Physics 224
The Interstellar Medium

Lecture #11: Dust Composition, Photoelectric Heating, Neutral Gas
Outline

• Part I: Dust Heating & Cooling continued
• Part III: Dust Emission & Photoelectric Heating
• Part II: Dust Composition
• Part IV: Neutral Gas
How we learn about dust

• Extinction: wavelength dependence of how dust attenuates (absorbs & scatters) light

✓

• Polarization: of starlight and dust emission

• Thermal emission from grains

• Microwave emission from spinning small grains

• Depletion of elements from the gas relative to expected abundance

• Presolar grains in meteorites or ISM grains from Stardust mission (7 grains!)
Dust Thermal Balance

Steady State emission = absorption.

\[
\left(\frac{dE}{dt}\right)_{\text{abs}} = \langle Q_{\text{abs}} \rangle_\star \pi a^2 u_\star c
\]

\[
\left(\frac{dE}{dt}\right)_{\text{em}} = 4\pi a^2 \langle Q_{\text{abs}} \rangle_T \sigma T^4
\]

\[
T \approx 22.3(a/0.1\mu m)^{-1/40} U^{1/6} K \quad \text{carbon}
\]

\[
T \approx 16.4(a/0.1\mu m)^{1/15} U^{1/6} K \quad \text{silicate}
\]
Dust Thermal Balance

Not all grains are in steady state…

When:
\[(dE/dt)_{\text{cool}} \ll \text{photon absorption rate}\]

and/or

\[hv \gg E_{ss}\]

Need to consider non-steady state
Dust Thermal Balance

Probability of finding grain with temp $T$ in average MW ISRF.

PDF narrows with increasing size.
Dust Thermal Balance

While it is unlikely to find a small grain at very high temperatures, most energy is emitted there!

\[
\left( \frac{dE}{dt} \right)_{\text{em}} = 4\pi a^2 \langle Q_{\text{abs}} \rangle_T \sigma T^4
\]

\[
\langle Q_{\text{abs}} \rangle_T \sim 1.3 \times 10^{-5} T^2 \quad \text{silicate}
\]

\[
dE/dt \sim T^6
\]
Dust Thermal Balance

Is collisional heating important?

Absorption: \( \left( \frac{dE}{dt} \right)_{\text{abs}} = \langle Q_{\text{abs}} \rangle_* \pi a^2 u_* c \)

Collisions: \( \left( \frac{dE}{dt} \right)_0 = n_H \pi a^2 \langle v_H \rangle 2kT \alpha \)

Assuming collisions with H and dust grain is not charged.

Factor \( \sim \) unity for energy transfer from collider to grain.
Dust Thermal Balance

Is collisional heating important?

\[
\frac{(dE/dt)_{\text{col}}}{(dE/dt)_{\text{abs}}} = \frac{3.8 \times 10^{-6}}{U} \frac{\alpha}{\langle Q_{\text{abs}} \rangle} \left( \frac{n_H}{30 \text{cm}^{-3}} \right) \left( \frac{T}{10^2 \text{K}} \right)^{3/2}
\]

radiation field strength
normalized to MW average ISRF

collisional heating important in dense and/or hot gas
Dust Thermal Balance

Is collisional heating important?

More generally:

\[
\frac{(dE/dt)_{\text{coll}}}{(dE/dt)_{\text{abs}}} \approx \frac{2nkT}{u_*} \times \frac{\gamma}{\langle Q_{\text{abs}} \rangle_*} \times \frac{(8kT/\pi m_e)^{1/2}}{c}
\]

- density of colliders
- if grain and/or collider is charged, Coulomb focusing factor
- thermal pressure (thermal energy density) relative to starlight energy density
- velocity of colliders relative to speed of light
Dust Thermal Balance

Is collisional heating important?

- in places where radiation energy density is very low, (e.g. cores of molecular clouds)
- in places where thermal pressure is very high (e.g. hot plasma behind shock waves in SNe)
Dust Thermal Balance

Collisional heating in hot, dense plasmas

Temperature of an 0.1 µm graphite particle for various gas temperatures as a function of density

$T_d \sim 22$ K for MW ISRF
Dust Emission

Emissivity
[erg/s/cm$^3$/Hz/sr]

\[ j_\nu = \sum_i \int da \frac{dn_i}{da} \int dT \left( \frac{dP}{dT} \right)_{i,a} Q_{\text{abs}}(\nu; i, a) \pi a^2 B_\nu(T) \]

sum over different grain compositions

integral over grain size distribution

integral over temperature probability distribution function for grain of size $a$ and composition $i$

energy/time/solid angle/freq emitted by a grain of size $a$ and composition $i$
Dust Emission

For grains that are large enough, \( \frac{dP}{dT} \) is \( \sim \) delta function & \( Q_{\text{abs}} \) is smooth and prop to \( \lambda^{-2} \).

Also \( T_{\text{SS}} \) is \( \sim \) independent of grain size.
At long wavelengths $Q_{\text{abs}}/a \propto \lambda^{-2}$ i.e. $Q_{\text{abs}} \propto a\lambda^{-2}$
Dust Emission

For “equilibrium” grain emission

\[ j_\nu = \sum_i \int da \frac{dn_i}{da} \int dT \left( \frac{dP}{dT} \right)_{i,a} Q_{\text{abs}}(\nu; i, a) \pi a^2 B_\nu(T) \]

\[ \pi a^3 Q_{\text{abs},0} \lambda^{-2} B_\nu(T_{SS}) \]

can go outside integral
over size distribution

End up with: \( j_\nu = \) function that depends on grain pop \( \times B_\nu(T_{SS}) \)
Dust Emission

For grains that are large enough, \( \frac{dP}{dT} \) is \( \sim \) delta function & \( Q_{\text{abs}} \) is smooth and prop to \( \lambda^{-2} \).

Also \( T_{\text{SS}} \) is \( \sim \) independent of grain size.
Change of units:

\[ S_\lambda = \text{surface brightness} \]
(typical unit: MJy/sr or Jy/arsec\(^2\))

“Modified Blackbody”

Only works for equilibrium emission!

\[
\kappa_\lambda = \frac{K_{\text{eff},160} S}{160 - \beta_{\text{eff}}} \lambda^{-\beta_{\text{eff}}}
\]

from Gordon et al. 2014

In general, the surface brightness of dust with temperature, \( T_d \), is

\[
S_\lambda = \tau_\lambda B_\lambda(T_d)
\]

\[
= N_d \pi a^2 Q_\lambda B_\lambda(T_d)
\]

\[
= \frac{\Sigma_d}{m_d} \pi a^2 Q_\lambda B_\lambda(T_d)
\]

\[
= \frac{\Sigma_d}{\frac{4}{3} a^3 \rho} \pi a^2 Q_\lambda B_\lambda(T_d)
\]

\[
= \frac{3}{4 a \rho} \Sigma_d Q_\lambda B_\lambda(T_d)
\]

\[
= \kappa_\lambda \Sigma_d B_\lambda,
\]

where \( \tau_\lambda \) is the dust optical depth, \( N_d \) is the dust column density, \( a \) is the grain radius, \( Q_\lambda \) is the dust emissivity, \( B_\lambda \) is the Planck function, \( \Sigma_d \) is the dust surface mass density, \( m_d \) is the mass of a single dust grain, \( \rho \) is the grain density, \( \kappa_\lambda \) is the grain absorption cross section per unit mass. These equations can be evaluated in standards units (e.g., cgs or MKS). We found it convenient to express \( \Sigma_d \) in \( M_\odot \text{ pc}^{-2} \), \( \kappa_\lambda \) in \( \text{cm}^2 \text{ g}^{-1} \), and \( B_\lambda \) and \( S_\lambda \) in \( \text{MJy sr}^{-1} \) and then Equation (6) is

\[
S_\lambda = (2.0891 \times 10^{-4}) \kappa_\lambda \Sigma_d B_\lambda.
\]
As strength of radiation field increases, $T_{d,ss}$ goes up like $U^{1/6}$.

This part of the spectrum is well-described by "modified blackbody".
Draine & Li 2007 dust model

Stochastically Heated Dust: Intensity of radiation field doesn’t change shape of spectrum and $j_\nu \propto U$

why:
- temp of small grains depends on average photon energy which isn’t changing here (i.e. $dP/dT$ doesn’t depend on $U$)
- grains cool completely between photon absorptions
Photoelectric Heating

Almost all photons absorbed by dust go to heating the grain, but a small fraction go to:

Luminescence = radiative transition in grain
(fluorescence - prompt, phosphorescence - delayed)

Photoelectric Effect = ejecting electron from grain
Photoelectric Heating

\[
\left( \frac{dN}{dt} \right)_{pe} = \int d\nu \frac{u_\nu c}{h\nu} \pi a^2 Q_{abs} \ Y_{pe} \]

rate at which photoelectrons are ejected

\[ n\nu\sigma \]

\[ Y_{PE}(h\nu,a,\Phi) \]

function of photon energy, grain size, composition, grain charge
Photoelectric Heating

For small grains and energetic photons, more than 1 electron can be ejected.

PE yield for uncharged carbonaceous grains of various sizes for different absorbed photon energies.
Photoelectric Heating

Grains are charged in the ISM!

Competition between:

collisions & sticking of electrons

&

photoelectric ejection of electrons

depends on:
electron density,
temperature,
grain size, charge,
"sticking" coeff

depends on:
photon density,
grain size, charge,
PE yield

negatively charges grain

positively charges grain

"sticking" coeff
Grain Charge

carbonaceous, $n_H = 30 \ \text{cm}^{-3}$, $x_e = 0.001$, $T = 100\text{K}$, MMP83 ISRF

![Graph showing grain charge distribution](image)
What is dust made of?
Dust Composition

- Spectroscopic features in absorption
- Spectroscopic features in emission
- Depletions of heavy elements from the gas
Dust Composition

The problem with spectroscopic features:

for macroscopic particles:
absorption & emission is mostly continuous and
any features there are broad
Dust Composition

Spectroscopic features in absorption

2175 Å bump:
- strong
- central $\lambda$ fixed
- width varies a bit
- widespread in the MW
- rare at low metallicity!
Dust Composition

Mixtures of PAHs in the lab can reproduce similar shapes, from a transition in C-C bonds.
Dust Composition

Spectroscopic features in absorption

Silicate bending/stretching modes at 9.7 and 18 µm.

Smooth profile = amorphous silicate
Silicate Absorption in a protostar in Orion

Poteet et al 2011

Observed spectrum

Continuum normalized spectrum

Amorphous silicate absorption

GCS-3 $\times$ 1.30

Crystalline Silicate Absorption

Ice Absorption

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Dust Composition

Spectroscopic features in absorption

> 400 near-IR to near-UV absorption features discovered in 1922, vast majority unidentified.

Two bands identified with $C_{60^+}$

Campbell et al. 2015
Dust Composition

Spectroscopic features in emission

ISO spectrum of NGC7023
(D. Cesarsky et al. 1996)

Polycyclic
Aromatic
Hydrocarbons
(probably)
Dust Composition

POLYCYCLIC AROMATIC HYDROCARBONS AND THE UNIDENTIFIED INFRARED EMISSION BANDS: AUTO EXHAUST ALONG THE MILKY WAY!

L. J. Allamandola and A. G. G. M. Tielens
Space Science Division, NASA/Ames Research Center

AND

J. R. Barker
Department of Chemical Kinetics, SRI International

Received 1984 October 19; accepted 1984 November 27
Dust Composition

PAHs radiate ~10% of the infrared emission from ~solar metallicity galaxies.

Smith et al. 2007
Depletions

Abundance in gas relative to Solar

Expect: \( A_{\text{gas}} = A_\odot \)

depletion

Abundances toward \( \xi \) Oph
\((v_\odot = -15 \text{ km/s component})\)

Morton 1975
Savage, Cardelli & Sophia 1992
Cardelli et al. 1993
Federman et al. 1994
Crinklaw, Federman & Joseph 1994
A UNIFIED REPRESENTATION OF GAS-PHASE ELEMENT DEPLETIONS IN THE INTERSTELLAR MEDIUM

EDWARD B. JENKINS
Princeton University Observatory, Princeton, NJ 08544-1001, USA; ebj@astro.princeton.edu
Received 2009 February 23; accepted 2009 June 1; published 2009 July 13

ABSTRACT

A study of gas-phase element abundances reported in the literature for 17 different elements sampled over 243 sight lines in the local part of our Galaxy reveals that the depletions into solid form (dust grains) are extremely well characterized by trends that employ only three kinds of parameters. One is an index that describes the overall level of depletion applicable to the gas in any particular sight line, and the other two represent linear coefficients that describe how to derive each element’s depletion from this sight-line parameter. The information from this study reveals the relative proportions of different elements that are incorporated into dust at different stages of grain growth. An extremely simple scheme is proposed for deriving the dust contents and metallicities of absorption-line systems that are seen in the spectra of distant quasars or the optical afterglows of gamma-ray bursts. Contrary to presently accepted thinking, the elements sulfur and krypton appear to show measurable changes in their depletions as the general levels of depletions of other elements increase, although more data are needed to ascertain whether or not these findings are truly compelling. Nitrogen appears to show no such increase. The incorporation of oxygen into solid form in the densest gas regions far exceeds the amounts that can take the form of silicates or metallic oxides; this conclusion is based on differential measurements of depletion and thus is unaffected by uncertainties in the solar abundance reference scale.

Key words: ISM: abundances – ISM: atoms – ultraviolet: ISM

Online-only material: machine-readable tables
Depletions

Jenkins 2009: compiled depletion measurements for 17 elements on ~250 lines-of-sight

Model for depletions includes:

- $F_* = \text{parameterization of overall depletion}$
- $[X_{\text{gas}}/H]_0 = \text{“baseline” or “initial” depletion}$
- $A_X = \text{depletion rate for element } X$ as a function of $F_*$

$$[X_{\text{gas}}/H]_\text{fit} = [X_{\text{gas}}/H]_0 + A_X F_*$$
Depletions

[Graph showing depletion factors for various elements (C, N, O, Mg, Si) with different depletion factors on the x-axis and observed depletion on the y-axis. The graph includes error bars and shaded areas representing different depletion factors.]
-3

C    N    O    Mg    Si    P    Cl    Ti    Cr    Mn    Fe

F\ast = 0
F\ast = 0.25
F\ast = 0.5
F\ast = 0.75
F\ast = 1

"baseline depletion"

\ Like \(\zeta\) Oph

\(N_H \sim 10^{21}\)
Dust Composition

![Graph showing the logarithm of dust-to-H mass ratio against F* Depletion Index. Curves represent different elements and compositions.]
Dust Composition

The observation that $F_*$ depends on density and $\text{H}_2$ fraction shows us that grains evolve in the ISM.
Dust is Awesome.