INTRODUCTION

The early Solar System was a happening place: it only took ~100 million years (myr) for a cloud of gas and dust to evolve into moons and planets. If all 4.5 billion years of Solar System history were condensed into 24 hours, then the Solar System would have formed in about 30 minutes. Other processes, such as late migration of the giant planets, may have sculpted the Solar System for another ~700 – 800 myr, but the moons and planets themselves formed quite rapidly.

For decades, scientists thought the Solar System formed in a series of sequential steps. In this model, little clumps of gas and solids grew into progressively larger objects until, finally, they reached the size of planets. Over the past several years, however, scientists realized that Solar System formation was not a neat, orderly process. While the physical processes of planet formation definitely involved little clumps of rock, ice, and gas growing into big ones, events in the early Solar System overlapped in time.

DIRECTIONS

You will construct a basic timeline of the first 100 million years of Solar System history. Your timeline will reveal how quickly key events happened and expose the processes that occurred simultaneously. To complete this assignment:

1. Read the “Background” section to learn about the types of information you will use to construct your timeline.

2. Use the information in the “Constraints” section to construct a timeline showing when the following key events started and how long they lasted. Keep in mind that some events lack sharp beginnings and endings. Current data might limit us to saying that a particular event happened sometime within a specified period (e.g., 1 – 3 million years). Your timeline should reflect these uncertainties. Remember that more than one event might be happening at any given time.

Your timeline must include:

- Formation of CAIs
- Chondrule formation
- Formation of ordinary chondrite parent bodies
- Thermal metamorphism on ordinary chondrite parent bodies
- Formation of carbonaceous chondrite parent bodies
- Aqueous alteration on carbonaceous chondrite parent bodies
- Formation of iron meteorite parent bodies
- Moon-forming impact
- Core formation on Mars
- Core formation on Vesta
- Core formation on Earth
- Planetesimal formation
- Planetary embryo formation
- End of giant planet formation
- End of terrestrial planet formation

3. Write a short (½ page long) description of why you arranged events on your timeline the way you did. Comment on what your timeline reveals about the timing of events in the early Solar System.
To build a timeline of early Solar System history, researchers combine information from three sources: theoretical studies, astronomical observations, and detailed analyses of asteroids, comets, and meteorites. Like professional scientists, you will need to integrate information from all three of these sources to construct a timeline of early Solar System history.

Theory. Theoretical considerations and computer models provide insight into Solar System formation and the length of key events (e.g., how long it takes to make the terrestrial planets). However, theories and models depend on parameters whose values may be poorly known, such as the ratio of solids to gas in the protoplanetary disk. To combat this limitation, modelers explore how changes in various parameters affect their conclusions, a process that offers a window into factors that control the timing of events in the early Solar System. Computer models of planet formation are often called “dynamical models” or “N-body simulations”

Astronomical observations. Powerful telescopes, like Hubble, can directly study protoplanetary disks around other stars. Studies reveal that some disks are composed of both gas and dust (Figure 1). Other disks, however, appear to consist only of dust and rocky material, with little to no gas (Figure 2). Astronomers can estimate the age of the star from such observations. Typically, the stars with gas-rich disks are younger than stars with solid-dominated, gas-poor disks.

Isotopic analyses. Certain isotopic ratios in samples from asteroids, comets, and meteorites reveal a wealth of information about the sequence of events in early Solar System history. A variety of isotopic systems can be used, but we will focus on only two of them: the hafnium-tungsten and aluminum-26.

As we discussed in class, the hafnium (\(^{182}\text{Hf}\))-tungsten (\(^{182}\text{W}\)) system tracks the timing of core formation. Because of differences in geochemical behavior, Hf stays in the silicate mantle during differentiation but W is scavenged into the metallic core. If a planetary body differentiated early enough, then the rocky (silicate) mantle of the object will have excess radiogenic \(^{182}\text{W}\) compared to chondritic meteorites, which never differentiated. However, if a planetary body differentiated after \(^{182}\text{Hf}\) had decayed away, then the \(^{182}\text{W}\) composition of the rocky mantle of that object would be identical to chondrites. As a result, comparing the W isotopic composition of a particular sample to the W isotopic composition of chondrites reveals when metal and
rock separated on the parent body of that particular sample.

The $^{26}$Al-$^{26}$Mg system also provides key information about the timing and sequence of events during Solar System formation. In addition to helping tease apart the chronology of the early Solar System, the energy released by the decay of a $^{26}$Al atom to a $^{26}$Mg atom provided a potent source of heat during the first few million years of Solar System history. The radioactive decay of $^{26}$Al to form $^{26}$Mg releases so much heat that asteroid-sized bodies would have melted (and thus allow for differentiation) if they formed less than $\sim 1.5 – 3$ million years after the Solar System started forming.

**CONSTRAINTS**

**Astronomical**

- Telescopic observations of young stars reveal that protoplanetary disks usually last for 2 – 3 million years (\~10 million years, at most). After that, radiation from the star removes any gas that is not bound to the star or to a planet. The solid rock and ices, however, survive this process and stay in the disk.

**Isotopic**

- Isotopes of lead in calcium- and aluminum-rich inclusions (CAIs) indicate that CAIs condensed 4.567 billion years ago. CAI formation probably lasted < 50,000 years. The formation of CAIs is conventionally used to define “time = 0” for the Solar System. Other events are often reported as to when they happened relative to CAIs, that is event “Y” happened “X years after CAIs”.

- Recent studies based on $^{26}$Al reveal that some chondrules formed at the same time as CAIs. Not all chondrules are the same age. Chondrule formation may have lasted for 1 to 4 million years after CAIs.

- Different types of chondrites formed at slightly different times over a 1 to 3 million year period. Ordinary chondrite parent bodies formed \~2 – 3 million years after CAIs, whereas the carbonaceous chondrite parent bodies formed \~2 – 4 million years after CAIs.

- The W isotope composition of most iron meteorites shows that the rocky and metallic parts of iron meteorite parent bodies separated \~0 – 1.5 million years after CAIs.

- Detailed isotopic analyses reveal that aqueous alteration on carbonaceous chondrite parent bodies began as soon as \~2 million years after CAIs and lasted until 10 million years after CAIs.

- $^{26}$Al data suggest that thermal metamorphism on ordinary chondrite parent bodies started as soon as 3 million years after CAIs and continued for up to another 7 million years.

- Dating of meteorites shows that planetesimals 10 – 100 km in size formed during the first 4 million years after CAIs.

- W isotopic data indicate that the Moon-forming impact probably happened 30 – 150 million years after the Solar System began forming.
W isotopes show that the following objects differentiated at about the following times:

<table>
<thead>
<tr>
<th>Body</th>
<th>Estimated time of core formation (myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>29.6</td>
</tr>
<tr>
<td>Iron meteorites</td>
<td>0 to 2.9, depending on type</td>
</tr>
<tr>
<td>Vesta</td>
<td>2.6</td>
</tr>
<tr>
<td>Mars</td>
<td>3.3 to 9.7, depending on sample analyzed</td>
</tr>
</tbody>
</table>

Data from Jacobsen (2005)

**Theoretical**

- Dynamical models suggest that it took $< 50,000$ years to form centimeter-sized “pebbles” once solids began condensing in the protoplanetary disk. Some models indicate it may have only taken 1,000 years.
- N-body simulations show that 100 – 1000 km-sized planetesimals form in as little as 1 million years.
- Dynamical models also reveal that Moon- to Mars-sized planetary embryos formed from growing planetesimals in 100,000 to a few million years.
- N-body simulations indicate that it takes ~30 to 100 million years for planetary embryos to finally accrete into the terrestrial planets.

**Other Observations**

- The ordinary and carbonaceous chondrite parent bodies never completely melted.
- The parent bodies of iron meteorites melted extensively because large melt fractions are needed to segregate the nickel and iron from rocky material.
- Cooling rates of iron meteorites indicate that their parent bodies were ~150 to 1000 km in size.
- The giant planets are made mostly of gas.

**SOURCES**


Key Events

Time after CAIs (millions of years)

(10,000 years)  (100,000 years)

Name: __________________________