“The Planets”
Astro/EPS C12 (CCN 17045 or 32505)

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Mon 3–4 and Tue 5–6

STARFORMATION

CLOUD COLLAPSE AND FRAGMENTATION

CLOUD CORE CONTRACTION

T-TAU RI STAR

PROTOTAI STAR

3 x 10^4 yr

10^5 yr

10^7 yr

to 10^8 yr

INTERSTELLAR MEDIUM

INTERSTELLAR MEDIUM
• ~1 H atom per cm^3

H II REGIONS
• ionized hydrogen
• energy from hot stars causes ionization

H I REGIONS
• can sometimes contain denser MOLECULAR CLOUDS with H_2 molecules

• emission nebulae are found here

DUST
**ATOMS and their IONS**

- ions are formed by removing or adding electrons to the neutral atom
- ions are charged particles
- UV radiation is strong enough to ionize

**H I and H II REGIONS**

- Helium atom
- Hydrogen atom

**H I REGIONS**

- 21-cm emission from H I

**21-cm H EMISSION**

- transition energy very small
- spin-state transition

Ly $\alpha$ (1216 Å)

Energy (eV)

21 cm
SPIN-STATE TRANSITION

MOLECULES AND DUST GO TOGETHER

- $H_2$ can form on dust grains
- Dust shields other molecules from UV in space that would disassociate the molecules

CO: TRACER MOLECULE

INTERSTELLAR CLOUDS

- CO reveals locations of dust and $H_2$
INTERSTELLAR CLOUDS

DENSE DUST CLOUDS
IC 2944

CLOUD CONTRACTION

TRIGGERING CLOUD COLLAPSE
Protostars

Orion Nebula - OMC-1 Region

WFPC2

Protostars

Disk

Jet

Protostar

Spherical wind

The Dynamic HH 30 Disk and Jet
Hubble Space Telescope + WFPC2
A STAR IS BORN...

...OR NOT.

Brown Dwarf Gliese 229B
20–50 M_J

Palomar Observatory
Discovery Image
October 27, 1994

Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995

L-DWARF BINARY

BROWN DWARFS

Sun
M-type (star)
L-type (brown dwarfs)
T-type (brown dwarfs)
Jupiter (planet)

- primary: 90 M_J
- secondary: 70 M_J
- brown dwarf cutoff: 75–80 M_J

1050 M_J
**THE LIFE OF THE SUN**

**CORE COMPOSITION**
- over billions of years, H gets used up in the core
- He increases over time in the core
- NUCLEOSYNTHESIS is the conversion from one element to another

**THE SOLAR INTERIOR**
- H fusion continues in a shell around the core when there is no more H in the core
- H-burning is still confined to high-density, high-T regions

**THE SOLAR INTERIOR**
- Concentric shells with different nuclear fuels surround the C-Ne-O core near the end of the Sun’s life
- The sun would really be red not yellow
PLANETARY NEBULAE

- not really associated with planets
- this is Abell 39
- good spherical symmetry in the expanding shell
- the shell can look like a ring if it is thin

RING NEBULA

- different colors -> different atomic emissions -> different energies

HELIX NEBULA

- visible light image
- central star clearly visible
HELIUM NEBULA

nebular “knots” are ~100 AU

HEAVY STARS

- higher Ts in heavy star cores leads to nucleo-synthesis of heavier elements

HEAVY STAR DEATH

- Fe (and heavier elements) cannot be burned as fuels
- core implosion, rebound, supernova

CRAB NEBULA

- SN observed 1054 AD
- Vela SN remnant
- ~9000 BCE

- Tycho's SN remnant
- Chandra x-ray image
- SN observed 1604

- REDDENING from dust
- Barnard 68
- 0.2-pc cloud (~0.6 light years across)
- Cass A
- Chandra x-ray image
- SN in 1680
**TRIFFID NEBULA**
- **H II region**
  - blue: reflected starlight
  - red: Hα

**ORION NEBULA**
- visible; H II region
- infrared
  - starlight can penetrate the dust

**REDDENING**
- Star
- Dust cloud
- Scattered light
- Blue light greatly reduced
- Red light slightly reduced
- Stellar absorption lines still detectable

**Closeup of Triffid nebula**
- HST image
CONDENSATION

- refractory materials
- volatile materials

**TABLE 2**

<table>
<thead>
<tr>
<th>Element</th>
<th>A(El)</th>
<th>N(El)</th>
<th>A(El)</th>
<th>N(El)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>10.984 ± 0.02</td>
<td>234.5 × 10^10</td>
<td>As</td>
<td>2.49 ± 0.05</td>
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<tr>
<td>Li</td>
<td>3.43 ± 0.06</td>
<td>55.57</td>
<td>Si</td>
<td>3.43 ± 0.04</td>
</tr>
<tr>
<td>Be</td>
<td>1.48 ± 0.08</td>
<td>0.7354</td>
<td>Br</td>
<td>2.67 ± 0.09</td>
</tr>
<tr>
<td>B</td>
<td>2.88 ± 0.04</td>
<td>17.32</td>
<td>K</td>
<td>3.36 ± 0.08</td>
</tr>
<tr>
<td>C</td>
<td>8.46 ± 0.04</td>
<td>7.079 × 10^10</td>
<td>Rh</td>
<td>2.43 ± 0.06</td>
</tr>
<tr>
<td>N</td>
<td>7.50 ± 0.11</td>
<td>1.505 × 10^10</td>
<td>Tb</td>
<td>0.98 ± 0.03</td>
</tr>
<tr>
<td>O</td>
<td>8.76 ± 0.05</td>
<td>1.415 × 10^10</td>
<td>Sr</td>
<td>2.99 ± 0.04</td>
</tr>
<tr>
<td>F</td>
<td>4.33 ± 0.06</td>
<td>24.11</td>
<td>Sc*</td>
<td>3.99 ± 0.04</td>
</tr>
<tr>
<td>Ne</td>
<td>7.95 ± 0.10</td>
<td>2.146 × 10^10</td>
<td>Y</td>
<td>2.28 ± 0.03</td>
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<tr>
<td>Mg</td>
<td>6.27 ± 0.03</td>
<td>5.751 × 10^9</td>
<td>Zn</td>
<td>2.67 ± 0.03</td>
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<tr>
<td>Si</td>
<td>7.62 ± 0.02</td>
<td>1.075 × 10^10</td>
<td>Nb</td>
<td>1.64 ± 0.03</td>
</tr>
<tr>
<td>Al</td>
<td>6.54 ± 0.02</td>
<td>8.410 × 10^9</td>
<td>Mo</td>
<td>2.03 ± 0.04</td>
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<tr>
<td>S</td>
<td>7.61 ± 0.02</td>
<td>1.000 × 10^10</td>
<td>Ru</td>
<td>1.99 ± 0.08</td>
</tr>
<tr>
<td>P</td>
<td>5.54 ± 0.04</td>
<td>8.737</td>
<td>Rh</td>
<td>1.88 ± 0.03</td>
</tr>
<tr>
<td>Cl</td>
<td>7.26 ± 0.04</td>
<td>4.449 × 10^9</td>
<td>Pd</td>
<td>1.77 ± 0.03</td>
</tr>
<tr>
<td>Ca</td>
<td>5.33 ± 0.03</td>
<td>5.372</td>
<td>Ag</td>
<td>1.30 ± 0.06</td>
</tr>
<tr>
<td>K</td>
<td>5.18 ± 0.05</td>
<td>3.092</td>
<td>Cd</td>
<td>1.81 ± 0.03</td>
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<tr>
<td>Cr</td>
<td>5.18 ± 0.05</td>
<td>3.097</td>
<td>Sn</td>
<td>2.19 ± 0.04</td>
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<tr>
<td>Co</td>
<td>5.01 ± 0.03</td>
<td>3.016</td>
<td>In</td>
<td>0.87 ± 0.03</td>
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<tr>
<td>Mn</td>
<td>5.01 ± 0.03</td>
<td>3.017</td>
<td>Sn</td>
<td>2.19 ± 0.04</td>
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<tr>
<td>Fe</td>
<td>5.41 ± 0.06</td>
<td>5.730</td>
<td>Fe</td>
<td>1.64 ± 0.03</td>
</tr>
<tr>
<td>Cu</td>
<td>4.70 ± 0.04</td>
<td>1.226</td>
<td>U</td>
<td>0.42 ± 0.04</td>
</tr>
<tr>
<td>Zn</td>
<td>4.17 ± 0.06</td>
<td>35.97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Values for elements marked with an asterisk are abundances 4.55 × 10^10 yr ago. Mass fractions for proto-Sun: X_0 = 0.7110, Y_0 = 0.2741, Z_0 = 0.0146, and X_0/Z_0 = 0.0209. The astronomical fog scale and the cosmic chemical abundance scale by number are coupled by A(El) = log(M(El)) + 1.64.  

**CHONDrites and PROTOSOLAR ABUNDANCES**

**TEMPERATURE IN THE DISK**

- Metals
- Silicates, rocky material
- Water ice
- Ammonia ice

**Distance from Sun (A.U.)**

- Earth
- Jupiter
- Saturn
- Uranus
### PLANET FORMATION

- coagulation
- planetesimals
  - gravitational focusing begins
- planetary embryos
- giant impacts and planets

### CONDENSATION SEQUENCE

<table>
<thead>
<tr>
<th>Substance</th>
<th>Formula</th>
<th>Temperature of condensation (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>corundum</td>
<td>Al₂O₃</td>
<td>1758</td>
</tr>
<tr>
<td>perovskite</td>
<td>CaTiO₃</td>
<td>1647</td>
</tr>
<tr>
<td>spinel</td>
<td>Mg₂Al₂O₄</td>
<td>1513</td>
</tr>
<tr>
<td>nickel–iron metal</td>
<td>Ni, Fe</td>
<td>1471</td>
</tr>
<tr>
<td>pyroxene (diopside)</td>
<td>CaMgSi₂O₆</td>
<td>1450</td>
</tr>
<tr>
<td>olivine (forsterite)</td>
<td>Mg₂SiO₄</td>
<td>1444</td>
</tr>
<tr>
<td>alkali feldspars</td>
<td>(Na,K)Al₃Si₃O₈</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>troilite</td>
<td>FeS</td>
<td>700</td>
</tr>
<tr>
<td>hydrated minerals</td>
<td>(variable)</td>
<td>550–330</td>
</tr>
</tbody>
</table>

- The temperatures of condensation given are those that would occur if the pressure in the nebula had been about 10⁻⁵ bar (10² Pa). At lower pressures, the condensation temperatures would have been reduced slightly.
- Hydrated minerals are chiefly silicates with OH or H₂O in their formulae.

### COAGULATION

- Diagram showing gas, dust, and embryo growth.

### ACCRETION

- Graph showing cumulative number of bodies versus mass.

### SOLAR NEBULA COLUMN DENSITY

- Plot showing column mass per kg² versus radius in AU.
ACCRETION

PLANET BUILDING

- GRAINS -- dust, form by condensation, grow by sticking, coagulation
- PLANETESIMALS -- grow by accretion, gravitational focusing becomes important for large planetesimals

- PLANETARY EMBRYOS or PROTO-PLANETS -- grow by giant impacts, gravitational focusing is very important, can perturb each others' orbits
GIANT IMPACTS
during the planetary embryo accretion stage

IMPACT ON THE EARLY EARTH

MOON-FORMING IMPACT

- 6-day simulation
- colors represent density
- iron: ~8 g/cm³
- rock: ~3 g/cm³
- ice: 1 g/cm³
- Earth average: 5.5 g/cm³
- Moon average: 3.3 g/cm³
MOON-FORMING IMPACT

Run 24n

- 24-hour simulation
- colors represent temperature

LUNAR METEORITES

1cm

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COMPOSITION: EARTH vs MOON

<table>
<thead>
<tr>
<th></th>
<th>CI chondrite (primitive meteorite)</th>
<th>Earth (crust + mantle)</th>
<th>Moon (crust + mantle)</th>
<th>Ratio of trace element abundance Moon/Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile* elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K (ppm)</td>
<td>545</td>
<td>180</td>
<td>83</td>
<td>0.46</td>
</tr>
<tr>
<td>Rb (ppm)</td>
<td>2.32</td>
<td>0.55</td>
<td>0.28</td>
<td>0.51</td>
</tr>
<tr>
<td>Cs (ppb)</td>
<td>279</td>
<td>18</td>
<td>12</td>
<td>0.67</td>
</tr>
<tr>
<td>Moderately volatile</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Na (ppm)</td>
<td>1500</td>
<td>1000</td>
<td>1200</td>
<td>1.20</td>
</tr>
<tr>
<td>Refractory elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr (ppm)</td>
<td>3975</td>
<td>3000</td>
<td>4200</td>
<td>1.40</td>
</tr>
<tr>
<td>Th (ppb)</td>
<td>30</td>
<td>80</td>
<td>112</td>
<td>1.40</td>
</tr>
<tr>
<td>Eu (ppb)</td>
<td>87</td>
<td>131</td>
<td>210</td>
<td>1.60</td>
</tr>
<tr>
<td>La (ppb)</td>
<td>367</td>
<td>551</td>
<td>900</td>
<td>1.63</td>
</tr>
<tr>
<td>Sr (ppm)</td>
<td>7.26</td>
<td>17.8</td>
<td>30</td>
<td>1.69</td>
</tr>
<tr>
<td>U (ppb)</td>
<td>12</td>
<td>18</td>
<td>33</td>
<td>1.83</td>
</tr>
<tr>
<td>Siderophile* elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni (ppm)</td>
<td>16500</td>
<td>2000</td>
<td>400</td>
<td>0.200</td>
</tr>
<tr>
<td>Mo (ppb)</td>
<td>1380</td>
<td>59</td>
<td>1.4</td>
<td>0.024</td>
</tr>
<tr>
<td>Ir (ppb)</td>
<td>710</td>
<td>3</td>
<td>0.01</td>
<td>0.003</td>
</tr>
<tr>
<td>Ge (ppb)</td>
<td>48000</td>
<td>1200</td>
<td>3.5</td>
<td>0.003</td>
</tr>
</tbody>
</table>

MARE IMBRIUM

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ORIGIN OF TERRESTRIAL PLANET ATMOSPHERES

PRIMARY ATMOSPHERE
- composed of whatever gases available at time of formation
  - hydrogen
  - helium
  - methane (CH₄)
  - ammonia (NH₃)
  - water (H₂O)
- light gases (H & He) would have rapidly escaped

SECONDARY ATMOSPHERE
- produced by outgassing
  - gases released from melts in the interior
  - volcanically introduced
  - water (H₂O)
  - sulfur dioxide (SO₂)
  - carbon dioxide (CO₂)
  - nitrogen compounds
- also delivered by impacts of asteroids and comets
  - mainly water
  - impacts also remove atmosphere
  - interactions with surface

PLANETARY EMBRYO ACCRETION

Raymond et al. 2006

Graphs showing changes in eccentricity and semimajor axis over time.

Factor of 3 in Period

Graph showing relative water mass fraction against semimajor axis.