Today in Astronomy 142

Interstellar dust

- Extinction, reddening and polarization of starlight
- Composition and structure of dust grains

The Lund Observatory painting of the sky, dominated by the Milky Way

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How do we know that there is interstellar dust?

Extinction: dark markings on the Milky Way: absorption and/or of background starlight, rather than holes in the distribution of stars.

Reddening: stars 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.

Polarization of (originally unpolarized) starlight: naturally explained by selective absorption by nonspherical, aligned, submicron-size solid particles.

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View toward the Milky Way's bulge

Visible-light photograph by David Malin (AAO)

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NGC 6520 and Barnard 86

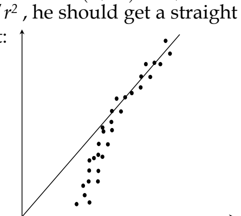
Visible-light image by [Jean-Charles Cuillandre (CFHT)].

NGC 2024 and the Horsehead Nebula ([NOAO])

Discovery of extinction: Trumpler's experiment on open clusters

Plot 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 $\Omega = \pi(D/2r)^2 \propto 1/r^2$, and since flux also scales with $1/r^2$, he should get a straight line through the origin. He got:

Total flux $\left(\propto 1/r^2\right)$



Solid angle $\left(\propto 1/r^2\right)$

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

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

([Trumpler 1930])

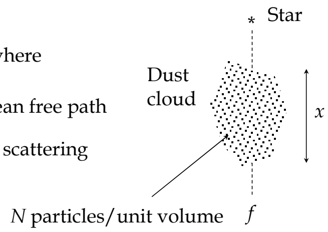
Rayleigh scattering

Results for scattering by non-absorbing dielectric spheres with refractive index n and radius a << l, on the flux from a background source that would give a flux f_0 in the absence of dust:

$$f = f_0 e^{-\alpha x} = f_0 e^{-\tau} \quad \text{, where}$$

$$\alpha = \frac{32\pi^3 (n-1)^2}{3N\lambda^4} = 1/\text{mean free path}$$

$\tau = \alpha x$= optical depth in scattering



Rayleigh scattering (continued)

These expressions will be derived for you in PHY 218. We won't use them further but they serve as a useful illustration of the strong wavelength dependence of light scattering by small particles.

Note that the larger τ is, the less light is transmitted, and the more light is scattered into other directions.

Also note that short-wavelength light is scattered more effectively than long-wavelength light, because $\tau \propto 1/\lambda^4$.

- Thus **the sky is blue**, as are reflection nebulae.

By the same token, what gets transmitted is redder, because the blue is scattered away.

- Thus **sunsets are red**, as is other extinguished starlight.
- Longer-wavelength light (e.g. infrared, radio) can see through dust.

Trifid Nebula (M20)

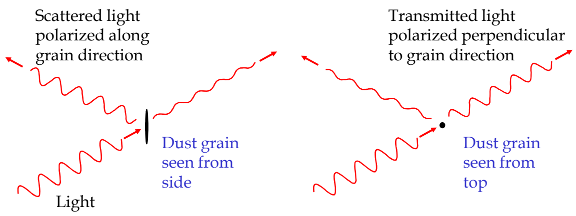
Photograph by David Malin (AAO).

Note:

- Dark lanes in upper, *ionized*, nebula (extinction)
- Blue color of lower, *reflection*, nebula (scattering)
- Many bright red stars in field (reddening)

Polarization of light scattered by nonspherical dust grains

Interstellar dust grains are usually far from spherical: they tend instead to be needle- or flake-like. Thus they can absorb or scatter light with some polarizations – the components of ***E*** along the long dimension of the grain – better than others.



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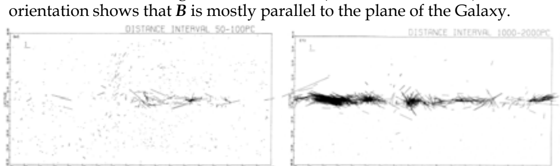
Polarization of light scattered by nonspherical dust grains (continued)

Interstellar dust grains are often aligned with their long axes along some given direction. That direction can be determined by external magnetic fields and/or gas motions.

- Most common alignment: ***B*** perpendicular to the long axis of spinning dust grain.

Below: electric polarization of stars in different distance ranges, as a function of Galactic longitude and latitude (Axon and Ellis 1976). The orientation shows that ***B*** is mostly parallel to the plane of the Galaxy.



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Extinction and reddening by real dust grains

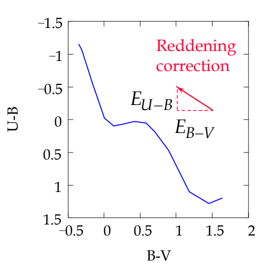
Most interstellar grains aren't just dielectric; they absorb light, too. Empirical relation for τ:

$$\tau \propto \lambda^{-1.85} \quad , \quad \lambda = 0.5 - 20\ \mu\text{m}$$

(except for certain special wavelengths - see below).

Reddening – or differential extinction – is defined by the **color excesses**, $E(U-B)$ and $E(B-V)$, where

$$\frac{E(U-B)}{E(B-V)} \cong 0.72 \quad .$$



Empirical color-color relation for unextinguished zero-age main sequence stars

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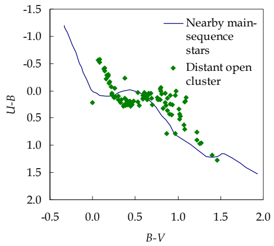
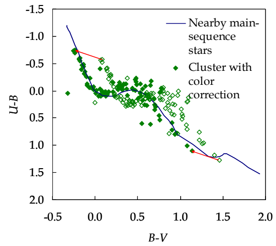
How can you tell your cluster suffers reddening, and how do you measure and correct it?





Take U, B and V observations; 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 $E(U-B)$ (0.32 and 0.18, here).

Color excess and extinction

The B-V color excess is related to extinction optical depth. Empirically, for diffuse-cloud extinction:

$$\tau_V = 2.76 E_{B-V}$$

In magnitudes: $A_V = RE(B-V)$

$$m_{V0} = m_V - A_V$$

$$(B-V)_0 = B - V - E(B-V)$$

$$f_V = f_{0V}(2.5)^{-A_V} = f_{0V} \times 100^{-A_V/5}$$

where, for diffuse clouds, R = 3.06. Effects:

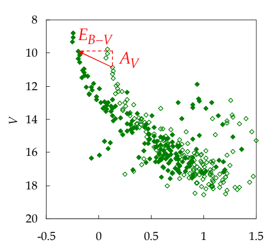
- ❑ Stars look too red for their temperature.
- ❑ Stars look too faint for their distance.

Extinction correction

Recipe:

- ❑ Reduce every B-V by the same amount, $E(B-V)$.
- ❑ Reduce every V by the visual extinction A_V.
- ❑ The whole HR diagram shifts to bluer and brighter values.

You'll be doing some of this in Homework 5, this week's recitation, and future homework sets.



Interstellar dust grains themselves

Size: more like smoke than household dust. < 0.1 μm in dark clouds, up to ~1 μm in the darkest molecular clouds (?), and down to 0.001 μm (50-100 atoms) in diffuse clouds and UV-illuminated clouds.

Amount: about 1% by mass of the interstellar medium (see next class).

Made of: silicates, carbon and probably metallic iron, just like terrestrial planets.

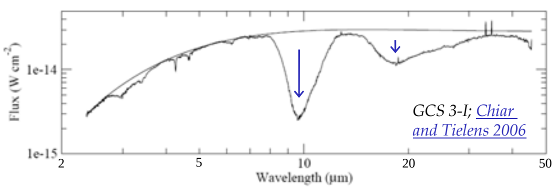
Temperature: T = 10-100 K.

- ❑ Heated by ultraviolet starlight.
- ❑ Cooled by blackbody emission. The radiation by interstellar dust grains can be seen at infrared wavelengths.

Interstellar silicate dust grains

Especially evident at wavelengths **9.7 and 18 μm**, interstellar silicates are submicron in size, and **amorphous** (not crystals).

- ❑ By mass, > 96% magnesium silicates, half Mg_2SiO_4, half $MgSiO_3$; ~3% SiC, < 1% crystalline silicates. Highly irregular in shape. (Min et al. 2007)

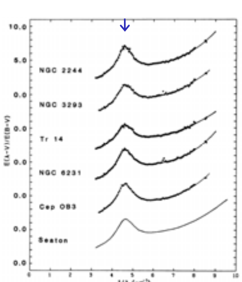


GCS 3-I; Chiar and Tielens 2006

Interstellar carbon dust grains

Also submicron, and extinguishes due both to amorphous and molecular components, both pure and hydrogenated.

- ❑ Most distinctive feature of the bulk of carbon grains is a **217.5 nm** absorption due to graphite.
- ❑ Largest contribution to extinction is due to continuous absorption: both graphite and amorphous carbon are electrical conductors.

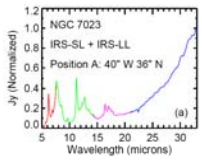


Massa and Fitzpatrick 1986

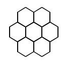
Interstellar carbon dust grains (continued)

The smallest carbon dust grains only have tens of atoms, and have several unusual aspects:

- Only seen by emission features, never in absorption.
- Appear hot even when far from a star, because that heating requires only single UV photons (Sellgren 2004).
- Pattern of infrared features indicates that these grains are **polycyclic aromatic hydrocarbons** (PAHs; Leger and Puget 1984).



Werner et al. 2004



A typical PAH: coronene, $C_{24}H_{12}$

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, condensed from cold gas and perhaps conglomerated with other grains.

- Dust 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 interstellar medium, 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, 2009)