Astro 2299

The Search for Life in the Universe
Lecture 11

Last time
- A few things about the epoch of reionization and free fall times
- Magnetic fields in the universe, including planets

This time
- Formation of the solar system
- Contents of the solar system: present day
- Things are as they are because they were as they were

Reading: as indicated in Syllabus on web

Assignment 3 will be posted next week
Midterm exam March 15

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http://www.astro.cornell.edu/academics/courses/astro2299/
Figure 1: Steps in Forming the Solar System. This illustration shows the steps in the formation of the solar system from the solar nebula. As the nebula shrinks, its rotation causes it to flatten into a disk. Much of the material is concentrated in the hot center, which will ultimately become a star. Away from the center, solid particles can condense as the nebula cools, giving rise to planetesimals, the building blocks of the planets and moons.

https://courses.lumenlearning.com/astronomy/chapter/formation-of-the-solar-system/
Timeline

Big bang ~ 9 Gyr before formation of solar system
First stars ~ 8.5 Gyr before
Many generations of stars have come and gone before the solar system was formed
Figure 2: Chemical Condensation Sequence in the Solar Nebula. The scale along the bottom shows temperature; above are the materials that would condense out at each temperature under the conditions expected to prevail in the nebula.

https://courses.lumenlearning.com/astronomy/chapter/formation-of-the-solar-system/
### Terrestrial Timeline

<table>
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<tr>
<th>Time Before Present (Gyr)</th>
<th>4.6</th>
<th>4</th>
<th>3</th>
<th>2</th>
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<td>First fossils</td>
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<td>Growth of atmospheric $O_2$</td>
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<td>Snowball Earth?</td>
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- **SS formed**
- **LHB**
- **Moon formed**
- **Cambrian explosion**
- **5 Major Extinctions**
- **Hominids/tools**
Time line for the solar system

1. Collapse of molecular cloud core
   1. Protosolar nebula → protostar + disk + jet
2. Formation of planets (10⁵-10⁷ yr)
3. Debris:
   1. Comets = pristine material deflected to outer solar system
   2. Trans-neptunian objects (TNOs)
   3. Asteroid belt mostly between Jupiter, Mars
4. Proto-Earth
   1. Formation of Moon in a major impact event (< 100 Myr)
   2. Late-heavy bombardment (continuing impacts for 100s Myr) brought water and other volatiles (comets vs. asteroids)
5. Earth ~ as we know it (oceans, continents, tectonics) at age ~ 1 Gyr (or slightly less)
6. Continuing impacts at low rate
   1. Comets from outer solar system
   2. Near-Earth objects (short-period comets, asteroids)
The Earth and its Evolution

• Impacts of debris have shaped and will shape the biosphere; there are three debris reservoirs:
  • Main asteroid belt
  • Kuiper belt = Trans-Neptunian objects
  • Oort comet cloud

• The last, large accretion event was the impact of a Mars-sized object that created the Moon

• Tidal interactions of the Earth and Moon:
  • Stabilize the spins of both objects
  • The Moon gains angular momentum at Earth’s expense
  • The length of day is steadily increasing as the Moon moves further away (early days: one day ≈ 4 hr)
Length of Day Variations

- Secular change in LOD $\sim 1.7$ ms/century
- $\Rightarrow$ a change of 20 hr in 4.5 Gyr
- $\Rightarrow$ the Earth was spinning fast

**SECULAR VARIATION OF EARTH'S ROTATION: INFERRED FROM THE CHINESE ANCIENT SHOU SHI CALENDAR (AD 1281)**

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Abstract. The Shou Shi calendar (epoch of AD 1281, *Zhao* dynasty) is famous and very accurate in ancient China. It has evolved perfect and complete theoretical models of solar system objects, such as solar and lunar motions during that period. Almost every part of this work corresponds to the modern astronomical yearbooks. Compiled by native Chinese astronomers, it summed up through their studies many real observing results. The mathematical methods were adopted in this calendar before the foundation of Newton’s mechanical system. It is presented in this paper that the indirect system is also very useful to recover the real observing historical material. By selecting these calculating results, we may sum up the integral data of the secular variation of the Earth’s rotation from 1000 BC to AD 1500.
The Earth and its Evolution

Important features of the Earth relevant to the formation of life and the apparent increase in complexity of life:

- Large quantity of water in sustained liquid state
- Impacts (comets and asteroids)
- Continents
- Plate tectonics (volcanism)
- Stability of the Earth’s spin axis
- Orbital stability
- Greenhouse effect
- Stability of the solar luminosity

These and other factors are discussed in *Rare Earth* and used to argue that complex life like ours is exceedingly rare in the Galaxy (in spite of $\sim 10^{11}$ sun-like stars)
The Earth and its Evolution

Possible fallacies of the *Rare Earth* argument:

- Implicit is the assumption that the path by which life has evolved on Earth is the only path that would lead to creatures like ourselves.
- Perhaps there are multiple trajectories that a biosphere can take, contingent on chance events (volcanism, impacts, fraction of surface water, distance from host star, spin rate and spin stability, etc.).
- Nature is more inventive than the human mind!
- The large numbers of stars and planets in the Milky Way alone provide a huge number of biological experiments by nature for the last ~ 13 Gyr (and continuing).
Most large (over a kilometre in diameter) near-Earth asteroids are now known, but recognition that airbursts (or fireballs resulting from nuclear-weapon-sized detonations of meteoroids in the atmosphere) have the potential to do greater damage than previously thought has shifted an increasing portion of the residual impact risk (the risk of impact from an unknown object) to smaller objects. Above the threshold size of impactor at which the atmosphere absorbs sufficient energy to prevent a ground impact, most of the damage is thought to be caused by the airburst shock wave, but owing to lack of observations this is uncertain. Here we report an analysis of the damage from the airburst of an asteroid about 19 metres (17 to 20 metres) in diameter southeast of Chelyabinsk, Russia, on 15 February 2013, estimated to have an energy equivalent of approximately 500 (±100) kilotons of trinitrotoluene (TNT, where 1 kiloton of TNT = 4.185×10^{15} joules). We show that a widely referenced technique of estimating airburst damage does not reproduce the observations, and that the mathematical relations based on the effects of nuclear weapons—almost always used with this technique—overestimate blast damage. This suggests that earlier damage estimates near the threshold impactor size are too high. We performed a global survey of airbursts of a kiloton or more (including Chelyabinsk), and find that the number of impactors with diameters of tens of metres may be an order of magnitude higher than estimates based on other techniques. This suggests a non-equilibrium (if the population were in a long-term collisional steady state the size-frequency distribution would either follow a single power law or there must be a size-dependent bias in other surveys) in the near-Earth asteroid population for objects 10 to 50 metres in diameter, and shifts more of the residual impact risk to these sizes.
Impact of a Mars-sized object led to the formation of the Moon, which helps stabilize Earth’s spin axis.

Impact of a ~10 km sized object induced a mass extinction 65 Myr ago.
Relevant Facts about the Moon

- The Moon has relatively little iron (~2%) compared to the Earth (~33%)
- Mean densities:
  - Earth: 5.5 gm cm$^{-3}$
  - Moon: 3.4 gm cm$^{-3}$
- The ratio of the Moon’s mass to the Earth’s is small
- Rocks: mostly sedimentary on Earth, igneous on the Moon
- Lunar rocks are silicon rich
- Not much iron on or in the Moon (primarily from impacts subsequent to its formation)
- Lunar rocks returned by several Apollo missions range from 3.5 – 4.5 Gyr old
- The moon has a significant amount of angular momentum and it is gaining via tidal interactions with the Earth
Formation of the Moon

• Three competing theories at the time of planning for the Apollo project:

1. Capture Theory: Moon formed elsewhere but was captured gravitationally by the Earth
2. Co-evolution with Earth: the Moon formed from material orbiting the Earth that collected during the formation of the Earth by accretion
3. Fission Theory: a rapidly spinning Earth became unstable and flung off material that formed the Earth

• Favored theory now: the Moon formed from a giant impact late in the accretion process that formed the Earth (proposed in the 1970s)

• Recent issues have come up with this picture as well:
  • Nearly identical isotopic ratios of oxygen, titanium
Impact of Mars-size object
A time sequence computer simulation (beginning top left) shows a potential moon-forming impact modeled using the smoothed-particle hydrodynamics method. The mantles of the Earth and impactor are represented by red particles that change to orange when heated, while the iron cores are shown with blue particles that change to green with increasing temperature. The initial impact imparts a counterclockwise spin to the Earth, and part of the impacting body temporarily re-coalesces before colliding with the Earth a second time.

After the second hit, material primarily from the impactor’s mantle is sheared into a disk of debris; the total amount of iron left in orbit is consistent with the moon’s small core. The total time simulated by this run is about a day. Simulations such as this one demonstrated that a Mars-sized body colliding with the Earth with something close to the current Earth-moon system angular momentum could leave roughly a lunar mass worth of material in orbit.

(Courtesy Dr. Alastair Cameron, Harvard University)
The greatest accident in Earth's history was probably no accident at all, according to new computer simulations of the early solar system. Planetary scientists believe that sometime in the first 100 million years after the solar system took shape from gas and dust, a Mars-sized planet smashed into Earth. The impact liquefied Earth's surface and ejected a huge blob of material that coalesced into the moon. Far from being a chance encounter that defied all the odds, the new simulations suggest, an impact like this is expected to occur in the solar system's first 100 million years.

"The lesson is that giant impacts are common," says Robin Canup of the Southwest Research Institute (SWRI) in Boulder, Colorado, who developed one of the models. "They're not the wild, ad hoc event that they were once believed to be." Her simulations, which were announced last month at the Origin of the Earth and Moon conference in Monterey, also tracked for the first time how smaller collisions following the giant impact could have tweaked Earth's rotation rate and the tilt of its axis to match what is seen today.
Forming a Moon with an Earth-like Composition via a Giant Impact

Robin M. Canup

In the giant impact theory, the Moon formed from debris ejected into an Earth-orbiting disk by the collision of a large planet with the early Earth. Prior impact simulations predict that much of the disk material originates from the colliding planet. However, Earth and the Moon have essentially identical oxygen isotope compositions. This has been a challenge for the impact theory, because the impactor’s composition would have likely differed from that of Earth. We simulated impacts involving larger impactors than previously considered. We show that these can produce a disk with the same composition as the planet’s mantle, consistent with Earth-Moon compositional similarities. Such impacts require subsequent removal of angular momentum from the Earth-Moon system through a resonance with the Sun as recently proposed.
Fig. 1. An SPH simulation of a moderately oblique, low-velocity ($v_{\text{rel}} = 4$ km s$^{-1}$) collision between an impactor and target with similar masses (Table 1, run 31). Color scales with particle temperature in kelvin, per color bar, with red indicating temperatures $>$6440 K. All particles in the three-dimensional simulation are overplotted. Time is shown in hours, and distances are shown in units of 10$^5$ km. After the initial impact, the planets recollided, merged, and spun rapidly. Their iron cores migrated to the center, while the merged structure developed a bar-type mode and spiral arms (24). The arms wrapped up and finally dispersed to form a disk containing $\sim$3 lunar masses, whose silicate composition differed from that of the final planet by less than 1%. Because of the near symmetry of the collision, impactor and target material are distributed proportionately throughout the final disk, so that the disk's $\mathcal{M}_D$ value does not vary appreciably with distance from the planet.
The terrestrial planets may have acquired oceans of water (and other surface volatiles) as a late-accreting veneer from impacts of comets and carbonaceous asteroids during the period of heavy bombardment 4.5 to 3.5 Gyr ago. On any given body, the efficiency of this mechanism depended on a competition between impact delivery of new volatiles and impact erosion of those already present. For the larger worlds of the inner Solar System, this competition strongly favoured the net accumulation of planetary oceans.

Moon: many more old craters than new ones

\[ N(>4 \text{ km}, t) = 2.68 \times 10^{-5} \left[ t + 4.57 \times 10^{-7} (e^t - 1) \right] \text{ km}^{-2} \]
Simulation showing the outer planets and the **Kuiper belt**:  

a) Before **Jupiter–Saturn 2:1 resonance**.  
b) Scattering of Kuiper belt objects into the Solar System after the orbital shift of **Neptune**.  
c) After ejection of Kuiper belt bodies by Jupiter. Planets shown: Jupiter (green circle), Saturn (orange circle), **Uranus** (light blue circle), and Neptune (dark blue circle). Simulation created using data from the **Nice Model**.[1]