Whittle : EXTRAGALACTIC ASTRONOMY

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9. GAS & DUST IN GALAXIES

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(1) Galaxy ISMs : An Overview

- Like the Earth, galaxies have an **atmosphere** $\rightarrow$ a gaseous component held "down" by gravity
  this atmosphere fills the space between stars, hence: **interstellar medium** (ISM)
  by mass, the ISM is usually not very important: $M_{ISM} \approx 1\% \, M_{stars}$
  The **average** midplane density is ~1 cm^{-3} $\rightarrow$ columns ~$3\times10^{21} cm^{-2}$/kpc (~0.005 gm cm^{-2}/kpc)
  $\rightarrow$ galaxy disks have "thickness" $\equiv$ 5 cm of Earth's atmosphere (~1 meter of air to the GC).
- The ISM contains: starlight; gas; dust; cosmic rays; magnetic fields
  Near the sun they all have similar energy density $\equiv$ pressure $\approx$ 1 eV cm^{-3}
- The element mix is the usual: H/He/others: 74/24/2 (% by mass); 90/10/0.01 (% by number)
  Of the "others", ~10-50% have condensed out as solid particles: "dust".
- Despite its low mass, the ISM is ultimately very important, for several reasons:
  1. It plays a crucial role in the star $\leftrightarrow$ gas cycle
     - in spirals and irregulars, it facilitates ongoing (& current) star formation
     - it is a repository for element buildup and is therefore integral to chemical evolution
  2. Because it can cool, its collapse is **dissipational**
     - stars can form !! hot gas $\rightarrow$ cold gas $\rightarrow$ stars
     - new generations of stars "cool" spiral disks, allowing arm formation
     - globally, gas can migrate inwards to smaller radii:
       $\rightarrow$ galaxies are smaller than dark matter halos !

→ galaxies have steep density gradients
→ galaxy nuclei can have very high densities, including an SMBH

3. Being atomic/molecular, its emission & absorption provides enormous diagnostic information
   Some examples :
   - Doppler motions reveal galaxy dynamics
   - abundance measurements allow study of chemical evolution
   - physical conditions: density; temp; pressure; turbulence; columns; mass, can all be derived
   - some emission lines can be seen (relatively) easily at cosmological distances.
   - high redshift QSO absorption lines reveal halo & disk evolution.

4. The ISM can dominate a galaxy's integrated SED (spectral energy distribution):
   starlight dominates the UV-NIR; but the ISM dominates outside this range.
   - Mid-IR to Sub-mm is dominated by emission from **dust**
   - Soft X-rays come from the **hot ISM phase** (though X ray binares can be important)
   - cm-radio comes either from **HII regions** or a **relativistic magnetoionic plasma**
   - certain emission lines (eg Lyα; [CII]λ158μ) can be **major coolants**

- The ISM is energized primarily by **stars** (starlight, winds, supernovae)
  → UV starlight photoionizes atoms & dissociates molecules; photo-ejected electrons heat gas
  → SN shocks heat/ionize/accelerate gas & are largely responsible for the ISM's complexity.

- The ISM can be highly **inhomogeneous**, with several **phases**
  These phases are (roughly): hot/warm/cold, with low/medium/high density
  In a wide range of conditions these phases have **similar pressures** → $P/k \equiv nT \approx 10^4 \approx 1$ eV cm^{-3}.
  However, in dynamic situations, pressure balance is no longer applicable.

  The ISM contains **cloud** and **intercloud** components with density contrast ~ 10^2-10^5
  → these clouds are not like terrestrial clouds; more like blocks of wood or lead hanging in the air.

- The ISM is a **dynamic environment**, with **mass exchange** between phases
  - cooling facilitates: hot → warm → cold → stars.
  - supernovae inject energy which accelerates the gas and continuously rearranges the geometry
    → e.g. a disk ISM will "boil" & "bubble" with gas cycling out & back above the disk.
  - sporadically, tidal encounters & their resulting starbursts can:
    - add fresh (low metallicity) gas
    - energize and evacuate large regions
    - cycle gas into the halo, some of which may return later.
    - radically alter the ISM, e.g. spiral + spiral → elliptical.

  As always, our current view is just one frame of a long and intricate movie.

- What about the **distribution** of ISM (particularly in spiral disks)?

  1. **Globally** the scale height depends on the phase's temperature/velocity dispersion and $\nabla\phi$
     → colder phases are confined closer to the plane
     → hotter &/or more turbulent phases are thicker
     → in disks, the ISM flares at large radii and is thinner at small radii).
     However, high local energy density can affect this distribution by driving vertical blow-out.

  2. **Locally**: the ISM is highly complex & "foamy"
     SN evacuate complex interconnected "superbubbles"
     between are sheets & clouds of denser colder gas.

- The Milky Way can act as a **template** for studying other galaxy ISMs
  As usual, the proximity of the MW's ISM offers important insights
  Hence, MW ISM studies are now extensive & comprise a major area within astronomy

Here, we consider only the bare essentials, providing a framework for discussing ISM in other galaxies.

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(2) ISM Components & Their Observational Signatures

(a) Introduction

While ultimately ISM gas spans all conditions, in practice much resides in one of several **components**
These components are distinguished by their **phase** (n,T,X_e) and their **location**
This figure and the following table summarize the major components:

Component	Temp K	Density midplane cm^{-3}	Pressure nT $K\ cm^{-3}$	X_e ionization	FF filling %	<h> thickness pc
Intercloud						
Hot HII (HIM)	10^6	0.002	2000	1	50:	3000:
Warm HII (WIM)	8000	0.15	1200	1	20	1000
Warm HI (WNM)	8000	0.3:	2400	0.5	30:	500
Clouds						
Cold HI (CNM)	120	25	3000	0.1	2	100
Cold H_2 (CNM)	15	200	3000	10^{-4}	0.1	75

Note that overall, the intercloud/cloud fraction by <u>mass</u> is ~50 : 50 but by <u>volume</u> it is ~98 : 2

- Three other important components add to the mix :
  1. **Dust**: 1nm - 1μm solid particles are found in essentially all phases
     ~50% heavy elements are in dust (~100% of the refractories)
     Dust is discussed more in section 8 (link)

  2. **Magnetic fields**: generally a few μGauss in both ordered and random components
     energy density: $B^2/8\pi \approx 10^{-12}$ erg $cm^{-3} \approx 1$ eV cm^{-3}
     field compression in superbubble expansion effects on ISM structure (see below).

  3. **Cosmic Rays**: relativistic electrons & protons, created in SN shocks
     these diffuse throughout the galaxy and permeate all phases (some even hit the earth)
     they are a primary heating source in DMC cores (which are otherwise shielded).
     the most energetic electrons + magnetic fields $\rightarrow$ radio synchrotron
     proton collisions with nuclei $\rightarrow$ diffuse gamma emission
     equipartition with B field likely, so suspect ~1 eV cm^{-3}

(b) Observational Signatures: General Considerations

All observations involve either emission or absorption
these, in turn, depend on **Emission Measure** (EM) and **column density** (N)

- Emission processes are usually **collisional**, so are $\propto n^2$

surface brightness is therefore $\propto \int \langle n^2 \rangle \, dl$ pc cm^{-6} $\equiv$ **Emission Measure** (EM).

- Absorption processes, in contrast, are $\propto \int \langle n \rangle \, dl$ cm^{-2} $\equiv$ **Column Density** (N).
- For ionized gas, the relevant density is usually n_e
  The table shows EM & N_e for various systems:

Medium	**n_e** cm^{-3}	**Size** pc	**EM** pc cm^{-6}	**Emission Visibility**	**N_e** cm^{-2}	**Absorption Visibility**
Young Nova	10^7	10^{-3}	10^{11}	v. bright!	3×10^{22}	thick
PN	10^4	10^{-1}	10^7	bright	3×10^{21}	good
HII Region	10	10^2	10^4	fine	3×10^{21}	good
Diffuse ISM	10^{-1}	10^3	10	difficult	3×10^{20}	good
Halo	10^{-3}	10^4	10^{-2}	invisible	3×10^{19}	fine

Note, for a typical crossection ~ a_{Bohr} ~ 10^{-16} cm^{-2}, N ~ 10^{14} cm^{-2} gives τ ~ 1%
This is easily measurable with suitable background source
$\longrightarrow$ low density gas invisible in emission can often be studied in absorption.

- Photoioniztion thresholds render the ISM highly opaque in the EUV:
  ionization potentials χ for H, He, He$^+$ are 13.6, 24.6, 54.4 eV (= 91, 50, 25 nm)
  since $\sigma_{photo} \propto (E-E_i)^{-3}$, then:
  - the ISM is **highly opaque** in EUV (13.6 - 100 eV)
  - it is becoming transparent in soft X-ray (~0.6 keV)
  - it is completely transparent by 2 keV.
- A wide range of δE transitions yield features at many wavelengths:

Transition δE eV	**wavelength range**	**Cause**
10^{-6}	21 cm	electron spin flip in atomic H
10^{-2} - 10^{-3}	FIR - mm	molecular rotation
0.1 - 0.01	NIR - FIR	gas molecular vibration; bond bending in dust
0.03 - 0.003	MIR - sub-mm	phonons in dust @ T ~ 1000-10 K
1 - 10	UV - NIR	outer shell electron transitions in atoms <u>and</u> molecules
10 - 10^3	EUV - X-ray	inner shell electron transition; 50 - 500 km s^{-1} post shock gas

Note some useful conversions: $E_{eV} \equiv 1240/\lambda_{nm} \equiv T_K / 7740$ per particle.

so @ T $\gtrsim 10^5$K, H & He are fully ionized, and kT ~ EUV - soft X-ray

(c) Warm Ionized Gas

- This gas has T ~ 8000K and resides in:
  - star forming HII regions (n_e ~ 1 - 100+ cm^{-3})
  - diffuse ionized gas (n_e ~ 0.01 - 1 cm^{-3})

- In both cases, equilibrium occurs when:
  1. ionization rate = recombination rate (ionization balance)
  2. heating = cooling (thermal balance)

  ionization is from stellar UV photons; **recombination** occurs naturally
  heating is from photo-ejected electrons; **cooling** is via emission lines

- Note that in these circumstances the ionization degree **does not** reflect the temperature
  e.g. at 8000K, $O \longrightarrow O^+ \longrightarrow O^{2+}$ cannot occur by collisions (it is too cold)
  but a weak radiation field of 50 eV (250A) photons can ionize up to O^{2+}.

(i) Hydrogen Recombination Radiation

- electrons are captured by protons and the resulting cascade emits photons.
  the rate is $\alpha\, n_e n_p$ cm^{-3} s^{-1}, where α is a recombination coefficient (units are cm^3 s^{-1}).

- Usually, the gas is optically thick to Ly-α, which is trapped (termed: case B)
  the **total** recombination rate is then α_B = 4.52 & 2.58 × 10^{-13} $cm^3 s^{-1}$ (for 5000 & 10,000 K)
  While for just Hβ it is $\alpha_{H\beta}$ = 5.38 & 3.01 × 10^{-14} $cm^3 s^{-1}$ (for 5000 & 10,000 K)

- The table gives some useful Hydrogen line wavelengths and relative strengths (Case B; T = 10^4 K):

Series (lower level)	α wav ratio/Hβ	β wav ratio/Hβ	γ wav ratio/Hβ	δ wav ratio/Hβ	**Series Limit** wav
1: Lyman	1216 A_{vac} 23	1026 A_{vac} ??	973 A_{vac} ??	950 A_{vac} ??	912 A_{vac}
2: Balmer	6563 A 2.86	4861 A 1.00	4340 A 0.47	4101 A 0.26	3646 A
3: Paschen	1.87 μ 0.339	1.28 μ 0.163	1.09 μ 0.090	1.00 μ 0.055	0.82 μ
4: Brackett	4.05 μ 0.080	2.63 μ 0.045	2.16 μ 0.028	1.94 μ 0.018	1.45 μ

  Note that the Ly-α flux is often difficult to predict:
  it is resonantly scattered and either:

  it is absorbed by dust, or
  the 2 $\longrightarrow$ 1 transition goes via 2-photon decay

- Cascades between very high n (~100) give **radio recombination lines**
  e.g. H109α at 5.8cm comes from transitions n=109 $\longrightarrow$ 108

These lines are useful since they are unaffected by dust; though they are quite weak.

(ii) Collisionally Excited Fine Structure Lines

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(d) Hot Ionized Gas

(e) Warm & Cold Atomic Gas

(f) Molecular Gas

(g) Dust

(h) Relativistic Component

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(3) Theories of the Multi-Phase ISM

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(4) Gas in Disk Galaxies

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(5) Gas in Elliptical Galaxies

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(6) Gas in Galactic Nuclei

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(7) Gas in Galaxy Halos

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(8) Dust: Particles in the ISM

(a) Overview

- All ISM **gas** phases are optically **transparent** (or very nearly)
  However, the Milky Way shows patchy **obscuration** of background starlight (image)
  What causes this optical absorption? $\longrightarrow$ **solid particles** with size a $\approx \lambda_{light}$ (nm - μm)

Astronomers call these particles **"dust"**, though a better word might be "smoke".

- By human standards, the ISM is **exceedingly filthy**.
  Imagine bringing the ISM to atmospheric number density (3×10^{19} cm^{-3})
  $\rightarrow$ it would be a **thick smog** with ~1 mag/meter [~1 mag/inch at ρ_{air}] !!
  $\rightarrow$ You could not see across a room [your hand in front of your face] !!
  $\rightarrow$ Walking just a few paces, you'd be covered in an extremely fine black soot.
  $\rightarrow$ This is a chain-smoker's heaven/nightmare: the smoke is rich in carcinogenic PAHs.

- Why is the ISM so dirty ? Because stars are **dirty furnaces**.
  For 10 Gyr they've been "polluting" the ISM by making & blowing off **heavy elements**
  Typically, 10-50% of these elements condense as tiny solid particles: graphite/silicates/ices
  $\rightarrow$ Our atmosphere is clear by comparison because it doesn't contain ~1% particulates.

- Dust has a huge impact on EM radiation, spanning **3 decades** (~1000A - 100μm).
  It **absorbs** UV & optical but is transparent in the IR (grains have size $\sim\lambda_{UV}$).
  $\rightarrow$ important contributions have come from Copernicus, IUE, HST.
  It **emits** in the IR (since its equilibrium temperature is ~10-100K)
  $\rightarrow$ important contributions have come from IRAS, COBE, ISO, Spitzer.

(b) Quick estimates of some important dust properties

Let's gain some insights from a simplified, yet useful, treatment.
Assume an ISM metallicity of Z~2% (by mass) of which $f_d \sim 0.1$ is condensed as grains.
Assume all grains have dimension a (~0.1μm) and density ρ (~1 gm cm^{-3}).
The grains absorb and emit as black bodies modified by efficiencies $Q_{abs}(\lambda)$ and $Q_{em}(\lambda)$
In reality, $Q_{abs} \sim 1$ in the UV, and $Q_{em} << 1$ in the IR (see below)
However, for now let's take $Q_{abs} = Q_{em} = 1$ (perfect black bodies)

(i) H column for significant dust opacity

What hydrogen column has geometrical covering factor 1 in dust particles?

- In terms of the hydrogen column, N_H cm^{-2}, the projected mass density in dust is simply:
  $N_d \rho a^3 = N_H m_p Z f_d$ gm cm^{-2} where N_d cm^{-2} is the column in dust.

  Substituting for N_d, the total **geometrical cross section** in dust particles is :
  $N_d a^2 = (N_H m_p Z f_d)/(\rho a^3) \times a^2 \approx 3 \times 10^{-22} \times N_H f_d (Z/Z_\odot) \times (\rho a_\mu)^{-1}$ cm^{-2}
  where ρ is in gm cm^{-3}, a is in μm, and $Z_\odot = 0.02$ is solar metallicity.
  (using a^2 is OK here, since the absorption efficiency $Q_{abs} \sim 1$ in the UV/opt).

- For our fiducials, unit covering factor ($N_d a^2 \sim 1$ cm^2) occurs for $N_H \sim 3 \times 10^{21}$ cm^{-2}
  Thus, hydrogen columns $\sim 10^{21.5}$ cm^{-2} mark when dust absorption will be important.
  In fact, this simple estimate is very close to the observed value: $A_V \approx N_H / (2 \times 10^{21})$ mags.

- Using the observed value, paths through the ISM suffer an absorption $A_V \sim 1.6 \times n_H d_{kpc}$ mags
  $\rightarrow$ Spiral disks are optically thick **in the plane**, for which $\langle n_H \rangle \sim 1$ cm^{-3}
  $\rightarrow$ However, with $N_H \sim 10^{21}$ cm^{-2} **perpendicular** to spiral disks, they are borderline transparent.
  $\rightarrow$ DMCs are extremely opaque, since $n_H \sim 10^5$ gives $A_V \sim 100$ mag across 1 pc.
  $\rightarrow$ The hot phase ($n_H \sim 10^{-3}$ cm^{-3}) is tansparent (even without likely dust destruction).

(ii) Dust number density

Continuing briefly, the dust particle number density is:

- $n_d/n_H = (m_p Z f_d) / (\rho a^3) = 3.3\times10^{-14} (Z/Z_\odot f_d) / (\rho a_\mu^3) = 3.3\times10^{-12}$ for a ~0.1μm and f_d~0.1
  For $n_H \sim 1$ cm^{-3} (the ISM average) this gives $n_d \sim 1$ per (100m)^3;
  For $n_H \sim 10^6$ cm^{-3} (a DMC core) it is ~1 m^{-3}
  $\rightarrow$ dust particles are **few and far between** !!

(iii) Dust Temperature

- In the ISM, ambient starlight usually has a much greater energy flux than local particles.
  $\rightarrow$ dust is heated mainly by starlight
  At equilibrium, therefore, starlight heating balances radiative cooling
  There are two common geometries:
  1. For **isotropic** starlight flux J_s erg/s/cm^2/sr we have:
     $4\pi J_s \pi a^2 Q_{abs} \approx 4\pi a^2 \sigma T_d^4 Q_{em} \rightarrow T_d \approx (\pi J_s / \sigma)^{1/4} (Q_{abs}/Q_{em})^{1/4}$
  2. For a distance d from a **point source** of luminosity $L_\star$ we have:
     $L_\star/(4\pi d^2) \pi a^2 Q_{abs} \approx 4\pi a^2 \sigma T_d^4 Q_{em} \rightarrow T_d \approx (L_\star/16\pi d^2\sigma)^{1/4} (Q_{abs}/Q_{em})^{1/4}$

  Both are independent of a, and T_d applies equally for interstellar asteroids, planets, or people.
  [This is not quite true, since both Qs do in fact depend on a].

- Consider dust in the general interstellar radiation field. What is J_s?
  It is roughly what we witness on a clear moonless night, ~0.002 erg/s/cm^2/sr.
  For $Q_{abs} = Q_{em} = 1 \rightarrow T_d \approx 3.2$K $\rightarrow$ interstellar space feels very cold!
  This result was first obtained by Eddington in 1926.

- This value is, in fact, too low by about ×5.
  The reason is that dust **does not behave like a black body**
  It absorbs UV better than it radiates IR $\rightarrow$ **a "green-house" effect**.
  The correction factor, $[Q_{abs}(UV)/Q_{em}(IR)]^{1/4}$ is discussed below (link).

- Dust embedded in HII regions is exposed to a more intense radiation field.
  From 2 we have: $T_d \approx 0.62 \times [(L_\star/L_\odot) / d_{pc}^2]^{1/4} (Q_{abs}/Q_{em})^{1/4}$ K
  giving $T_d \sim 10$K for $L_\star \sim 10^5 L_\odot$ and d ~ 1pc (with $Q_{abs} = Q_{em} = 1$)

  Again, this is a factor of a few too low, but still illustrates just how cold dust usually is.

- Dust never achieves high enough temperature to emit outside the IR because:
  it has no internal energy source
  it's only energy input is starlight
  it can emit with fairly high efficiency, because it is a solid
  it behaves as a macroscopic, not quantum, system (with one exception, see below)
  above ~1500K it evaporates $\rightarrow$ it **never** contributes below the Near-IR

(iv) Dust Emission Efficiency

- In a typical spiral, $M_{ISM} \approx 0.05\ M_{stars}$ and $M_{dust} \approx 0.01\ M_{ISM}$ giving $M_{dust} \approx 0.0005\ M_{stars}$
  However, within factors of a few, $L_{IR} \approx L_{opt}$ and we discover that $L_{dust} \approx L_{stars}$
  How can such a tiny mass of very cold dust compete with nuclear furnaces $10^4\times$ more massive?
  $\rightarrow$ dust has a huge **surface area to mass ratio**

- Consider the sun: it has 1 $M_\odot$, and a surface with area $A_\odot = 1.3 \times 10^{11}$ cm^2, at $T_\odot \sim 6000$K

Now consider 1 $M_\odot$ of ISM with 2% heavy elements in dust with a ~ 0.1μm and ρ ~ 1 gm cm^{-3}
That makes 4 × 10^{46} grains with total surface area 5 × 10^{37} cm^2 ~ 10^{15} $A_\odot$!!
Per unit area, the dust has vastly lower radiative efficiency:

$(T_d/T_\odot)^4 \sim (10/6000)^4 \sim 10^{-11}$

$Q_{em}(IR) \sim 10^{-4}$ relative to black body efficiency (see below)

After integrating over populations of both dust and stars:
$\rightarrow$ dust is a more efficient radiator than stars, per unit mass

(c) The Importance of Dust

For our purposes, dust is important for least two reasons

1. it can significantly affect our view of galaxies :
   - it blocks UV and optical, which may need correcting
   - its emission may enhance or even dominate a galaxy's IR emission

2. it can significantly affect crucial ISM processes:
   - it facilitates ISM chemistry (surface catalysis)
   - it can alter HII region structure (e.g. via Lyα destruction)
   - it dominates DMC cooling, helping star formation
   - it can effectively short circuit the deposition of UV/optical input to the ISM (absorbing and then reradiating in the FIR; e.g. starbursts & AGN).

(d) The Path Ahead

- The simple estimates in (b) above hide a multitude of details
  Specifically, we want to explore:
  - the composition of grains and their size distribution
  - the life cycle of grains: origin, growth and destruction
  - dust's affect on light: its emission and absorption properties
  - whether dust properties depend on environment (e.g. different ISM phases)
  - dust's contriubution to galaxy SEDs (spectral energy distributions)

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(9) Dust: Physical Properties

Ascertaining the properties of dust grains has been remarkably difficult, and is still incomplete.
There are two main reasons for this difficulty:
- They are solids; most astrophysical material is ionic/atomic, with simpler associated physics
- Because they are solids, they have more complex/unclear spectral signatures

Nevertheless, progress has been steady, and the subject is now quite sophisticated.
Here we cover just the basic results.

(a) Dust Composition From ISM Gas Depletion

- If heavy elements reside in dust, they must be missing from the ISM gas.
  One can study dust composition by studying **gas depletion**
  Gas phase abundances are measured from interstellar absorption lines in stellar spectra.

- **The depletion index** is defined logarithmically:

  $D(X) = \log_{10}[N(X)/N(H)]_{obs} - \log_{10}[N(X)/N(H)]_{ISM}$

  where $[N(X)/N(H)]_{ISM}$ is the normal relative abundance of element X (usually taken to be solar).

For example, D(C) = -0.7 means C/H is only 20% of its expected value $\rightarrow$ 80% must be in dust.

- Measurements of diffuse clouds (n_H~10-100 cm^{-3}) shows **significant total depletion** ~50%.
  Expressed as a total "metallicity", Z_d ~ 0.008 (where $Z_\odot$=0.016)
  $\rightarrow$ ~1% of the ISM is in dust, or equivalently ~50% of ISM metals reside in dust.

- However, the depletion varies greatly from element to element.
  Specifically, depletions increase with **condensation temperature**, T_c (see figure).
  [T_c(X) is the temperature when 50% of element X is solid, for equilibrium conditions]
  e.g. Al, Ca, Ti, Fe, Ni are ~100% depleted, while C, N, O, S, Zn show modest or no depletion.
  $\rightarrow$ dust formation involves condensation/adsorption, & not all elements bind efficiently to dust.

- Depletions also vary with **environment**: (see figures)
  depletion is less for hotter/turbulent ISM & higher velocity clouds
  $\rightarrow$ harsh environments (eg shocks) destroy dust &/or prevent it growing
  depletion increases with ISM gas density, at least for some elements
  $\rightarrow$ higher densities facilitate grain growth via adsoption

- In terms of total mass, depletions give the following **overall content for dust**:
  O: 50% C: 20% Fe: 13% Si: 7% Mg: 6% others: 5%
  How they are combined is less clear, though IR spectral features help:
  $\rightarrow$ Silicon is in silicates ($XSiO_3$ pyroxines; $XSiO_4$ olivines), where X is mainly Mg, with some Fe.
  $\rightarrow$ Carbon is in graphite, Polycyclic Aromatic Hydrocarbons (PAH), and amorphous carbon
  $\rightarrow$ Fe in metallic iron inclusions
  (these results do not include the various ices which probably condense onto dust in DMCs)

- The depletion patterns support a dust model with **resilient refractory core + transient mantle**
  The elements Fe, Ti, Ni, Ca are primarily core while Mg and Si can be gained and lost.

- Here's a table which summarizes the various dust populations and their properties: figure

(b) Dust Creation

- There are several sites of dust formation (images)
  1. winds from evolved RG and AGB stars
  2. winds from young massive stars (e.g. η Carina).
  3. nova ejecta
  4. supernova ejecta
  5. directly from gas phase condensation

- These all involve outflowing winds with decreasing density and temperature
  Refractory seeds form and grow by adsorption
  The growth rate depends on the wind density, temperature, velocity, and time in the flow.
  The growth is non-equilibrium -- simple condensation tracks wont work
  The growth also involves feedback:
  As dust forms $\rightarrow$ radiation pressure increases $\rightarrow$ wind speed increases $\rightarrow$ stops dust growth.

- There are **two types of winds** (figures)
  1. O-rich winds $\rightarrow$ make silicate grains
     metal oxide seeds (e.g. Al_2O_3 ; $CaTiO_3$)
     silicate mantles added (e.g. $MgSiO_4$ fosterite; $MgSiO_4$ enstatite)
     Fe may also be included (e.g. $FeSiO_3$ pyroxene).
  2. C-rich winds $\rightarrow$ make graphite & Polycyclic Aromatic Hydrocarbon (PAH) grains
     C_2H_2 (acetylene) nucleation $\rightarrow$ 1-few benzene rings $\rightarrow$ PAHs
     grow to ~10-50A (~500 atoms), so these are **small** grains.

(c) Subsequent Growth and Destruction of Grains

- In some environments, **grains can grow** by adsorption
  most efficient when $kT_{gas} \approx \epsilon_{phonon}$ so collisions lose energy to lattice and adhere
  $\rightarrow$ results in <u>depletion</u> of metals from the gas phase
  Examples:
    - in cold DMCs, grains can grow ice mantles (e.g. H_2, CO, CO_2, CH_4)
    - in proto-stellar disks it is sufficiently dense for grain + grain coagulation
      $\rightarrow$ large "fluffy" grains ($\gtrsim$ 1 μm $\lesssim$ 75% filling factor).

- Many environments are **hostile to grains**
    - Near stars, photon heating can sublimate icy mantles
    - More extreme radiation environments can sublimate the entire grain
      (e.g. near AGNs, $T_{dust} \gtrsim$ 1000K).
    - Shocks from SNRs and stellar winds $\rightarrow$ high kT particles $\rightarrow$ "sputtering"
      > 400 km s^{-1} $\rightarrow$ ion-grain sputtering
      < 400 km s^{-1} $\rightarrow$ grain-grain shattering
      both tend to break up grains $\rightarrow$ power law size distribution (see below).
      ultimately, shocks and high T ISM phases can destroy grains completely.

(d) Dust Grain Size Distribution

- **Grain sizes span three decades**: 0.001μm (1nm) $\rightarrow$ 1 μm (~100 $\rightarrow$ 10^{11} atoms)
  Thats equivalent to salt grains $\rightarrow$ basket balls !
  Clearly, within this huge range one might expect quite distinct grain populations,
  perhaps with different compositions, origins and histories (images).

- The final grain size distribution depends on :
    - the injected size distribution from stellar winds
    - subsequent modification by growth and destruction processes.

  Both these can vary from location to location

- The final mix usually contains varying amounts of the following components:
    1. **A "classical" population** of relatively large, dielectric (silicate?) grains
       There is evidence for a power law size distribution: dn/da $\propto a^{-3.5}$ with a_{max} ~ 0.3μm
       This population explains:
       the basic λ^{-1} form of the UV/optical extinction curve;
       large scattering efficiency (~60%) and scattering angle (~45^o) in the optical
       a_{max} comes from dust's IR transparency
    2. **Very small grains** (nano-grains) are required in several contexts:
       almost isotropic scattering in the FUV
       the 2175A broad near-UV absorption feature suggests ~20 nm graphite grains
       2-20μ emission $\rightarrow$ T_d ~1000K $\rightarrow$ single photon heating of $\lesssim$ 100 atom grains (see below)
    3. **Large grains** ~1-10μm can form in **DMC cores**
       Only in these sheltered environments can ices condense and grains coagulate
       these grains are found in **solar system materials** (a relic of formation)
       they are very cold, and should emit in the extreme FIR and sub-mm (invisible to IRAS).
       other evidence & statements ? (TBD)

- Different extinction laws can be explained by different proportions of these components [10biv]

(e) Interaction with Light: Mie Theory

If you assume grains are spheres with uniform refractive index, they yield to classical electrodynamics.

This was first worked out by G. Mie in 1908 (in a different context), and the theory goes by his name.
Being a classical theory, wavelength and grain size enter only as their ratio: $X = 2\pi a/\lambda$
Here, we only note a few important results.

- First, recall **a general refractive index is complex**, m = n - ik, where k tracks absorption.
  Ices are good dielectrics, so k is small and n is roughly independent of wavelength.
  Metals have k ~ n and both may vary significantly with wavelength.

- Absorption and scattering **efficiences**, Q_{abs} Q_{sca}, are expressed **relative to geometrical** :
  e.g. for a particular grain/wavelength/index, Mie theory evaluates (see figure, for m = 1.5 - 0.05i)
  $Q_{abs}(X,m)$ = (absorption cross-section) / πa^2
  $Q_{sca}(X,m)$ = (scattering cross-section) / πa^2
  which define
  extinction efficiency : $Q_{ext} = Q_{abs} + Q_{sca}$
  and albedo : $Alb = Q_{sca} / Q_{ext}$

- Scattering can be studied by observing reflection nebulae and the diffuse galactic light.
  In the optical and UV, **scattering is significant** with Alb ~ 0.6 (figure)
  $\rightarrow$ grains have significant dielectric character, consistent with silicates.

- The mean scattering **angle** can reveal grain **size**:
  forward for $\lambda << a$ $\rightarrow$ isotropic for $\lambda >> a$
  Observations suggest :
  $\rightarrow$ significant (~45^o) angle in optical, **increasing** (more isotropic) in UV
  $\rightarrow$ optical scattering grains have a~0.1-0.3μm,
  $\rightarrow$ UV scattering grains are much smaller

- In the limit of $\lambda << a$, Mie theory gives: (figures)
  $Q_{abs} = 1$ (ie πa^2 as expected, independent of wavelength)
  $Q_{sca} = 1$ (also πa^2, from diffraction)
  $Q_{ext} = Q_{abs} + Q_{sca} = 2$, which is double the simple geometrical cross section.

- In the limit of $\lambda >> a$ (i.e. $X = 2\pi a/\lambda << 1$), Mie theory gives:
  $Q_{abs} \approx -4\, X\, \mathrm{Im}[M] \propto \lambda^{-1}\, \mathrm{Im}[M]$ where $M = (m^2 - 1)/(m^2 + 2)$
  $Q_{sca} \approx 8/3\, X^4\, |M|^2 \propto \lambda^{-4}$
  $\rightarrow$ For pure dielectrics (m real, k = 0) then $Q_{sca} = Q_{ext} \propto \lambda^{-4}$ and we recover Rayleigh scattering.
  $\rightarrow$ For some absorption (m complex, $k \neq 0$) then $Q_{ext} \approx Q_{abs} \propto \lambda^{-1}$
  which is the correct form for the extinction law in the near, mid and far-IR
  $\rightarrow$ confirming that there are no very large grains (a << 1 - few μm).

- Mie theory calculates $Q_{abs}(\lambda)$ for absorption, but what about **emission**: $Q_{em}(\lambda)$?
  By great good fortune, they are the same !!
  $\rightarrow$ Recall Kirchoff's law: "good (bad) absorbers are good (bad) emitters".
  more specifically, for thermal emission:
  $F_{em}(\lambda) = Q_{em}(\lambda) \times B_\lambda(T)$ per unit area, where $B_\lambda(T)$ is the Planck function; and
  $Q_{em}(\lambda) = Q_{abs}(\lambda)$ whose functional form is given above
  (this has its roots in the reversibility of all interactions; a principle called "detailed balance")

- It is now clear that since dust grains **don't** absorb much in the IR, they will be **poor IR emitters**
  Of course, being good emitters in the UV doesn't help, since $B_{UV}(T)$ is tiny when T ~ few K !
  We now have the "green-house" factor:

$\rightarrow$ $Q_{abs}(UV) / Q_{em}(IR) \equiv Q_{abs}(UV) / Q_{abs}(IR)$

(f) Dust Temperatures

(i) Inferred from IR emission

- First, recall the basic Wein relations for the peak of the Planck function (there are two of them!)
  The peak of $B_\lambda\, d\lambda$ is at $\lambda \approx 2900\mu m/T(K)$
  The peak of $B_\nu\, d\nu$ is $\nu \approx 2.82kT/h$ or $\lambda \approx 5000\mu m/T(K)$
  $\rightarrow$ Often, the difference won't matter.
  $\rightarrow$ Sometimes it does: so check if spectra are in f_λ vs λ or f_ν vs ν (e.g. Jy vs λ^{-1}).

- In fact, since dust's radiative efficiency $Q_{em} \propto a/\lambda$ (see below)
  $\rightarrow$ even a single T_d & single size population doesn't yield a Planck function!
  In reality, a range of T_d and grain sizes undermines a straightforward inference of T_d
  Nevertheless, emission in NIR (1-5μm) MIR (5-25μm) and FIR (25-300μm) sub-mm (300-1000μm) does indicate clearly different mean values of T_d.

- Overall, dust emission can span a broad range, NIR to FIR (sub-mm at higher redshift):
  $\rightarrow$ T_d spans a wide range: 1000 - 10K, however ...
  In most galaxies, the bulk is in the FIR, ~60 - 200μm
  $\rightarrow$ the majority of dust has T_d ~ 10 - 50K

(ii) Equilibrium T_d Estimates

- The zeroth order calculation was done in 8-b-iv above: (link)
  $\rightarrow$ dust heating balances black body cooling, with both modified by efficiency (Q) factors
  For pure black bodies, this yields the Eddington values, which are **too low** by factors ~few.

- To improve on this we need :
  the absorption and emission efficiencies, $Q_{abs}(a,\lambda,m)$ and $Q_{em}(a,\lambda,m)$
  which need integrating over grain size distribution, and incident and outgoing spectra
  if the region is ionized, one should include the important isotropic trapped Lyα field
  any collisional heating terms should also be included

- Let's consider the most important factors: Q_{abs} and Q_{em}
  Treating grains as black bodies: $Q_{abs} = Q_{em} = 1$ at all λ is:
  OK in the UV - they are good absorbers
  BAD in the IR - they are poor emitters (since $a << \lambda$).
  $\rightarrow$ the correction factor $[Q_{abs}(UV)/Q_{em}(IR)]^{1/4} > 1$
  $\rightarrow$ the resulting **"green-house effect"** pushes T_d **above** the Eddington value.
  Fortunately, uncertainties in the correction term are muted by the 1/4 power.

- Let's use the Mie theory from above to estimate the correction term
  First, consider the absorption efficiency for optical/UV starlight:
  For grain sizes ~0.1μm, $X = 2\pi a/\lambda \approx 1 - 5$ for $\lambda \approx 5000A - 1000A$
  $\rightarrow$ Q_{abs} ~ 1 even for poorly absorbing grains (m = 1.5 -0.05i) (see figure).
  But, at longer wavelengths and smaller grains Q_{abs} drops well below 1
  $\rightarrow$ in practice, then, $L_\star$ should be replaced by $L_{\star,UV}$ and Q_{abs} can be set to 1

- For $Q_{em}(IR)$ we use Kirchoff's law and ask instead: what is $Q_{abs}(IR)$?
  Again, relying on Mie theory; for $\lambda >> a$, we have $Q_{abs} \approx -4\, X\, Im[M]$
  for a~0.1μm, $X = 2\pi a/\lambda$ ~ 0.005 in the FIR

Im[M] ~ -0.5 $\rightarrow$ -0.025 for 1.5-1.0i (eg metal oxide) $\rightarrow$ m = 1.5-0.05i (eg an ice)
$\rightarrow$ Q_{em}(FIR) = Q_{abs}(FIR) ~ 0.01 - 0.0005.

- Thus, our correction factor to T_d is $(Q_{abs}/Q_{em})^{1/4}$ ~ 3 - 7
  We expect ~3 for poor dielectrics/shorter wavelengths/warmer temps/larger grains
  We expect ~7 for good dielectrics/longer wavelengths/colder temps/smaller grains

- Using the modified equilibrium relation, we find:
  1. Interstellar dust, warmed by a weak isotropic radiation field: J_s ~ 0.002 erg/s/cm^2/sr yields
     $T_d \sim (\pi J_s/\sigma)^{1/4} \times (Q_{abs}/Q_{em})^{1/4} \approx 3.2 \times 5 \sim 15$K
     This cold component is called interstellar "cirrus", and emits in the FIR ~ 100-300μm
     It is seen in other galaxies when not dominated by warmer (eg star formation) components
     It is slightly warmer in Ellipticals, with their higher interstellar radiation field.
     It probably shows a temperature gradient decreasing outwards, as J_s declines.

  2. Because they are complex environments, HII regions have a range of T_d
     Close to O stars T_d ~ 50K; In shrouded regions T_d ~ 10K
     Heating by trapped Lyα is often important: T_d ~ 100K

  3. Deep inside DMCs, shielded from all external radiation, T_d ~ few K
     Here, the source of heating is X-rays from the surrounding hot phase, and cosmic rays.

  4. In AGN the dust can be appreciably warmer, for example:
     using $L_{AGN} \sim 10^{10} L_\odot$ and grain green-house factor ~5, we get
     $\rightarrow$ Narrow Line Region (~100pc) temperatures: T_d ~ 100K
     $\rightarrow$ Broad Line Region (~0.1 pc) temperatures: T_d ~ 3000K
     AGN's typically have "warm" IRAS colors from NLR dust: $F_{25} / F_{60} \gtrsim 3 \times F_{60} / F_{100}$
     Note that dust may not survive in the BLR: $T_d \gtrsim T_{sublimate}$ ~ 2000 K (check)

(iii) Thermal Spikes from Single Photons

- There are some puzzling observations:
  sometimes, where we expect T_d ~ 30K, we find 2 - 25μm emission $\rightarrow$ $T_d \lesssim$ 1000K !!
  there are galactic sources where T_d is **independent of distance** from the central star
  How do we understand these results?

- A population of **very small** grains: $\lesssim$ 100 atoms; possibly PAH
  For these grains a **single UV photon** carries enough energy to heat the entire grain to ~ 1000K.
  e.g. 1000A photon has 10eV, and a grain of N atoms has thermal capacity ~3Nk per Kelvin
  $\rightarrow$ 10eV = 3NkδT giving δT ~ 500K for an N=100 atom grain.
  $\rightarrow$ well above the equilibrium temperature from a classical (non-photon) radiation field.
  Such hot grains radiate in the NIR

- However, they don't stay hot long !!
  At a few 100K they quickly radiate their thermal energy: $t_{cool} \lesssim$ 1 second
  These grains have a "spikey" thermal history: mostly cold, with brief spikes of a few 100K (image)

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(10) Dust: Emission & Absorption

- As expected, there are two types of emission/absorption associated with dust:

Continuum: thermal emission; and roughly λ^{-1} absorption and scattering
Lines and Bands: both emission and absorption features.

- We have already encountered dust's thermal continuum emission;
  it is thought to be roughly Planckian, modified by an emissivity $\propto \lambda^{-1}$

Now let's look at the other emission and absorption signatures of dust.

(a) Line & Band Features

- Lines & band features derive from specific bond stretching or bending modes
  However, they are shifted and/or broadened due to the lattice environment.
  Most, though not all, of these features are now identified.

- Examples:
  1. There is a very broad near-UV **absorption** feature centered at 2175A
     it is thought to arise from a surface charge resonance on small (20nm) graphite grains.
  2. The 3-12μm region has several PAH features (image)
     e.g. 3.3, 6.2, 7.7, 8.6, 11.3, 12.7μm
     these arise from various C-H and C-C bending and stretching modes.
  3. Broad silicate absorption (and emission) features (see fig)
     3.1μm : O-H stretch
     6μm : H-O-H bend
     9.7μm : Si-O stretch
     18μm : Si-O-Si bend
  4. The so-called Diffuse Infrared Bands (DIB) are emission/absorption features near ??-??μm
     their total and relative strengths vary, though are relatively low
     their origin is still unknown. uncertain.

(b) Dust Absorption

(i) Basic Scenario

- Interstellar dust both **absorbs** and **scatters** light, blue more than red
  Stars therefore appear both fainter (extinction) and redder (reddening)
  The absorbed light is reradiated in the FIR & escapes the galaxy
  The scattered light contributes to the diffuse background light
  (and in certain circumstances can appear as a reflection nebula).

- Adopting a standard radiation transfer scenario (see fig)
  If $I_{0,\lambda}$ enters a region and I_λ emerges, with I_λ(abs) absorbed and I_λ(sca) scattered, then
  $I_\lambda = I_{0,\lambda} - I_\lambda(\mathrm{abs}) - I_\lambda(\mathrm{sca})$ and $I_\lambda / I_{0,\lambda} = \exp(-\tau_\lambda)$
  where τ_λ is the extinction optical depth

- In terms of magnitudes of extinction, A_λ,
  $A_\lambda = -2.5 \log_{10}(I_\lambda / I_{0,\lambda}) = -2.5 \log_{10}[\exp(-\tau_\lambda)] = 1.086 \times \tau_\lambda$
  $\rightarrow$ extinction in magnitudes **<u>is</u>**, roughly, the optical depth.
  Observationally, of course, A_λ gives an increase in apparent magnitude:
  e.g. for the V band: $A_V = m_V - m_{V,0} \equiv V - V_0$ (A_λ is always +ve)

(ii) Standard Extinction Law

- Extinction depends on wavelength, and many studies have tried to measure this dependence
  e.g. divide spectra of two stars of the same spectral type, only one of which is reddened. (figure)
  The results are surprisingly consistent, and one speaks of a **standard extinction law**
  (variations do exist (see below), and should be kept in mind as a source of uncertainty)

- One way to describe extinction is using the normalized function A_λ / A_V where $A_V = A_{\lambda=5500A}$
  Here is a plot of A_λ / A_V : (figure)

  It rises from zero in the IR, roughly as λ^{-1}, and peaks in the UV at 700A
  There are features superposed at 2175A; 9.7μm; and 18μm (see above)
  (Note: because $A_\lambda \propto \lambda^{-1}$ over a wide range, extinction laws are usually plotted vs λ^{-1})

- A number of algebraic fits to this "reddening law" exist.
  A commonly used one is given by Cardelli , Clayton, & Mathis (1989, ApJ 345 245) e-link

- A more physically based approach models the extinction curve using different dust populations
  Two such models are shown here: figures

- The innocuous looking extinction curve hides an enormous variation in transparency:
  For example: at 4400A $A_B/A_V \approx 1.33$ and at 5μm $A_M/A_V \approx 0.023$
  So, comparing extinction in the blue and mid-IR, we have $A_B / A_M \approx 57$
  A good example is the Galactic center, for which:
  $\rightarrow$ $A_M \sim 0.6$ mag (57% transparent),
  $\rightarrow$ $A_B \sim 34.5$ mag (1.6×10^{-12}% transparent -- utterly invisible) !!

- Note that since $A_\lambda \propto \lambda^{-1}$ at long wavelengths, we can obtain A_λ in the mid and far IR
  e.g. $A_{60\mu} = 1/60\ A_{1\mu} = 1/60\ A_J$, and hence $A_{60\mu} = 1/60 \times A_J/A_V \times A_V = A_V / 212$.

(iii) Some Other Parameters

- So far, we have encountered A_λ and A_V, or in general A_X for band X (e.g. UBVRIJHKLMN)

- Often, **reddening** is easier to measure than **extinction**
  so another useful parameter is :
  $E_{B-V} = (B - V) - (B - V)_0 = A_B - A_V$ or its generic relative $E_{\lambda - V} = A_\lambda - A_V$
  E values are differences in color and are therefore easier to measure
  (you may know the color of an unreddened F5 star, but you don't know its apparent magnitude).

- Since all optical depths are additive, E_{B-V} and A_V are **proportional**
  specifically, we define
  $R_V = A_V / E_{B-V} \approx 3.1$ for the standard extinction law.
  Note that $1/R_V = (A_B - A_V) / A_V = A_B / A_V - 1$
  which measures the **slope** of the extinction curve in the 4500A - 5500A region
  Note that bigger values of R_V mean shallower slope and less UV extinction for a given A_V.

- Since E's are more easily measured than A's, the extinction law is often given in the form:
  $E_{\lambda-V} / E_{B-V}$ (see figure)
  If R_V is known, one may obtain A_λ / A_V from the relation:
  $E_{\lambda-V} / E_{B-V} = R_V (A_\lambda / A_V - 1)$
  Since extinction goes to zero as $\lambda \rightarrow \infty$, we have :
  $E_{\lambda-V} / E_{B-V} \equiv (A_\lambda - A_B) / (A_B - A_B) \rightarrow (-A_V) / (A_B - A_B) \equiv -R_V$
  which is the usual way that R_V is measured.
  Hence, if the **full** range of $E_{\lambda-V} / E_{B-V}$ is known, one may obtain A_λ / A_V

(iv) Variations in the Extinction Law

- Above $\lambda \sim 7000$A (R), the extinction law seems quite universal
  $\rightarrow$ one can correct with confidence using the standard law.
  this is because for $\lambda >> a$, standard scattering theory works (see below), and $A_\lambda \propto \lambda^{-1}$

- Below $\lambda \sim$ 5500A (V), the form of A_λ can vary with both environment and metallicity (this is why B&M advocate A_J as normalization rather than A_V)
  There has been considerable effort to characterize these variations.

- Generally, lower density and lower metallicity gives
  $\rightarrow$ weaker 2175A feature and steeper UV slope (lower R_V)
  Here's a comparison of three curves of decreasing metallicity: (figures)
  MW $\rightarrow$ LMC $\rightarrow$ SMC : relative metallicities 1 $\rightarrow$ 1/2.5 $\rightarrow$ 1/7

- Similarly, there is some evidence for higher R_V (4-5) in DMCs
  $\rightarrow$ lower UV absorption, consistent with larger grains growing in the cold dense gas

- One version of the UV part of the extinction law makes these variations more explicit:
  $E_{\lambda-V} / E_{B-V}$ = [c1 + c2.x] + [c3.D(x)] + [c4.F(x)] for $x=\lambda^{-1} > 3.3\mu m^{-1}$ ($\lambda <$ 3000A)
  The three terms are roughly independent, and correspond to three grain populations:
  1. [c1 + c2.x] : large "classical" grains. Slope (c2) depends on size distribution:
     slope decreases as <a> increases (higher R_V).
  2. [c3.D(x)] : small (20nm) graphite grains.
     D(x) sets the location & width of the 2175A feature.
  3. [c4.F(x)] : v. small (dielectric?) grains which affect the FUV (1100-1700A) part
     F(x) is cubic polynomial fit to FUV rise after linear and 2175A features removed.

- Finally: knowledge of the extinction law in other galaxies (besides LMC,SMC) is still rudimentary. Hopefully, the various grain populations identified locally are neverthelss present.

(v) Correcting for Reddening and Extinction

- Often, dust is simply a nuisance, and we need to correct for the effects of extinction:
  This involves three steps:
  1. choose an extinction law (usually, the standard one)
  2. estimate A_V using something of known color
  3. apply the corrections, both to color and, if needed, flux.

- Here's an approach suited to an emission line spectrum:
  consider two emission lines at λ_1 and λ_2 with **true** fluxes F_1 and F_2
  Their **observed** fluxes are:
  $f_1 = F_1$ dex(-0.4 $A_{\lambda 1}$) and
  $f_2 = F_2$ dex(-0.4 $A_{\lambda 2}$)
  writing observed and true flux ratios as $f_1/f_2 = r_{1,2}$ and $F_1/F_2 = R_{1,2}$,
  and noting that $A_{\lambda 1} = A_V \times (A_{\lambda 1}/A_V)$, and $A_{\lambda 2} = A_V \times (A_{\lambda 2}/A_V)$, we have
  $r_{1,2} = R_{1,2}$ dex[-0.4 ($A_{\lambda 1} - A_{\lambda 2}$)]
  giving
  $-2.5 \log_{10} (r_{1,2}/R_{1,2}) = A_V$ [$(A_{\lambda 1}/A_V) - (A_{\lambda 2}/A_V)$]
  Hence, from measured $r_{1,2}$, and knowing $R_{1,2}$ and the extinction law A_λ/A_V, we can derive A_V

- Once A_V is known, it is straightforward to correct any other flux or flux ratio.
  for example :
  $F_3 = f_3$ dex[+0.4 $A_V \times (A_{\lambda 3}/A_V)$], and
  $R_{3,4} = r_{3,4}$ dex [+0.4 $A_V \times$ [$(A_{\lambda 3}/A_V) - (A_{\lambda 4}/A_V)$]]

- We need some initial line ratios where we **know** their unreddened values.
  There are several to choose from, but usually the **Balmer series** is used.
  For a wide range of conditions, the Balmer series have case B ratios:

$H\alpha$ (6563A)	$H\beta$ (4861A)	$H\gamma$ (4340A)	$H\delta$ (4101A)

2.86	1.00	0.47	0.26

So, for example, for a **measured** $H\alpha/H\beta$ ratio, we derive A_V from :

$$A_V = -2.5 / [A_{H\alpha} - A_{H\beta}] \times \log_{10} [(H\alpha/H\beta) / 2.86]$$

where $A_{H\alpha}$ is A_{6563A}/A_V is given by the extinction law (similary for $A_{H\beta}$)
For the standard extinction law, we get

$$A_V = ?? \times \log_{10} [(H\alpha/H\beta) / 2.86]$$

- Be careful in your choice of Hydrogen recombination lines.
  The Lyman and Balmer/Lyman ratios often suffer optical depth effects and deviate from case B.
  This is especially true at high densities, e.g. in AGN BLRs and even AGN NLRs.
  Usually, however, Balmer, Paschen, and Brackett series are OK
  The exception is $H\alpha/H\beta$ which in AGN NLRs is closer to 3.1 than 2.86.

- This whole analysis assumes the source lies behind **a uniform screen** of dust
  Be careful: if the emission region is itself pervaded by dust things are more complicated
  each color samples a different volume (more in the red)
  the dust may itself alter the ionization/emission structure of the region.
  the gas phase abundances may also be altered by depletion onto dust.
  Usually, there is insufficient information to improve on the foreground screen analysis.

(vi) Dust to Gas Ratios

- To first order, extinction & reddening are proportional to **total hydrogen column** (figure)
  $E_{B-V} \approx 1.72 \times 10^{-22} N_H$ mag
  $A_V \approx 5.34 \times 10^{-22} N_H$ mag
  where N_H (in cm^{-2}) is summed over H^+, HI, and H_2
  the quantity E_{B-V}/N_H is called the **dust to gas ratio**

- A **physical** measure of dust to gas ratio is
  Z_d = (mass in dust)/(mass in H + He)
  for solar metallicity, complete depletion yields $Z_{d,\odot} = 0.016$

- there is some evidence that the D-to-G ratio is **lower** (less dust) in
  hotter ISM phases
  higher velocity clouds
  consistent with dust destruction in shocks.

- Not surprisingly, a lower metallicity also seems to lower the total gas/dust ratio
  $A_V = 17 \times 10^{-23} R_V N_H$ (MW)
  $A_V = 4 \times 10^{-23} R_V N_H$ (LMC)
  $A_V = \sim 3 \times 10^{-23} R_V N_H$ (SMC)

(vii) X-ray Absorption

(viii) Polarization

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(11) Dust Emission from Galaxies

- The appearance of dust in galaxies has a long History: (see Topic 1.2c)
  In 1920 Curtis used dust lanes to argue (correctly) for the external nature of Spiral Nebulae,
  edge on nebulae have dark lanes which resemble the Milky Way's "zone of avoidance"
  $\rightarrow$ Spiral Nebulae are **external** versions of MW.

- Dust is **ubiquitous**: it is found in ~all galaxies; and throughout each galaxy (e.g. Sombrero)
  however, its role can vary greatly from one galaxy to the next.

- The subject has developed **slowly**: recent progress has been due mainly to advances in **IR detection**.

(a) Absorption of Galaxy Light

- since dust size a $\lesssim$ 0.5μm it absorbes UV & optical efficiently
  This can have two important impacts on our measurement of galaxies:
  it affects the optical/UV **appearance**, hiding important regions
  it can significantly reduce their **apparent luminosity**,
  $\rightarrow$ undermines studies of, e.g., M/L ratios; Tully-Fisher relation; Dark Matter.
  Need to understand and correct for this absorption.
  One approach: study how galaxy photometry depends on **galaxy inclination**.

(i) Inclination Effects

- This also has a long history; Holmberg (1950s) plots $\langle\mu_B\rangle$ vs a/b (mean surface brightness vs inclination)
  On average, as galaxies change from face on to edge on, one expects:
  if optically **thin**, one expects inclined galaxies to be **brighter** (same light, less projected area)
  if optically **thick**, one expects inclined galaxies to be **same or dimmer** (only see to $A_V \sim 1$).
  $\rightarrow$ he finds dust dimming is **modest-to-important**

- Since then, there have been many "correction formulae" published: δm_i = f(a/b, Hubble Type) [Topic 3.7e]
  Applying these corrections **reduces scatter** in astrophysically meaningful plots (figure)

- Be alert: some formulae correct to "face on"; others to "dust free", e.g.
  RC3 corrects to face on
  RSA corrects to dust free
  these can differ in B by ~1 mag for the same galaxy !

(ii) Perpendicular Opacity of Disks

A critical question is whether disks are optically thick or thin.... Much debate in the 1990s.
Without rehashing that debate, it now seems that disks are:

optically thick towards the center, but transparent at the edges
thick in patches, particularly near spiral arms
there can be significant variations between galaxies.

In response to the overall uncertainties,
$\rightarrow$ most work on M/L ratios (e.g. TF relation) is now done **in the near IR** (I or H band)

(iii) Hidden Star Formation

Near-IR & Mid-IR imaging can reveal optically invisible star formation regions

- in normal spiral disks, obscured SF knots can be seen in spiral arms (e.g. M51)
- in starbursts, much dust is made which obscures the optical light.
  $\rightarrow$ burried super star clusters emerge in the IR (e.g. the antennae)
  $\rightarrow$ from SB to LIG to ULIG; L_{FIR} up by 10^3 while L_{opt} up by only ×3 (see Topic 11.7d and SED image)
- At the highest luminosity, there is a population of optically invisible z~2 ULIGs

$\rightarrow$ probably young, buried SB/QSO before blow-out.

(b) Emission: Broad Band SEDs

- FIR emission from dust is a ubiquitous feature of galaxy spectra
since stars emit ~**no** radiation beyond 25μ, dust **dominates the Mid- Far-IR**
Since starbursts & AGN are powerful UV emitters, & dust is a good UV absorber:
$\rightarrow$ sometimes, Mid-Far-IR from dust dominates **entire** galaxy SED

- As an example, here is the MW's ISM SED, and the SED of two AGN: figures

(i) Four Contributions to the FIR

Mid- and Far-IR emission can have varying contributions from :

1. Cold dust in the general ISM heated by the blue/UV ISRF ("cirrus")
10 - 30K $\rightarrow$ 60 - 500μ
2. Warmer dust in molecular clouds heated by nearby star formation
50 - 100K $\rightarrow$ 25 - 100μ
3. Yet warmer dust heated by an AGN
150 - 200K $\rightarrow$ adds a 25μ component
4. Hotter dust in winds from evolved red giants
100 - 1000K $\rightarrow$ 12 - 25μ

(ii) Other Factors Affecting the IR output

a. Current & past star formation rates
UV output is a strong function of age (highest for **current** massive star formation).
b. Metallicity & dust composition/size distribution
composition & particle size affects absorption & radiation (e.g. single photon heating)
c. Relative location of dust & sources of radiation
UV **flux** defines eqlm dust temperature (dust **close** to SF; galaxy nuclei; is warmer)

(iii) Variation Along the Hubble Sequence

- A number of properties vary systematically along the Hubble sequence, E $\rightarrow$ Sc (see Topic 2.9)
e.g. star formation rates increase & HI content increases
$\rightarrow$ one might expect **systematic variation** of FIR/dust emission with Hubble sequence.

- Often **color-color** plots are useful
e.g. for IRAS with 4 bands: 12μ 25μ 60μ 100μ, one can define colors in **two** common ways:
1. Log of flux ratio [12]/[25] $\equiv$ log(F_{12}/F_{25}), with $F_{12} = f_\nu$ at 12 μ in Jansky's (i.e. per Hz)
2. An effective two-point spectral index, e.g. α_{12}^{25}, where α is defined by $f_\nu \propto \nu^\alpha$

Here are two such plots for various galaxy types: (image)

- Understanding these FIR color-color plots was slow to develop
One must consider **two** dust types:
a. large grains at eqlm temp, which increases with SFR
these affect the 25-60-100μ fluxes
b. small stochastically (quantum) heated grains with ~fixed (high) temperature
these affect the 12-25μ fluxes
And **three** radiation fields:
a. high flux UV field from young stars
b. UV from older population, whose flux depends on stellar density
c. an AGN, if present.

- The FIR colors arise in the following way:
  - Low SFR disks (e.g. Sa) have cirrus so cold that its 25μ flux is very low:
    $\rightarrow$ the large grains have **low** (cold) [60]/[100]
    $\rightarrow$ the small grains have ~ equal F_{12} & F_{25}
  - high SFR in irregulars (Sdm - Im) have warmer large grain emission,
    $\rightarrow$ [60]/[100] is **higher**, and begins to dominate the F_{25} band
    $\rightarrow$ with F_{25} rising fast, the [12]/[25] now appears **low**
  - In ellipticals & SOs, there is little/no star formation, however:
    Es & SOs have high stellar densities in the bulge with correspondingly high ISRF
    dust, if it is present, is usually in the **nuclear** regions, where the ISRF is high.
    $\rightarrow$ cirrus has intermediate temperature, with intermediate [12]/[25] & [60]/[100]
    $\rightarrow$ FIR luminosities consistent with heating by UV from post AGB stars ($r \lesssim 1$ kpc)
    (there is still some disagreememt over whether red giant winds contribute in E/SOs).
  - Dust composition is also relevent:
    It seems: from Im (low Z) $\rightarrow$ E (high Z), small/large grain ratio increases.

(iv) Starbursts

The IR SEDs of starbursts is discussed in Topic 11.7d
Briefly, as the luminosity of the starburst increases (see image)

$\rightarrow$ L_{IR} increases correspondingly; ~$\times 10^3$ @ ULIGS
$\rightarrow$ however, absorption suppresses **optical** increase to ~×3-4
$\rightarrow$ dust temperature gets **warmer**, mainly at 60μ (30-60K)

(v) AGN

- Accretion power in AGN generates an intense "hard" spectrum
  This can heat dust in the near-nuclear regions.
  $\rightarrow$ in the kpc-scale NLR, T_d ~ 150-200K giving a 25μ component.
  $\rightarrow$ in the sub-pc sclae BLR, T_d ~ 500-1000K
  can give a Near-IR component $1\text{-}5\mu$ (though may not survive)
- At higher luminosity, the dust signature may depend on age:
  early: post-merger, SB+AGN, shrouded
  late: ISM blown away, SB declines $\rightarrow$ bare AGN dominated SED.

(c) Emission: Spectral Features

While the IR has many spectral features, there are two major features attributable to dust:

1.

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