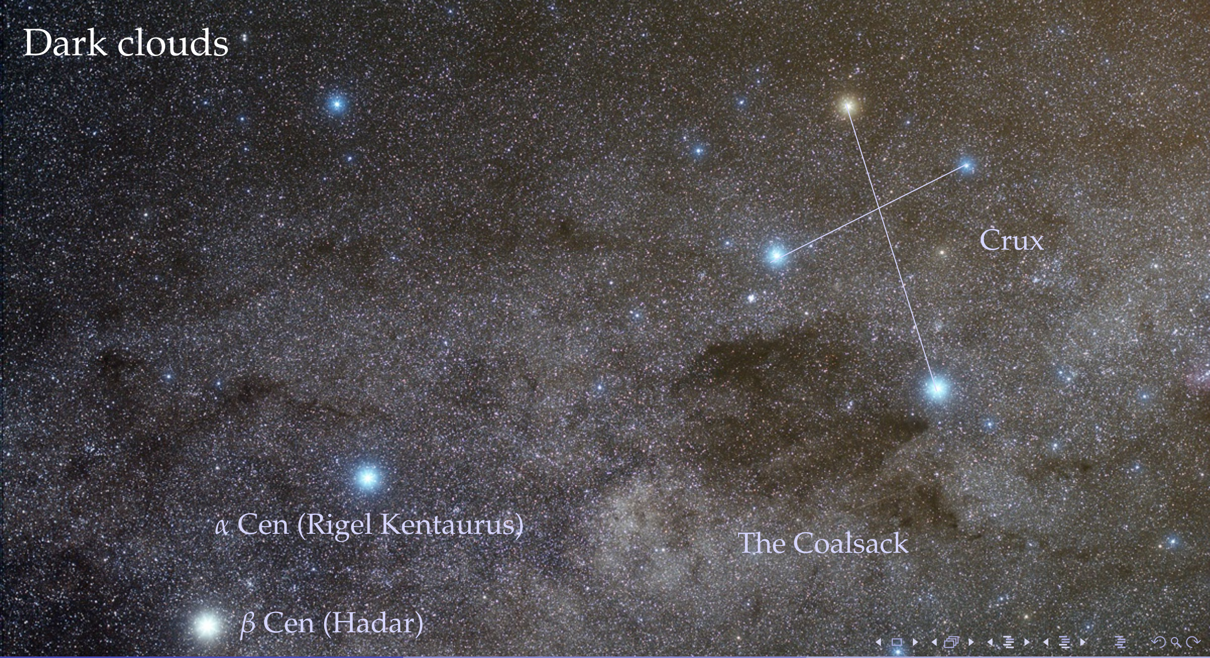


There are also many examples of “holes” in starfields or nebulosity so dense that it would be implausible for them to exist as holes for long enough so that we could see as many as we do. Image from Cuillandre 2017.

Dark clouds



Dark clouds



Dark clouds


σ Orionis (and cluster)
Alnitak
Horsehead Nebula
NGC 2024

A hole in the sky

NGC 1999 in Orion: an exception that proves the rule.

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

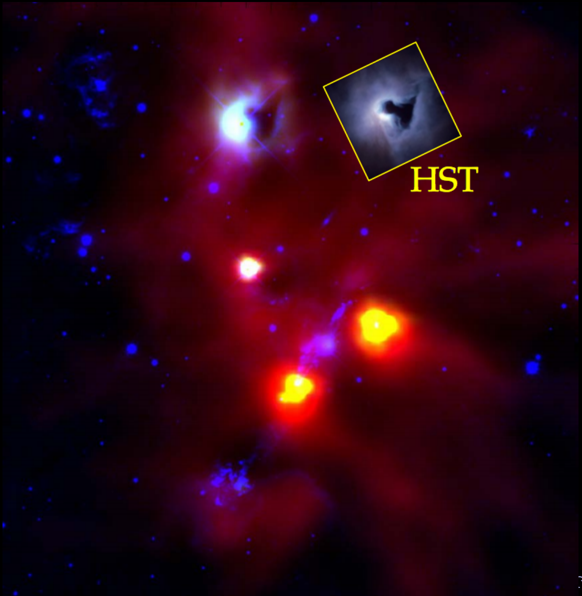
Visible image from NASA/HST/STScI

A hole in the sky

The "globule" turns out to be dark even at very long IR and sub-mm wavelengths.

- An ordinary globule would emit brightly at these long wavelengths.
- So in this case the hole really is a hole.

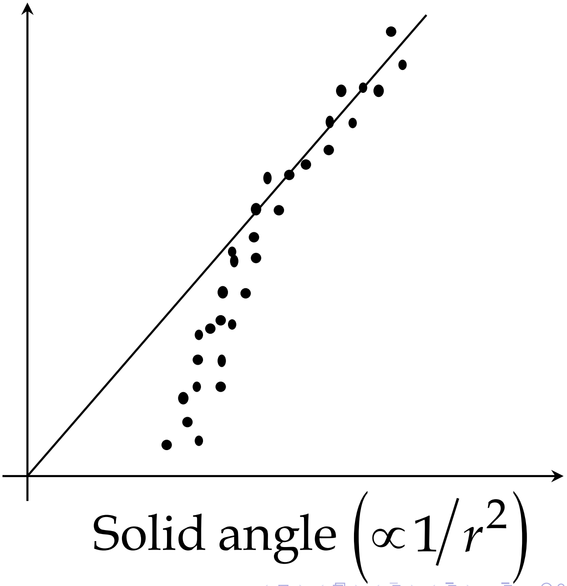
Image: blue = 4.5 μm, green = 70 μm, red = 160 μm. From Herschel Space Observatory (Stanke et al. 2010)



Proof of the existence of extinction

Trumpler's experiment on open clusters (Trumpler 1930): plot sum of fluxes from all stars in cluster versus solid angle occupied by the cluster.

- If all open clusters had the same diameter D then $\Omega = \pi \left(\frac{D}{2r}\right)^2 \propto r^{-2}$.
- Since flux scales like r^{-2} one should get a straight light through the origin.
- **Scatter**: clusters do not all have the same D.
- **Curve does not pass through origin**: flux falls faster than r^{-2}; implies extinction.



Rayleigh scattering

Scattering by non-absorbing dielectric spheres with number density N, index of refraction n and radius $a \ll \lambda$. If f_0 is the flux without extinction, then the observed flux f is given by the **Beer-Lambert Law**:

$$\boxed{f = f_0 e^{-\alpha x} = f_0 e^{-\tau_s}}$$

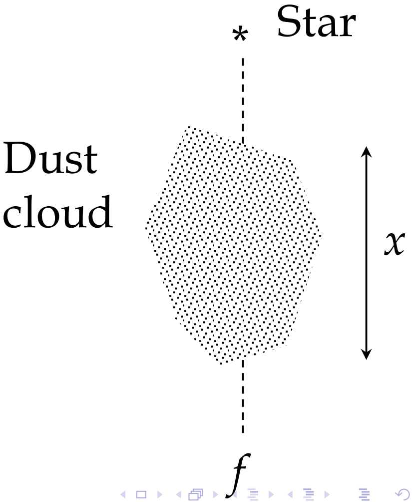
where

$$\alpha = \left(\frac{32\pi^3 (n-1)^2}{3N}\right)\frac{1}{\lambda^4} = \frac{1}{\ell}$$

is the volume scattering coefficient and

$$\tau_s = \alpha x = \int_0^x \alpha(x')\,dx'$$

is the optical depth in scattering.



Rayleigh scattering and the “blue sky effect”

- You will derive these expressions in an intermediate E&M course. The point to remember is the very strong wavelength dependence $\tau_s \sim \lambda^{-4}$.
- Large τ_s means more light is scattered out of the line of sight, and therefore less light is transmitted to you.
- Note that short-wavelength light is scattered more effectively than long-wavelength light because of the λ^{-4} dependence.
- Thus the **sky is blue**, as are reflection nebulae like NGC 1999, because blue light is side-scattered efficiently.
- By the same token, what gets transmitted is more red because the blue light is scattered out of the direct line of sight. Thus, **sunsets are red**, as is extinguished starlight.
- Note that long-wavelength light (IR, radio) can penetrate dust.

Rayleigh scattering

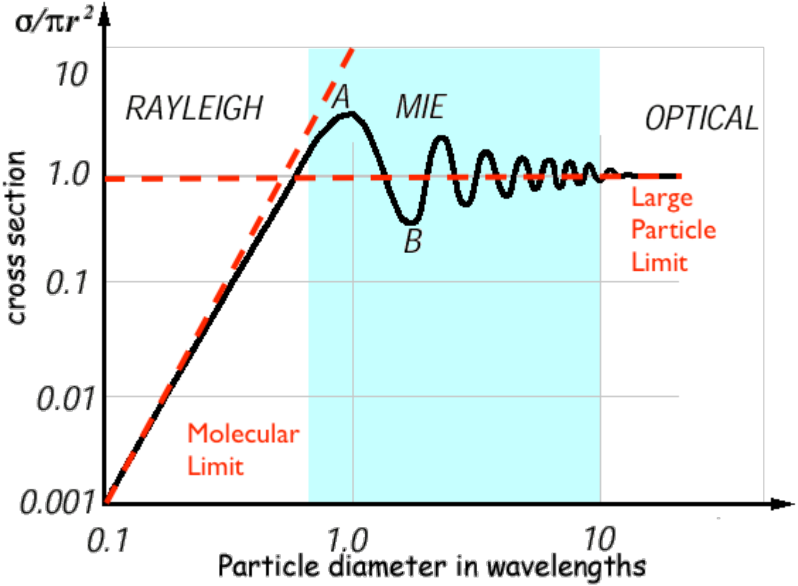
- The Trifid Nebula (M20) exhibits significant effects of scattering (Malin 2017).
- Dark lanes in upper, *ionized*, nebula: extinction
- Blue color of lower, *reflection*, nebula: scattering
- Many bright red stars in field: reddening

Scattering Regimes

$a \ll \lambda \qquad \tau \sim \lambda^{-4}$

$a \sim \lambda \qquad \tau \sim \lambda^{-1}$

$a \gg \lambda \qquad \tau \sim C$



Color excess & extinction

Color excess & extinction

Starting from the **Beer-Lambert Law** $f = f_0 e^{-\tau}$, we can express extinction in terms of magnitudes:

$$\begin{aligned} m_{\text{obs}} - m_0 &= 2.5 \log \left(\frac{f_0}{f_0 e^{-\tau}} \right) \\ &= 2.5 \log \left(e^{\tau} \right) \\ &= 2.5\tau \log e = 2.5\tau(0.434) \\ m_{\text{obs}} &= m_0 + 1.086\tau \end{aligned}$$

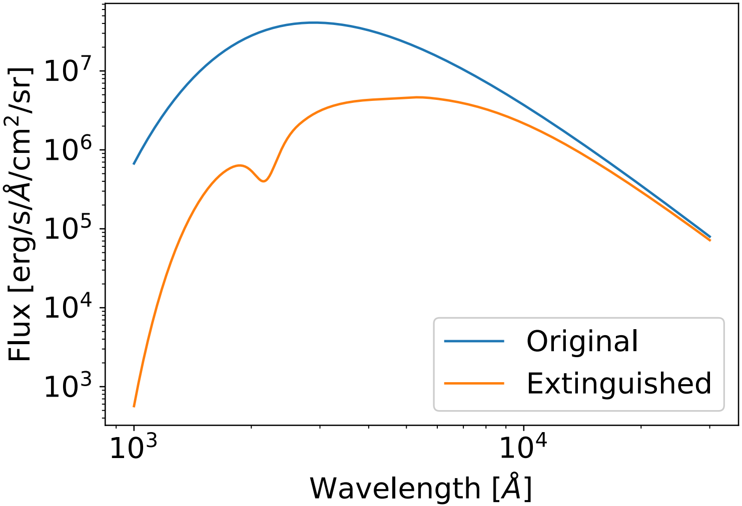
Thus we can define a wavelength-dependent extinction term $A(\lambda) = 1.086\tau(\lambda)$ such that

$$m_{\text{obs}}(\lambda) = m_0(\lambda) + A(\lambda) \qquad\qquad m_{\text{obs}} - M = 5 \log r - 5 + A$$

In other words, the effect of extinction is to make stars look fainter than they should given their distance.

Color excess & extinction

The effect of extinction is to reduce the flux at shorter wavelengths. This makes the color of the object redder, and it reduces the overall brightness of the object (making it appear further away).



Color excess & extinction

For a color index such as $B - V$, the individual magnitudes will be shifted by a passband-dependent extinction term:

$$V = V_0 + A_V \qquad B = B_0 + A_B$$

Color excess & extinction

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$$V = V_0 + A_V \qquad\qquad B = B_0 + A_B$$

Hence the observed color will be

$$B - V = (B - V)_0 + (A_B - A_V) = (B - V)_0 + E(B - V)$$

The term $E(B - V)$ is called the **color excess**. In terms of optical depth, the color excess is

$$E(B - V) = A_B - A_V = 1.086(\tau_B - \tau_V) = 1.086\tau_V \left(\frac{\tau_B}{\tau_V} - 1 \right)$$

Color excess & extinction

The wavelength dependence of extinction is written in terms of R, the ratio of total to selective extinction:

$$R_V = \frac{A_V}{E(B-V)} = \frac{1}{\frac{\tau_B}{\tau_V} - 1}$$

Since $\tau \sim \lambda^{-n}$ with $n > 0$, extinction is larger at shorter wavelengths (**reddening**). In other words, stars look redder than they should given their temperature. For particles with size $a \approx \lambda$, $\tau \sim \lambda^{-1}$ and

$$R_V = \frac{1}{\frac{\tau_B}{\tau_V} - 1} = \frac{1}{\frac{\lambda_{\text{eff},V}}{\lambda_{\text{eff},B}} - 1} \approx 4.2$$

for $\lambda_{\text{eff},B} = 445$ nm and $\lambda_{\text{eff},V} = 551$ nm.

For diffuse dark clouds, $R_V \approx 3.1$ and $\tau_V = 2.76E(B-V)$. And for dense molecular clouds, $R_V \approx 5.5$ and $\tau_V \approx 5.1E(B-V)$.

Extinction correction

Recipe:

1. Reduce every $B - V$ by the same amount $E(B - V)$
2. Reduce every V by the visual extinction A_V
3. The whole H-R diagram shifts to bluer and brighter values.

You will be applying these corrections in future homeworks and recitations.