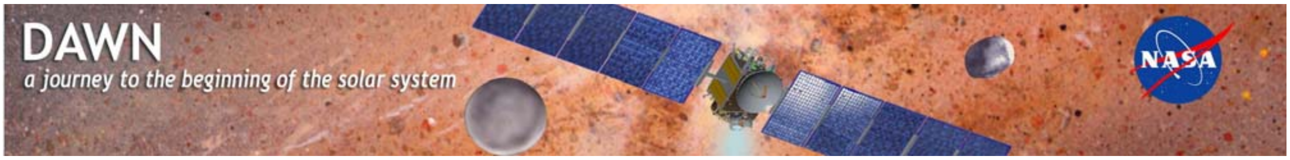

ACTIVE ACCRETION—An Active Learning Game on Solar System Origins

In *Active Accretion*, middle and high school students model the accretion of specks of matter in our early Solar System into planetesimals and protoplanets—and they do it dynamically. *Active Accretion* is a great way to teach cool science concepts about our Solar System's early formation and the development of asteroids and planets while burning off energy. Students will conclude by discussing the strengths and limits of their model.

Teacher Background

The current Condensation Theory of Solar System formation, often called the *modern* theory, is built on the oldest of ***evolutionary models***, the Nebular Contraction Theory. It originated in the 17th century by French philosopher Rene Descartes. In the 18th century, Pierre Simon de Laplace revised this theory. Both of these early astronomers based their theories on a disk-shaped solar nebula that formed when a large cloud of interstellar gas contracted and flattened under the influence of its own gravity. In the modern theory, interstellar dust is composed of microscopic grain particles that:

- are thin, flat flakes or needles about 10^{-5} m across;
- are composed of silicates, carbon, aluminum, magnesium, iron, oxygen, and ices;
- have a density of 10^{-6} interstellar dust particles/m^3.

There is some evidence that interstellar dust forms from interstellar gas. Interstellar gas, the matter ejected from the cool outer layers of old stars, is 90 percent molecular hydrogen (H_2) and 9 percent helium (He). The remaining 1 percent is a mixture of heavier elements, including carbon, oxygen, silicon, magnesium and iron. The interstellar dust from which the planets and asteroids formed was that mixture of heavier elements. The hydrogen and helium from the nebula was involved in the formation of our infant Sun and are its major components today.

According to the Condensation Theory, the formation of planets in our Solar System involved three steps, with the differentiation between planet and asteroid formation being a part of the second step.

Step 1: Planetesimals form by *"sticky collision" accretion*

During this phase of formation, dust grains formed ***condensation nuclei*** around which matter began to accumulate. This vital step accelerated the critical process of forming the first small clumps of matter, which then start to **collide** with each other at **low velocities.** The particles eventually stick together through **electrostatic forces**, forming larger aggregates of similar types of constituents. Over a period of a few million years, further collisions make more compact aggregates and form clumps a few hundred kilometers across. At the end of this first stage, the Solar System contained millions of ***planetesimals***—objects the size of small moons, having gravitational fields just strong enough to affect their neighbors.

Step 2: Planetary embryos/cores form by ***gravitational accretion***

The loose, granular structure of planetesimals formed in Step 1 made it possible for them to continue to

- form more massive bodies through **collisional coagulation** of "nebular dustballs" and
- prevent these small objects from bouncing off by absorbing the object's energy during collision.

The more mass the planetesimals accumulated, the greater their ***gravitational attraction*** would be for surrounding objects of all sizes—from dust grains to small planetesimals—until kilometer-sized planetesimals would collide with objects made up of several planetesimals. The result would be that these large planetesimals that were loose aggregates with differing compositions. This ***gravitational accretion*** led to protoplanet formation.

As the protoplanets grew, their strong gravitational fields began to produce many ***high-speed*** collisions between planetesimals and protoplanets. These collisions led to ***fragmentation**,* as small objects broke into still smaller chunks, most of which were then swept up by the protoplanets, as they grew increasingly large. A relatively small number of 10-km to 100-km fragments escaped capture to become the asteroids and/or comets.

Step 3: Planetary development

When the early asteroids were fully formed, the gas and dust continued to form planetesimals. The system of embryos in the inner Solar System becomes unstable and the embryos started to collide with each other, forming the ***terrestrial planets*** over a period of 10^7 to 10^8 years. The largest accumulations of planetesimals became the planets and their principal moons.

In the third phase of planetary development, the four largest protoplanets swept up large amounts of gas from the solar nebula to form what would ultimately become the ***jovian planets***. The smaller, inner protoplanets never reached that point, and as a result their masses remained relatively low.

Introduction

Ask students how they think bodies in the Solar System formed. Then, explain that they will be watching a short music video that shows the diversity of bodies that make up the Solar System. Show the *Space School Musical* clip, "Planetary Posse" (http://discovery.nasa.gov/musical/). Ask students the following two questions:

- How did this music video expand your thinking about the Solar System? What did you learn?
- How do you think these diverse bodies came to be? (Elicit student responses.)

Explain the current theory of Solar System formation.

> Scientists think that in the beginning of its formation, our Solar System was a big cloud of gas and dust. Some event made it begin to spin, and it eventually spun down into a disk of matter swirling around our protosun (think of it as a baby Sun).
>
> As material moved around the protosun, dust grains in the disk collided with each other and started sticking together to form larger rocks. These rocks in turn collided with

other rocks and either gravity held them together or they broke into smaller pieces, depending on the nature of the collision and the relative gravity of the individual rocks. **Over the next few million years, these rocks combined into larger and larger bodies and eventually, formed the planets and other large bodies we have today.** Evidence of these collisions is seen on the surface of the planetary bodies, including asteroids, in the form of craters left by the impacts.

Ask if students have ever seen dust in their home or in their bedroom. Ask if students have ever seen clumps of dust—dust bunnies—under their bed. Explain that this is similar to what it was like in the early Solar System. The dust particles "accrete"—or gather together. In today's activity, we will actively model one of the theories called "Accretion" that describes how scientists think asteroids and planets formed.

The Activity

Setting: A large open area where students can run.

Materials:

Student Role Cards (see examples at right):

- Interstellar Dust:
    - Metallic grains (~6 cards)
    - Rocky grains (~6 cards)
    - Icy Grains (~12 cards)
- Planetesimal (~4 cards)
- Protoplanet (~2 cards)

Interstellar Dust: Silicates and rocky grains including heavy elements such as silicon, iron, magnesium and aluminum combined with oxygen to form rocky materials at a temperature of about 1000 K. (Chaisson, 2008).

Interstellar Dust: Metallic grains including spherical balls of minerals and metal grew by condensation from a gas between about 1100 °C and 1000 °C formed around the orbit of Mercury http://www.psrd.hawaii.edu/Sept00/primitiveFeNi.html

Planetesimals are objects in the early Solar System that are the size of small moons and have gravitational fields strong enough to influence their neighbors

Interstellar Dust: Icy grains including the condensation of water, ammonia and because of the large amounts of the elements that make up these compounds they greatly outnumber the rocky and metallic grains. Icy grains formed around 5 AU (Chaisson, 2008)

Protoplanets are bodies that preceded the formation of planets in the Solar System

Student Role Cards

Advanced Preparation

Prepare the Student Role Cards, using either magic markers on poster paper or making computer-generated labels. The color codes of the paper are important so that students can see the color of other students' labels at a distance.

Prepare the Planetesimal and Protoplanet role cards. Take them with you when you go to the simulation setting.

Directions

This game is similar to "tag." When you tag a person they have to stay near you as you form an asteroid!

The goal is to tag as many students as you can as the game progresses.

- Distribute one Interstellar Dust Card to each student so that there are roughly equal numbers of types of grains (metallic, rocky, icy) represented in the class, making sure that all students have role cards.

- Move students to the setting for the simulation. Students should stand close for directions. When you have their attention, tell them. "This game is similar to 'tag.' When you tag a person they have to stay near you as you form 'clumps'. The goal is to tag as many students as you can as the game following the specific directions given as the game progresses."

- Have one student (or teacher/parent) be the Sun. Have that person stand in the middle of a circle of students.

- Tell students that they are modeling interstellar dust particles, the dust grains around which matter began to accumulate in the early Solar System. Have them note that there are three kinds of dust grains. Those wearing red colored tags are silicates and rocky dust grains; those with blue colored tags are metallic dust grains; and the white colored tags indicate icy grains. Have them read the description of their types of dust grains on their role cards.

- Give them directions for the game. They will jog (not run) in a counter clockwise circular path around the "Sun" which is in the center of the large open area. As students jog they should keep their arms to their sides until the come close to another student. Explain that for the first part of the activity, they are modeling "**sticky attraction**." That is, they can tag and stick **only** to **like grains**. For example, if one icy grain tags another icy grain, they form a pair and can now extend their arms in order to tag another icy grain. An icy grain, however, cannot tag a metallic or a rocky grain.

- Start the game.

a. Have students move out so the ring is large enough for safe orbiting and give them the "start orbiting" signal.

b. Allow the orbiting to continue for several minutes and then call time.

c. Explain that the students who are paired up are called **clumps.** Explain that **the force at work in the activity where like grains can attract and stick to like grains** is **electrostatic attraction.**

- Give students the following directions for the next orbiting period. "When the **clumps tag other <u>like</u> grains** (one or more) the group will stay together and can try to tag others."

- After a few more minutes, call time again.

- At this point, have students observe that there are groups of various sizes. Tell them that groups that have four or more students represent **planetesimals**.

- Hand a "planetesimal" sign to each of the student groups of <u>four or more</u> as you say: "You have just modeled the first phase of Condensation Theory of Solar System formation—from interstellar dust particles to planetesimals. Planetesimals are larger than "clumps" but **each planetesimal is made of the same type of constituents**. Some of you planetesimals are made of rocky materials, some are made of metallic materials, and others are made of icy materials." [Indicate examples of these various types of planetesimals as you name them.]

- Continue: "You were also traveling at relatively low velocities so that when you collided with the same type of dust particles you 'stuck' and didn't just bounce off them. If you were real planetesimal, you would have accumulated enough dust particles to be the size of a small moon."

- Give students these directions for the next phase of the simulation.

  a. **Those groups who formed planetesimals can now tag and stick to any other type of grain. You have formed large enough groups that you can use your gravitational force (extended reach) to attract other dust particles or other planetesimals**

b. Call time when they have tagged other planetesimals or icy, rocky, or metallic grains to form much larger clumps.

c. Designate the two planetesimals that form the largest clump after the allotted time as protoplanets by handing them cards labeled "Protoplanet."

   Explain that they have just modeled the second phase of Condensation Theory of Solar System formation—where planetesimals grew in size to form protoplanets using ***gravitational accretion***.

- Repeat the game and see if the results change.

Review the explanation and ask students the follow-up questions.

Explain to Students After the Game

Time involved and size of clumps: "Simulations indicate that, in perhaps as little as 100,000 years accretion resulted in objects a few hundred kilometers across" (Chaison, 2008). It is thought that the formation of protoplanets from nebular dust grains required a few million years. During classroom trials, one student asked how dust could become a rock. One way to think about this is for students to think about the amount of time involved in Solar System formation and that over a lot of time and with many dust particles, they will eventually form grains (like sand) and then like a little pebble then eventually the size of a baseball, then the size of a basketball and so forth.

Forces involved: Similar interstellar dust particles stick through electrostatic attraction; after clumps grow to a certain mass they gather materials to form planetesimals through the force of gravity.

Post-Activity Discussion Questions

The answers shown in parenthesis reflect possible student responses.

1. What happened to the student dust particles at the beginning of the game? (As students orbited the Sun some of them tagged others and clumped together, others remained as single dust particles.)

2. A. How did the clumps interact with students representing similar interstellar dust particles? (They were attracted to each other and stuck together.)
   B. Was the movement of the two students the same or different? (After they clumped together their movement was similar; they moved at the same speed.)
   C. What force was in effect? (Electrostatic attraction.)

3. Did unlike dust particles interact? Why or why not? (No, the clumps were not large enough to attract unlike particles due to gravity until there were four or more students per group.)

4. A. What happened when there were more than four clumps? (There were fewer dust particles around to tag, clumps of four or more were allowed to tag unlike dust particles.)
   B. Was the movement of the two students *after the interaction* the same or different? (The movement should have been the same.)
   C. Was the movement of student dust particles the same as that of the student clumps? (Different, the student dust particles could move easier.)
   D. What force was in effect? (Electrostatic attraction for similar dust particles, gravity for planetesimals.)

5. What did you notice about the dust particles at the end of the activity? (Many had clumped together, a few were still single dust particles.)

6. Think back to your response about how you thought asteroids formed. Based on this activity:
   a. In what ways was it is similar?
   b. In what ways was it is different? (Student answers will vary depending on their initial thoughts.)

7. How would the difference in the makeup of the solar nebula in the different regions of the asteroid nebula affect the "sticky" accretion that they were modeling?
   (When there are many of the same kind of grains, sticky accretion is easy. When there are few of the same kind of grains, sticky accretion is more difficult.)

8. Would you find the same kind of problem when you model gravitational accretion?
   (No, in gravitational accretion the mass of the planetesimal is the important factor.)

9. What do you think would happen if another large group of (maybe 100) students, which might represent a large planet like Jupiter, entered the circular path where you have been running?

10. Suppose that two fairly large planetesimals that are traveling at a high velocity were attracted to each other. Do you think that a collision between them would always result in accretion? (No.)

11. What else might happen? (Fragmentation.)

Continue to explain. "That's right. Accretion and fragmentation are competing processes. The planetesimals grew from dust grains by gradually sticking together, but small bodies were also broken apart by collisions with larger ones."

Wrap-up
Have students answer questions about physical modeling.

- How is the model different than the real thing?
  (In the activity dust [students] moved faster in an attempt to "catch" smaller objects. In reality the dust particles clump together because of electrostatic attractions and do not move faster in order to clump together. Similarly, large clumps were attracted to like and unlike dust grains in order to form planetesimals due to gravity.)
- Why are models and simulations useful?
  (While not completely accurate, physical models are useful to better understand processes that happened in the past that are not observable now.)
- What questions do you have?

Asteroid Gang Video
Ask students what comes to mind when they hear the term "asteroid."

- You may hear: "Large rocks that orbit the Sun," "meteor shower," or "comet."

Ask students how asteroids have been depicted in movies and TV.

- Students may refer to films like *Star Wars*, where asteroids are collide with one another or with futuristic spaceships providing hazards that they must zip through.
- Explain that in the asteroid belt today, these bodies are very far apart and that NASA mission spacecraft like Dawn can fly safely through the belt without worrying about maneuvering to safety, rarely coming within even hundreds of kilometers of another body of any size.

***Space School Musical's* Asteroid Gang**

Share another music video from *Space School Musical*, "The Asteroid Gang."

- How does this music video expand your thinking about asteroids? What did you learn?
- Give us a critique!
  - Are there any misconceptions this model might inadvertently promote?
  - What does this asteroid gang model about asteroids that seems accurate?

Extension
Show the Planet Families website:
http://www.alienearths.org/online/starandplanetformation/planetfamilies.php. Ideally, students can play the interactive in pairs in the computer lab after the activity.

- Place several small bodies onto the screen. Have students generate a list of questions they would like to ask about how these bodies move through space.
- Place Jupiter in the mix and allow students to observe what happens. What force would explain this?
- What other combinations of planets would you like to try?

Additional Resource

Concept adapted from the Lesson 10: Building Blocks of Planets Activity C: "Crunch! Accretion of Chondrules and Chondrites" activity from *Exploring Meteorite Mysteries*
http://ares.jsc.nasa.gov/Education/Activities/ExpMetMys/ExpmetMys.htm

National Science Standards Addressed

Grades 5–8
Earth in the Solar System

- The Earth is the third planet from the Sun in a system that includes the moon, the Sun, other planets and their moons, and smaller objects, such as asteroids and comets.
- Most objects in the Solar System are in regular and predictable motion.
- Gravity is the force that keeps planets in orbit around the Sun and governs the rest of the motion in the Solar System.

Grades 9–12
The Origin and Evolution of the Earth System

- The Sun, the Earth, and the rest of the Solar System formed from the solar nebula—a vast cloud of dust and gas—4.6 billion years ago.

Grades K–12
Evidence, Models, and Explanation

- Models are tentative schemes or structures that correspond to real objects, events, or classes of events, and that have explanatory power.

Active Accretion was developed by John Ristvey, Donna Bogner, and Whitney Cobb,
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