Lecture 8: "Dust Evolution and Surface Processes"
Outline

1. Phases of star-formation
2. Formation and evolution of dust
3. Chemical processes on dust surfaces
Heavy elements are synthesized in stars

Stellar nucleosynthesis:
- Nuclear fusion: PP cycles, CNO bi-cycle, He burning, C burning, O burning, Si burning $\Rightarrow ^{40}\text{Ca}$
- Intense gamma-ray radiation drives nuclear rearrangement $\Rightarrow ^{56}\text{Fe}$
- Neutron capture for heavier elements:
  - s-process, in which neutron addition is slow compared to $\beta$-decay
  - r-process, in which neutron addition is rapid compared to $\beta$-decay
Prestellar cores: units of star-formation

- Dust (1%), gas (99%)
- Typical mass $\sim 10 - 10^3 \, M_{\odot}$, size $< 1$ pc, $n > 10^4$ cm$^{-3}$, $T \sim 10$ K
- Dynamically "quiet", $t \sim 1 - 10$ Myr
- May start collapsing due to external or internal forces
From a prestellar core to a young star

- No hydrostatic equilibrium
- Prestellar core collapses
- Formation of a protostar: radiation is "trapped" inside

Protostar shrinks and heats as gravitational potential energy is converted into thermal energy.

Fusion rate increases until gravitational equilibrium stabilizes star.

Shrinking slows and surface temperature rises as nuclear burning begins.

Clump of gas becomes protostar when radiation can no longer escape from interior.

T > 100 K

T ~ 10 – 20 K
From a prestellar core to a young star

- Outflow + protoplanetary disks are formed due to conservation of angular momentum.
- Protostar shrinks and surface temperature drops $\Rightarrow$ no efficient radiation transport from interiors.
- Luminosity drops, $T_{\text{eff}} \sim$ constant $\Rightarrow$ Protostar moves vertically on HR-diagram (Hayashi track).
From a prestellar core to a young star

- Internal temperature rises to several $10^6$ K, nuclear burning starts $\Rightarrow$ surface $T$ rises, shrinking slows down

- Main-sequence is reached with gravitational equilibrium and nuclear fusion as a main source of energy
The evolution of the centrifugal radius of the central star is shown as a dotted line (corresponding axis: first to the left) for the model parameters of Table 4. The accretion rate onto the star mass is shown as a dash-dotted line (corresponding axis: far-right). Gray curves and dotted lines indicate time sequences when selected observational constraints are verified (see text).

Extended, flared, and its thermal structure is determined solely by stellar irradiation and a different initial condition or turbulence. This model evolves smoothly with values of density to satisfy the observational error bars discussed in Sect. 2. For a constant density, the accretion time is 0.18 Myr for DM Tau. The time-lapse when all observational constraints are satisfied (see text).

Figure 5 shows thick grey lines produced either within large error bars (thick grey line), or with small error bars on the right. The uncertainty in the early formation of the disk. The collapse of the molecular cloud mass as a function of orbital distance. The uncertainty in the initial conditions or turbulence (derived) is shown.

This model hence does fulfill the "strict" observational constraints we have considered. The dark-shaded region shows the ensemble of models fitting those constraints. The light-grey box marks the period of time when the observed values at 100 AU in the Taurus Aurigae region. The question then is: does this model satisfy the observational requirements for DM Tau? And in that case, what other values of the set of parameters represent the observed mass?

Table 4. Model parameters for examples 1 and 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Example 1</th>
<th>Example 2</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_\text{cd}$</td>
<td>0.3 (s$^{-1}$)</td>
<td>0.3 (s$^{-1}$)</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$c$</td>
<td>13 2.35 3.4 (g cm$^{-3}$)</td>
<td>13 2.35 3.4 (g cm$^{-3}$)</td>
<td>g cm$^{-3}$</td>
</tr>
<tr>
<td>$Q_\text{s}$</td>
<td>14 17 (K)</td>
<td>14 17 (K)</td>
<td>K</td>
</tr>
<tr>
<td>$T_\text{surf}$</td>
<td>14 17 (K)</td>
<td>14 17 (K)</td>
<td>K</td>
</tr>
<tr>
<td>$R_\text{d}$</td>
<td>11 830 (AU)</td>
<td>11 830 (AU)</td>
<td>AU</td>
</tr>
<tr>
<td>$M_\ast$</td>
<td>0.515 0.585 (M$_\odot$)</td>
<td>0.515 0.585 (M$_\odot$)</td>
<td>M$_\odot$</td>
</tr>
<tr>
<td>$M_\text{disk}$</td>
<td>0.515 0.585 (M$_\odot$)</td>
<td>0.515 0.585 (M$_\odot$)</td>
<td>M$_\odot$</td>
</tr>
</tbody>
</table>

Figure 6. The accretion rate is represented by a black line. The grey line represents the period of time when the mass accretion rate is shown.

Formation of a Sun-like star

R. Hueso and T. Guillot (2005)
Orion nebula: Trapezium cluster

The 4 trapezium stars: Brightest, young stars (< 2 million years old) in the central region of the Orion nebula

Infrared image: ~ 50 very young, cool, low-mass stars

X-ray image: ~ 1000 very young, hot stars
Timescales for a Sun-like star

- Prestellar core lifetime: $\sim$ several Myr
- Collapse and formation of a protostar: $\sim$ 0.1 Myr
- Dispersal of "prenatal" cloud material: $\sim$ 1 Myr
- Dispersal of protoplanetary disk: $\sim$ 10 Myr
- Pre-main-sequence phase: $\sim$ several 10 Myr
- Main-sequence phase: $\sim$ 10 Gyr
- Substantial mass loss $\Rightarrow$ planetary nebula: $\sim$ 0.01 Myr
- White dwarf
Life of the Sun

- Interstellar cloud
  - Several light years
  - Protostar
  - Sun (Today)
  - Red giant
    - Ejected gas shell
    - Planetary nebula
      - Central star
      - White dwarf
    - Red giant
    - Yellow giant
The beautiful end of the Sun

The descendants: planetary nebulae

- The Cat's Eye nebula
- The Ring nebula

New species are produced in the transition phase

- Extended shells of gas + freshly condensed solids
II. Dust Formation and Evolution
The role of dust

• Dust: ~25Å–1cm

• Widespread, 1% by mass (ISM)

• Opaqueness of matter

• Heating & cooling

• Sink of heavy elements (>Na)

• Provides surface for catalytic reactions & adsorption
Dust life cycle in the Milky Way

Dust around young stars is old, and dust around old stars is young!

Zhukovska & Gail (2011)
Dust and gas production rates

- Dust production rates:
  - Supernovae (>1.4M\textsubscript{sun})
  - Luminous Blue Variable (>30M\textsubscript{sun})
  - RR-Lyrae (0.8M\textsubscript{sun})
  - Wolf-Rayet (~20M\textsubscript{sun})
  - Asymptotic Giant Branch (~0.6–10M\textsubscript{sun})
  - C/O < 1
  - C/O ~ 1
  - C/O > 1

- Gas production rates:
  - (~8–20M\textsubscript{sun})
  - Supernovae (>1.4M\textsubscript{sun})

- Silicate production rates:
  - Luminous Blue Variable (>30M\textsubscript{sun})

- Carbon production rates:
  - Asymptotic Giant Branch (~0.6–10M\textsubscript{sun})

- Oxygen production rates:
  - Asymptotic Giant Branch (~0.6–10M\textsubscript{sun})

- Other production rates:
  - Asymptotic Giant Branch (~0.6–10M\textsubscript{sun})
## Dust production: intermediate-mass stars

<table>
<thead>
<tr>
<th>Object class</th>
<th>Example sources</th>
<th>Dust Mass Loss rate ($M_\odot yr^{-1}$)</th>
<th>Dust composition</th>
<th>Gas-to-dust ratio/refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asymptotic Giant Branch stars, carbon rich, 2-4 $M_\odot$</td>
<td>VHya, IRC+10216, AFGL 3068</td>
<td>$2 \times 10^{-9}$, $2 \times 10^{-8}$, $1.6 \times 10^{-7}$</td>
<td>Amorphous carbon, PAHs, MgS, SiC</td>
<td>700 Groenewegen 1998, Jura 1986, Jura &amp; Kleinman 1989</td>
</tr>
<tr>
<td>Asymptotic Giant Branch stars, oxygen rich, 0.8-2; 4-8 $M_\odot$</td>
<td>Mira, W Hya, RX Boo, OH 44.8-2.3, OH 26.5+0.6</td>
<td>$5.5 \times 10^{-10}$, $2 \times 10^{-9}$, $2 \times 10^{-9}$, $2.8 \times 10^{-7}$, $1.2 \times 10^{-6}$</td>
<td>Silicates, amorphous &amp; crystalline</td>
<td>280 De Beck et al. 2010</td>
</tr>
<tr>
<td>Red Giant 0.1-8 $M_\odot$</td>
<td>None, e.g. 47 Tuc</td>
<td>$\sim 0.0$</td>
<td></td>
<td>Boyer et al. 2010, McDonald et al. 2011</td>
</tr>
<tr>
<td>Novae 0.8-8 $M_\odot$ binaries</td>
<td>QV Vul, V1500 Cyg, V 705 Cas, V838 Her</td>
<td>$3.4 \times 10^{-8} M_\odot$, $2 \times 10^{-7}$, $2 \times 10^{-6}$, $3 \times 10^{-5}$</td>
<td>Amorphous carbon, PAHs, SiC, SiO$_2$</td>
<td>Gehrz et al. 1998</td>
</tr>
</tbody>
</table>
## Dust production: high-mass stars

<table>
<thead>
<tr>
<th>Object class</th>
<th>Example sources</th>
<th>Dust Mass Loss rate ($M_\odot yr^{-1}$)</th>
<th>Dust composition</th>
<th>Gas-to-dust ratio.refs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Super Giant</td>
<td>Betelgeuse MuCeph, VYCMa, NML Cyg, IRAS05280-6910 (LMC)</td>
<td>$3\times10^{-10}$, $5\times10^{-9}$, $1\times10^{-6}$, $6\times10^{-6}$, $3\times10^{-6}$</td>
<td>Metal Oxides, Amorphous silicates, Metallic iron?</td>
<td>Verhoelst et al. 2009, De Wit et al. 2008</td>
</tr>
<tr>
<td>Wolf-Rayet</td>
<td>WR121, WR103, WR113, WR140</td>
<td>$17\times10^{-9}$, $5.2\times10^{-9}$, $6.9\times10^{-9}$, $3\times10^{-9}$</td>
<td>Amorphous carbon, small ~0.04</td>
<td>Veen et al. 1998</td>
</tr>
<tr>
<td>Luminous Blue Variables</td>
<td>HD 168625, Wra 751, R71 (LMC), AGCar, Eta Carinae</td>
<td>$2.2\times10^{-7}$, $2.7\times10^{-6}$, $&gt;3\times10^{-6}$, $3.4\times10^{-5}$, $4\times10^{-4}$</td>
<td>Amorphous &amp; crystalline silicates, water ice, some PAHs, large grains</td>
<td>Gomez et al. 2009, O’Hara et al. 2003, Voors et al. 2000</td>
</tr>
</tbody>
</table>
### Dust production: supernovae

<table>
<thead>
<tr>
<th>Object class</th>
<th>Example sources</th>
<th>Dust Mass per explosion (M_⊙)</th>
<th>Dust composition</th>
<th>Gas-to-dust ratio/refs</th>
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</thead>
<tbody>
<tr>
<td>Supernovae</td>
<td>SN 2002hh</td>
<td>0.1</td>
<td>Amorphous silicates?, Amorphous carbon?</td>
<td>Barlow et al. 2002</td>
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<tr>
<td></td>
<td>SN 2003gd</td>
<td>&lt;0.02</td>
<td></td>
<td>Sugerman et al. 2006</td>
</tr>
<tr>
<td></td>
<td>SN 2004et</td>
<td>1.5×10^{-3}</td>
<td></td>
<td>Fabbri et al. 2011, sub.</td>
</tr>
<tr>
<td></td>
<td>SN 2007it</td>
<td>&lt;10^{-4}</td>
<td></td>
<td>Andrews et al. 2011</td>
</tr>
<tr>
<td></td>
<td>SN 2007od</td>
<td>4×10^{-4}</td>
<td></td>
<td>Otsuka et al. 2011, sub.</td>
</tr>
<tr>
<td>Supernova Remnants Young,&lt;400 years</td>
<td>CAS A</td>
<td>0.075</td>
<td>Amorphous carbon, silicates</td>
<td>Barlow et al. 2010</td>
</tr>
<tr>
<td></td>
<td>1E 0102.2-7219 (SMC)</td>
<td>3×10^{-3}</td>
<td></td>
<td>Sandstrom et al. 2009</td>
</tr>
<tr>
<td>Supernovae/ SNR 1987A (LMC)</td>
<td>SN 1987A Before</td>
<td>0.0001- 0.001</td>
<td>Amorphous carbon, metallic iron, FeS?</td>
<td>Ercolano et al. 2006</td>
</tr>
<tr>
<td></td>
<td>After Herschel</td>
<td>0.49-0.94</td>
<td></td>
<td>Matsuura et al. 2011, Sci. sub.</td>
</tr>
</tbody>
</table>
Evidence of dust evolution via UV spectroscopy

“Big 5 elements”: Mg, Si, Fe, O, C are depleted

- Dust evolve in the ISM
Physical processes leading to dust evolution

- Nucleation in AGB shells
- Destruction-processing by FUV photons
- Amorphization by cosmic rays
- Grain shattering/sputtering in supernovae shocks
- Grain shattering in turbulent Giant Molecular Clouds
- Grain coagulation, sedimentation, stirring, fragmentation in protoplanetary disks
Pause
Search for minerals via IR spectroscopy

• Vibrational bands (stretching, bending): 3–100µm
• Water ice: 3µm
• PAHs: 3.3, 6.2, 7.7-7.9, 8.6, 11.3 and 12.7µm, etc.
• Diamonds: 3.43, 3.53µm
• Hydrogenated amorphous carbon: 3.4, 6.8, 7.2µm
• Amorphous silicates: 9.8, 18µm
• Crystalline silicates: 10.2, 11.4, 16.5, 19.8, 23.8, 27.9, 33.7, 69µm
• Iron sulfides: ~23µm
• Featureless: Fe, FeO, organics, ...

Natta et al. (2006), van den Acker et al. (2004)
Example: silicate emission bands at 10 μm

Bouwman et al. 2001
Mineralogy of the early Solar system

- Cometary dust & meteoritic samples
- Other protoplanetary disks

- Water & CO₂ ices (40%)
- Volatile & refractory organics (30%): "CHON"
- Iron-poor amorphous & crystalline silicates (27%)
- Troilite FeS (~2%)
- High-T condensates: Fe, SiC, TiO, Al₂O₃ (<1%)

Pollack et al. (1994), Semenov et al. (2010)
Nucleation of dust in shells of AGB stars

- H/He burning shells, pulsations
- C & O are mixed up till photosphere
- Driving mechanism is not clear
- T and n go down outward $\Rightarrow$ at $T < 3000$ K dust condensation begins

$\sim 2 R_{\text{star}} = \sim 600-800 R_{\text{Sun}} (3-4 \text{AU})$

$\sim 200-400 R_{\text{Sun}} (\sim 1 \text{AU} = \text{Earth’s Orbital Radius})$

$\sim 0.01-0.1 R_{\text{Sun}} (\sim \text{Earth’s radius})$

Dust formation, stellar winds
Evidence: presolar grains in meteorites

- Identified by isotopic analysis: "fingerprints" of specific conditions of nucleosynthesis in various stars
- Survived shock passage & heating in the early Solar Nebula and ISM

Gail & Hoppe (2010)
Dust evolution in protoplanetary disks

Weidenschilling (2006)
Dust evolution in protoplanetary disks
Dust evolution in protoplanetary disks

- <10 cm/s collisions due to Brownian motion
- Sticking
- >1 μm–1 cm grains sediment
- "Rain drops"-like growth regime
- Fragmentation (>10–100 m/s)
- Erosion
- Turbulence brings small grains upward
- Inward drift due to gas friction

- Mostly proved by experiments

Weidenschilling et al. (1993), Blum (2010)
How to pass a 1 m-barrier?

- Big grains $\Rightarrow$ 100% Keplerian rotation
- Radial pressure gradient $\Rightarrow$ gas orbits at 99% Keplerian velocity
- Head wind $\Rightarrow$ inward drift
- All 1-m particle are gone in 0.01 Myr within 100 AU!

How to form >1-m bodies?
- Gravitational instabilities
- Rapid grain growth in long-lived pressure "traps"

Ciesla & Dullemond (2010)
Gravitational instability

• Dust settling ⇒ dust layer in the midplane

• If the layer becomes dense ⇒ density perturbations ⇒ gravitational collapse

• To operate, dust densities ~ 100 times the gas density in a typical low-mass nebula are required

• Relative velocities of dust particles should not be too large, < 10 m/s ⇒ grain sizes ~ 1 cm or below are needed
Grain growth in pressure "traps"

- Corotating patch in midplane
- Weak turbulence $\Rightarrow$ density fluctuations
- $\sim 1$ m-sized "bricks" concentrate in pressure bumps
- Self-gravitation bounds clumps for $>10$ orbital periods
- Local gravitational instabilities

Brauer et al. (2008), Johansen et al. (2011)
Evidence of dust growth in protoplanetary disks

- Shallow mm opacities require $a_{\text{max}} \gg 1$ mm
- Substantial fraction of $\sim 2–5$ Myr disks
- Inner dust holes are visible
III. Chemical Processes on Dust Surfaces

• ~1% of the mass of the ISM

• 2.5 nm – 1 cm

• Carbonaceous and silicate material

• Fluffy, open structure (porous)

• Provide surface for gaseous molecules

• ~ $10^6$ surface sites on a single 0.1 μm grain
Two sorts of binding sites for accretion

**Chemisorption Well**

Weak electrostatic (van der Waals) binding, energy $\sim 10$–$100$ meV

**Physisorption Well**

Binding energies $\sim$ chemical bond energies: $\sim 0.5$–$5$ eV
Formation of molecules on surfaces

• Heterogenous reaction at the dust particle’s surface
  – \( \text{H}_2 \) formed by such a reaction (Gould & Salpeter 1963)

• 2 mechanisms:
  – 2 \( \text{H} \) meet on surface (Langmuir-Hinshelwood)
  – 1 gaseous \( \text{H} \) meets an \( \text{H} \) on surface (Eley-Rideal)
Langmuir-Hinshelwood mechanism

- Accretion to a surface site
- Hopping/tunneling to a nearboring site
- If it finds a radical, then reaction may occur
- Excess of energy is absorbed by dust lattice
Surface timescales

Collision time: \[ t_c = \frac{1}{V(\pi r^2 n_d)} \sim 10^9/n(\text{cm}^{-3}) \text{ years} \]

Thermal hopping time: \[ t_h = v_0^{-1}\exp\left(\frac{E_b}{kT}\right) \]

Tunnelling time: \[ t_t = v_0^{-1}\exp\left[\left(\frac{4\pi a}{h}\right)(2mE_b)^{1/2}\right] \]

Thermal desorption time: \[ t_{ev} = v_0^{-1}\exp\left(\frac{E_D}{kT}\right) \]

Here \( E_b \sim 0.3E_D \), so hopping time < desorption time

For H at 10K: \( E_D = 300K \), \( t_t \sim 2 \times 10^{-11} \text{ s}, t_h \sim 7 \times 10^{-9} \text{ s} \)

Tunnelling time < hopping time only for lightest species (H, D)

For O: \( E_D \sim 800K \), \( t_h \sim 0.025 \text{ s} \)

For S: \( E_D \sim 1100K \), \( t_h \sim 250 \text{ s}, t_t \sim 2 \text{ weeks} \)
Evolution of ices

Ice and molecule formation

"Onions"

Heating and energetic processing

• Accretion
• Surface synthesis
• Photoprocessing of ices
• Desorption: T, UV, CRPs

Prediction for surface chemistry:
H-rich ices
O \Rightarrow OH \Rightarrow H_2O
N \Rightarrow NH \Rightarrow NH_2 \Rightarrow NH_3
C \Rightarrow CH \Rightarrow CH_2 \Rightarrow CH_3 \Rightarrow CH_4
CO \Rightarrow HCO \Rightarrow H_2CO \Rightarrow H_3CO
\Rightarrow CH_3OH
C + C, CO + OH, etc. in warm regions
Astrophysical ices

- Mostly water ice
- Substantial components: CO, CO$_2$, CH$_3$OH
- Minor components: HCOOH, CH$_4$, H$_2$CO
- Ices are layered: CO/CH$_3$OH atop of H$_2$O ice
- In the prestellar cores: solid H$_2$O, CO ~ gaseous H$_2$O, CO
- In cold regions of protoplanetary disks: >90% of H$_2$O and CO are solid
The End
Homework

1a) Assuming that lifetime of a star $\sim M/L \sim M^{-2.5}$, calculate the lifetime of a 30 $M_{\text{Sun}}$ star ($L^* = 50\,000\, L_{\text{Sun}}$)?

1b) What is a lifetime of a 0.1 $M_{\text{Sun}}$ star ($L^* = 10^{-5}\, L_{\text{Sun}}$)?

2) Why early stars were more massive than stars formed today?

3) Taking parameters of the Sun, $L_{\text{sun}} = 4\times10^{33}\, \text{erg/s}$, $M_{\text{sun}} = 2\times10^{33}\, \text{g}$, $R_{\text{sun}} = 699000\, \text{km}$, calculate its average density and average energy production rate per unit mass.

4) How Universe would look like if there were no stars more massive than the Sun?
Homework

5) Assuming that a 0.1 μm grain can accommodate $10^6$ chemical species in one layer on its surface, and that there is $10^{12}$ gaseous molecules per single grain, with relative abundances of gaseous water and CO of $10^{-4}$ (wrt to the total number of nuclei), calculate the total amount of monolayers of water and CO ice when 99% of these species deplete from the gas-phase on dust grains.
Suggested literature

- "Protoplanetary Dust" (2010), eds. D. Apai & D. Lauretta, CUP