

Meteorites and the Age of the Solar System

1 Rocks from the sky

Around about midnight on March 26, 2003, some people in the southern suburbs of Chicago had some unexpected visitors. Some time earlier, a meteoroid with a mass of 900 kilograms or more entered our atmosphere. As the object fell towards earth, it collided with air molecules which slowed it down, heated it up and also caused it to break into many pieces. The smaller pieces burnt up in the atmosphere, but hundreds of larger fragments survived and a series of pebble and cobble-sized rocks (called **meteorites**) crashed into sidewalks, houses and cars in and around the village of Park Forest.

The fragments of the Park Forest meteorite, as it is now called, are **chondrites**. Chondrites are the most common type of meteorites, accounting for about 90% of all meteorites that have made it to earth. Chondrites are stony meteorites, in that they are made out of silicate minerals (in other words, rock). This is in contrast to the comparatively few meteorites which contain significant amounts of metallic iron. Chondrites contain within them distinctive structures called **chondrules**; small spheres of rock about a millimeter across. The comparatively few stony meteorites which lack these distinctive spheres and are known as **achondrites**.

Except for the moon rocks brought back by the Apollo and Luna missions, meteorites are the only macroscopic samples from outer space we have. These objects are therefore a precious source of information about the solar system. In particular, since meteorites appear to contain very old material, they provide important information about how and when the solar system formed.

2 Dating Meteorites

Not surprisingly, the age of meteorites is measured using radiometric techniques. As we have seen in previous lectures, radioactive, unstable nuclei are useful tools for measuring age because they decay with time in a regular way with a well-defined half-life. Indeed, we have already seen (in the fifth lecture) how to estimate when certain rocks formed using the decay of Potassium-40 into Argon-40. In that case, a measurement of the current amount of Potassium-40 in the rock, combined with an estimate of how much Potassium-40 was in the rock when it first formed based on its Argon-40 content, provided the information required to calculate the fraction of the Potassium-40 atoms which had decayed since the rock cooled. From this ratio, we could then derive the amount of time that had elapsed since the rock formed.

While the half-life of Potassium-40 is sufficiently long (over 1 billion years) that it can be used to measure the age of meteorites, the Potassium-Argon system does not necessarily provide the most direct way to estimate when these objects first formed.

Recall that the Argon-40 escapes from the rock whenever it is heated sufficiently. This effectively re-sets the radiometric clock so the age measured by the Potassium-Argon method is how much time has elapsed since the last major heating event. Collisions between meteoroids and other objects in space are sometimes violent enough to jostle loose some amount of Argon-40, and corrupt the Potassium-Argon age. Other systems, such as Rubidium-Strontium, are less easily perturbed than the Potassium-Argon system and give more robust estimates of the age of the meteorites.

2.1 The Rubidium-Strontium System

Rubidium-87 is an unstable variant of the element Rubidium, with 37 protons and 50 neutrons. It undergoes beta decay and transform into a stable variant of Strontium, Strontium-87, with 38 protons and 49 neutrons. The half-life for this decay is about 50 billion years, so this system can be used to measure the age of very old rocks, like meteorites.

The Rubidium-Strontium system provides a way to estimate the age of a collection of rocks or minerals that all formed at the same time in the same environment. Each mineral absorbs some amount of Rubidium from the environment as it forms, and as time passes the Rubidium-87 decays into Strontium-87. The Strontium-87 stays in the mineral so the total combined number of Rubidium-87 and Strontium-87 atoms stays constant with time. However, Strontium is not a noble gas, so it does form bonds with other atoms and can be incorporated into a growing mineral, which means the initial amount of Strontium-87 in the rock does not necessarily have to be zero. This means we cannot use this system to estimate the age of a single sample.

Imagine we find a rock contains 10 grams of Rubidium-87 and 10 grams of Strontium-87, then we know it always had 20 grams combined of Rubidium-87 and Strontium-87. However, since the rock could have contained some Strontium-87 in it when it formed, we cannot say whether the rock initially had 20 grams of Rubidium-87, or 15, or 12. Therefore, we cannot compute the fraction of the Rubidium atoms that had decayed or the age of the rock with only these data. We need more information.

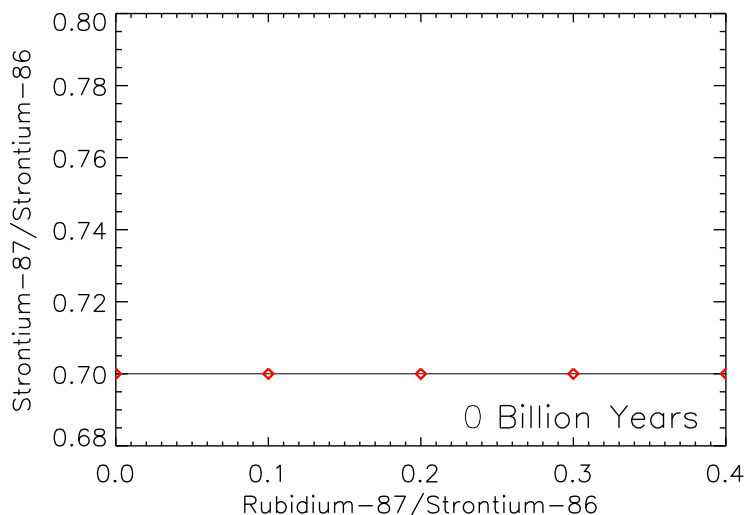
Say we take the rock and break off two different samples with different mineral compositions (call them A and B). We assume all these minerals formed at roughly the same time in the same environment. Besides measuring the Rubidium-87 and Strontium-87 content of these samples, we also measure the amount of another isotope of Strontium, Strontium-86, which is not produced by the decay of Rubidium. This isotope is handy because it allows us to compare the Rubidium-87 and Strontium-87 content of the two samples. For example, we can choose the size of the samples so that they both contain 20 grams of Strontium-86. When we analyze these samples we find that sample A contains 18 grams of Rubidium-87 and 12 grams of Strontium-87, while sample B contained 9 grams of Rubidium-87 and 11 grams of Strontium-87.

The fact that the two samples, which contain the same amount of Strontium-86, contain different amounts of Rubidium-87 is not unexpected. Rubidium and Strontium have different chemical properties and will be picked up at different rates by different minerals. On the other hand, Strontium-87 and Strontium-86 have nearly identical properties and therefore should have been picked up at the same rate by any mineral. Therefore, if these samples formed in the same environment and absorbed Strontium from the same source, they should have had the same amount of Strontium-

⁸⁷ relative to Strontium-86. However, sample A today has more Strontium-87 than sample B, even though they have the same amount of Strontium-86. Since the sample with more Strontium-87 also has more Rubidium-87, we can reasonably assume that these differences in the Strontium-87 content of the two samples measured today come from the Rubidium-87 that has decayed since the minerals formed.

Since Rubidium-87 decays with a well-defined half-life, we can compute how much Rubidium-87 and Strontium-87 was in the two samples at various times in the past. For example, we know that after 7 billion years, about 10% of the Rubidium-87 would convert to Strontium-87. Therefore, if we have 18 grams of Rubidium-87 in sample A today, 7 billion years ago the sample would have contained about 20 grams of Rubidium-87. Of course, this also means that there were two less grams of Strontium-87 at this time, so sample A contained 10 grams of Strontium-87 7 billion years ago. Similarly, we find that 7 billion years ago sample B contained 10 grams of Rubidium-87 and 10 grams of Strontium-87. These calculations therefore show that 7 billion years in the past, both samples contained the same amounts of Strontium-87 relative to Strontium-86. Therefore, these two samples could have formed from the same environment and drew their Strontium from the same source if they formed 7 billion years ago. Doing similar calculations shows this is the **only** time when this could have happened. If the rocks formed any other time, they would have different relative amounts of Strontium-87 and Strontium-86 and so could not have formed in the same environment. Therefore, if the samples formed at the same time in the same environment, they must have formed 7 billion years ago.

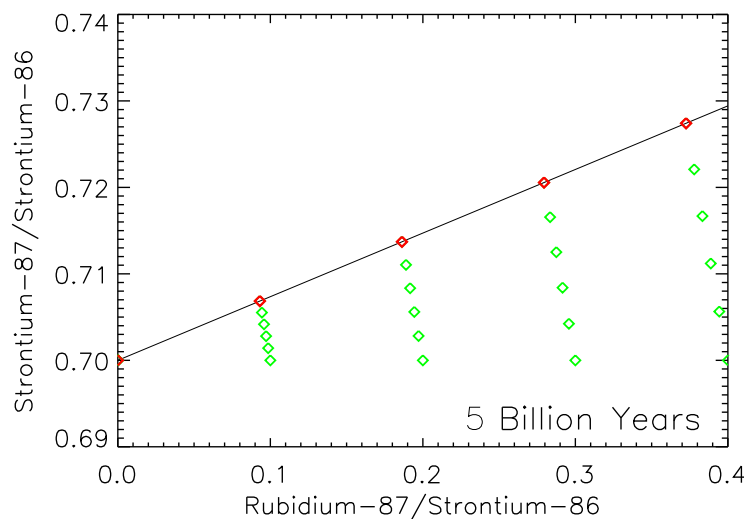
With only two samples, it is difficult to be sure whether the minerals all formed at the same time in the same environment. We can check this by considering more samples and making something called an **isochron diagram**, which is a plot of the Rubidium-87 content of the samples versus their Strontium-87 content. Both these numbers are measured relative to the Strontium-86 content of the samples and are presented as ratios. If we had a collection of minerals that just formed now from a single source, they will all have the same amounts of Strontium-87 relative to Strontium-86, so the rocks fall along a horizontal line as shown below.



All these rocks have a Strontium-87/Strontium-86 ratio of 0.7 (for every 10 grams

of Strontium-86 there are 7 grams of Strontium-87). The Rubidium-87/Strontium-86 ratios vary because the different minerals in the samples accumulated different amounts of Rubidium and Strontium.

Now, as time goes on, the Rubidium-87 in the samples decays into Strontium-87. After 5 billion years, 7% of the Rubidium has decayed. Thus the sample with an original Rubidium content of 0.4 has had its Rubidium-87 reduced by 0.03 and its Strontium-87 content increased by 0.03. Similarly, the rock with the original Rubidium content of 0.3 has had its contents changed by 0.02. If we re-draw the isochron plot at this time, we get the following result (the light gray dots show how the points moved over 5 billion years).



The points still fall along a line, but the line is no longer horizontal because samples which contained more Rubidium-87 had a larger amount of Strontium-87 generated through radioactive decays. However, the y-intercept of the line is still at 0.7. This makes sense, since if a rock had no Rubidium-87 in it at all, the Strontium-87 content would never change. Thus, by measuring the intercept of this line, we can infer the original Strontium-87 content of the samples. With this information, we can easily compute the original Rubidium-87 content of the rocks and then infer their age. We can also estimate the age more simply from the slope of the line, which steadily increases with time in a calculable way.

Such a plot allows us to check that a series of samples really does come from material that formed at the same time in the same environment. If the samples were formed at different times and places, then the points would be scattered haphazardly and would not fall on a line. Only if the objects drew their Strontium from a common source will we have such a tight correlation between the parameters displayed.

As a final note, realize that the Rubidium-Strontium clock is much harder to reset than the Potassium-Argon clock. To return the samples to zero age, we must return the slope of the isochron plot to zero. This means we must re-distribute the Strontium-87 between all of the different samples. In order to do this, all of the different parts of the rock would have to be melted and mixed before being allowed to solidify again. The age measured by the Rubidium-Strontium system thus gives the time when the rock last formed from a more-or-less purely molten (or at least fluid)

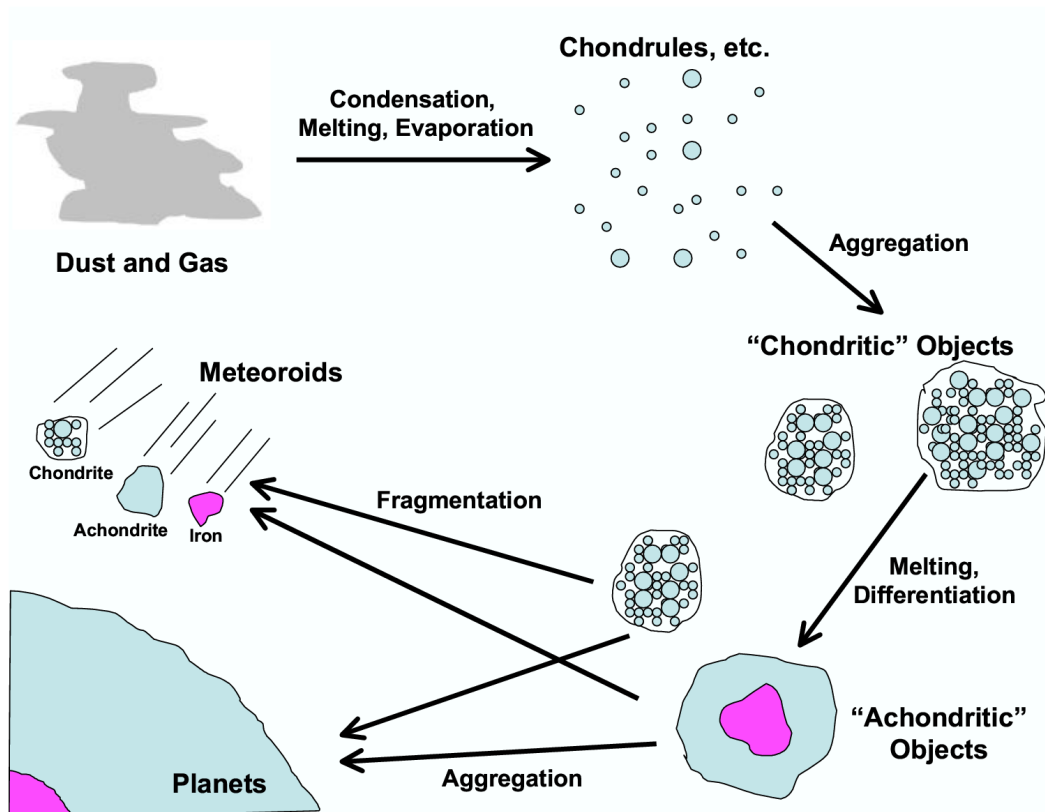


Figure 1: A cartoon illustrating the steps by which the rocky material in the solar system could have been made. First, the dust and gas surrounding the early sun condenses and melts to form small millimeter-sized objects like chondrules. Next, these chondrules aggregate into larger and larger “chondritic” objects. Some of these objects melt and differentiate, destroying the chondrules within them. These objects collide, which produces fragments like meteorites, but also causes some objects to accumulate material until they grow to the size of planets.

state.

3 Meteorites as relics of the early solar system

The age of numerous meteorites have been measured using the Rubidium-Strontium system. All chondrites and many achondrites have ages of around 4.5 billion years. These objects are therefore among the oldest objects in the solar system and could provide important clues about how the solar system formed.

The various planets and other objects that surround the sun today most likely formed from a disk of dust and gas that surrounded the early sun (and surrounds some young stars today). The processes which caused this material to accumulate and clump into planets are still not perfectly understood, but the structures of the chondritic meteorites indicate that at least some rocky material was made as an agglomeration of small millimeter-sized spheres. Indeed, it is reasonable to suppose that the chondrules and other inclusions preserved in the chondritic meteorites were among the first solid objects to appear in the solar system.

In this scenario, illustrated in Figure 1, the chondrules and other small objects would be formed as a combination of melted dust grains and condensed gasses. As time goes on, these little globs of rock run into each other and occasionally stick together, forming larger objects. Some of these objects would not accumulate much material, and remain compacted agglomerations of chondrules of dust. Others, which manage to accumulate more material, would begin to heat up due to the energy supplied by collisions and by the decay of the radioactive isotopes inside them. This heating caused the chondrules to melt so different chemicals can migrate throughout the object (for example, heavy metals fall towards its center) before minerals form anew. This of course destroys the “chondritic” texture of the material (and re-sets the radiometric clocks).

As these rocks continue to collide into each other, larger and larger collections of material appear. Since the gravity of the larger bodies is stronger than that of smaller bodies, a few of these objects eventually accumulate most of the rocky material and become the (terrestrial) planets we see today (The giant planets of the outer solar system probably formed in a somewhat different way). Some rocks avoid being incorporated into these large objects and become the asteroids, etc. These smaller bodies are occasionally broken into pieces by collisions, which produce fragments that come to earth as meteorites. Fragments of bodies that were still a collection of chondrules give us the chondrites, while pieces of objects that underwent wide-scale melting provide us with the achondrites and iron meteorites.

To better understand the various processes involved in these events, and indeed to check whether this scenario is correct at all, we need a much tighter control on the chronology of these events. For example, with more precise measurements of the age of the various types of meteorites and their components, we could see if achondrites are indeed younger than chondrites, as the above model predicts.

The long half-life of Rubidium-87 means that we cannot obtain the precision required to discriminate the age of chondrules from the age of achondrites from Rubidium-Strontium ages alone. Therefore, we must turn to other radiometric systems, like the Uranium-Lead system. It also turns out that short lived radioactive nuclei, like Aluminum-26 can be extremely useful in this situation.

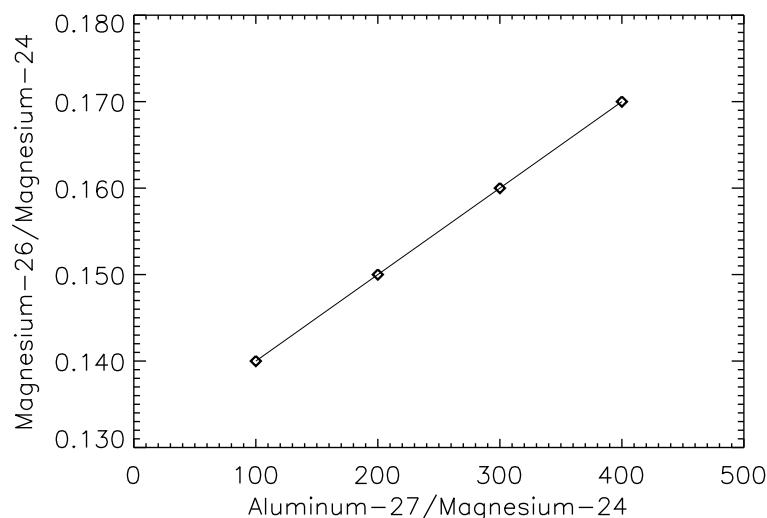
4 Refining Chronology with short-lived radioisotopes

It might seem odd that short-lived radioactive nuclei can help measure the age of meteorites which formed over 4.5 billion years ago. In fact, we cannot determine exactly how many years ago objects formed based on this data. However, we can possibly get an idea of when different objects formed relative to each other.

As with the Rubidium-Strontium system, imagine some rocks formed from a common environment. This environment contains short-lived radioactive isotopes such as Aluminum-26, which decays to form Magnesium-26 with a half-life of about 700,000 years. As time goes on, the Aluminum-26 content of the environment decreases, so rocks that form later get less Aluminum-26 than rocks that form earlier. Thus the initial amount of Aluminum-26 can be used as measure of the relative timing of these rocks' formation.

The initial amount of Aluminum-26 in a rock can be determined using plots similar

to the isochron plots discussed above. Say we take multiple samples of different minerals in a rock and obtain the Magnesium-26 content of each each sample. We want to know how much of this Magnesium comes from Aluminum-26 that was originally in the rock. To figure this out, we also measure the amounts of Magnesium-24 and Aluminum-27 contained in the samples. We can then create a plot like the one below, which shows the amount of Magnesium-26 and Aluminum-27 in the rock, relative to the amount of Magnesium-24.



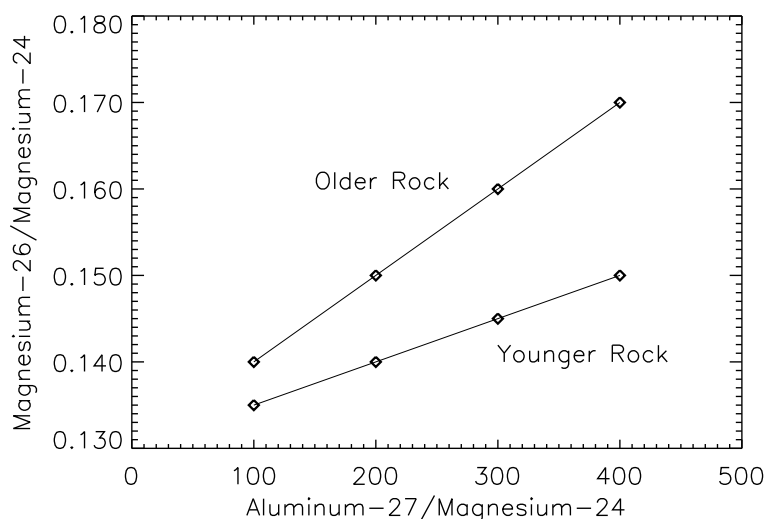
Each point gives the composition of a particular sample. Clearly, samples with more Aluminum-27 have a larger Magnesium-26/Magnesium-24 ratio. This trend indicates that these minerals originally contained some amount of Aluminum-26. If all the Magnesium-26 was acquired when the minerals originally formed, then all the minerals should all have the same relative amounts of Magnesium-24 and Magnesium-26 (remember, these isotopes have the same chemical properties), and all these points would fall along a horizontal line. However, if the minerals all formed in the same environment and picked up their Aluminum from the same source, which included both Aluminum-27 and Aluminum-26, then samples with more Aluminum-27 would also have originally contained more Aluminum-26. After this Aluminum-26 decayed into Magnesium, the sample with more aluminum would now have an excess of Magnesium-26, as seen here. (Also note that if the minerals formed in different environments, then there would not be such a tight correlation between the Magnesium isotope ratio and the Aluminum content.)

As with the Rubidium-Strontium isochron plot, the y-intercept of this line gives the original fraction of Magnesium-26 in all of the minerals, since it represents the Magnesium-26 content of a mineral that did not absorb any aluminum. The slope of the line, on the other hand, provides a measure of the original Aluminum-26 content of the rock.

If a large fraction of the Aluminum was originally in form of Aluminum-26, then a given difference in the Aluminum-27/Magnesium-24 ratios of two minerals would have been matched by a large difference in the original Aluminum-26/Magnesium-24 ratios. After the Aluminum-26 decays, these minerals would be left with very different Magnesium-26/Magnesium-24 ratios, and the resulting line on the isochron plot would

have a very steep slope. Conversely, if only a small fraction of the Aluminum was in the form of Aluminum-26, then the samples with different Aluminum-27/Magnesium-24 ratios will have only small differences in their Magnesium-26/Magnesium-24 ratios, and the slope will be shallow. The slope is thus directly proportional to the fraction of Aluminum absorbed into the minerals that was in the form of Aluminum-26. In fact, the slope of the line is exactly equal to the Aluminum-26/Aluminum-27 ratio of the original minerals and their environment.

Of course, the original Aluminum-26/Aluminum-27 fraction of the rock's environment does not tell us exactly how long ago the rock formed. However, we can determine if another rock which formed in the same environment formed earlier or later than this rock. Say we process this second rock as we did the first one and plot the data from both rocks below.



The data for the original rock (labeled as “older rock”) fall along a noticeably steeper line than this new rock (labeled as “younger rock”). In fact the slope of the older rock data are twice as steep as the data from the younger rock. This implies the younger rock obtained its Aluminum from a source with half the Aluminum-26/Aluminum-27 ratio as the older rock. If both these rocks obtained their aluminum from the same source at different times, then half of the Aluminum-26 must have decayed between the formation of these rocks. Since the half-life of Aluminum-26 is 700,000 years, the younger rock must have formed 700,000 years after the older rock.

Meteorites do appear to have contained Aluminum-26 when they formed, along with other short lived radioactive isotopes. Furthermore, the Aluminum-26 content of achondrites is lower than that of chondrules, which would be consistent with the idea that the achondrites formed later, by the re-processing of chondritic materials. Furthermore, there are objects within the Chondrites which have a higher Aluminum-26 fraction than the chondrules. These are the **CAIs** or Calcium-Aluminum-Rich Inclusions. CAIs are distinguished from chondrules by the fact that they are not round and they contain a higher quantity of those elements with high melting and boiling points. Since these elements would be the first to condense from the gas in the solar nebula, it would make sense that they formed somewhat early.

If we assume that these variations in the Aluminum-26 content are only due to

variations in when these objects formed, then it turns out the chondrules formed about 2-5 million years before the achondrites, and the CAIs formed maybe 1-2 million years before the chondrules. However, these relative time estimates rely on some major assumptions about where the Aluminum-26 came from and how it was distributed in the early solar system. Since objects from the early solar system contain a wide variety of short-lived radioactive elements, which show relatively consistent trends, it certainly appears that all these elements were dumped throughout the solar system at once in a single burst. This could occur, for example, if this material was debris from a nearby supernova. (This idea is appealing because the wind of particles from the supernova has been proposed as a mechanism that caused a diffuse gas cloud to collapse and form the sun and solar system). However, it is also possible that at least some these nuclei were produced more locally, and were not so evenly distributed in the solar system. For example, particles emitted by the sun can make radioactive nuclei, so we can imagine there was more Aluminum-26 nearer to the sun. These variations in the Aluminum-26 content of different objects could then be telling us more about *where* these objects formed than *when* they formed.

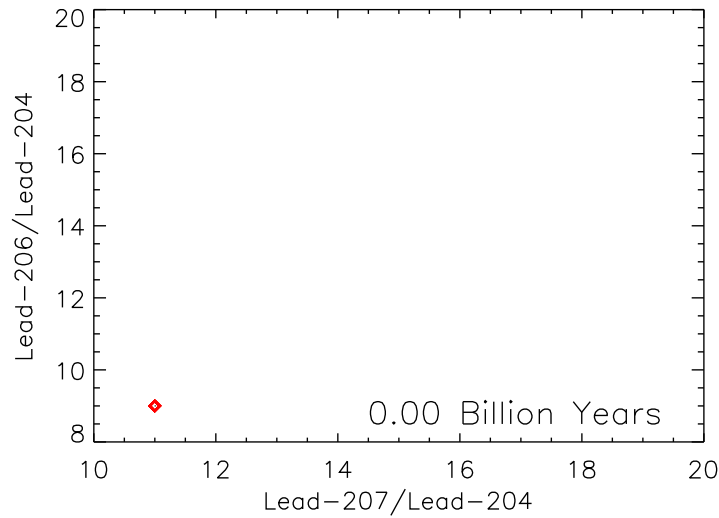
Recently, another radiometric method has been utilized to produce absolute age measurements with precision that rivals the results from the short-lived radioactive nuclei. This Uranium-Lead system provides a way to check and calibrate the relative timings suggested by the short-lived radioactive nuclei.

5 Fine scale absolute dates with the Uranium-Lead system

The Uranium-Lead system is much like the Rubidium-Strontium system in that the age measurement is made by comparing multiple minerals from a single rock that formed at the same time in the same environment. However, there are some important differences.

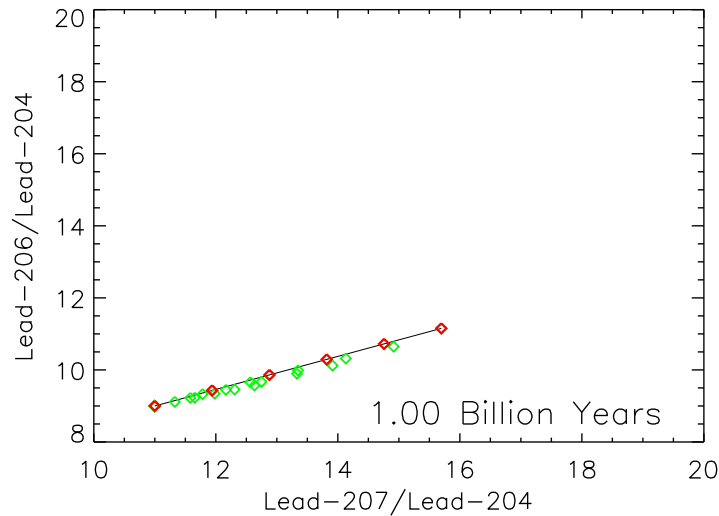
The two isotopes of Uranium, Uranium-235 and Uranium-238, are both radioactive and unstable. These nuclei do not undergo a single decay to produce a stable nuclei, but instead go through a series of transformations before they finally yield stable isotopes of lead. Uranium-235 decays into Lead-207 with a half-life of 700 million years, while Uranium-238 decays into Lead-206 with a half-life of 4.5 billion years. Thus the two different isotopes of Uranium decay into two different isotopes of Lead with two different half-lives. This permits a rather unique form of radiometric dating that relies only on the relative amounts of different isotopes of the same element.

Say we have a rock composed of several different minerals which just formed. We take samples of this rock and obtain the relative quantities of Lead-206, Lead-207 and Lead-204 (the last of which is not produced by the decay of Uranium). Since these isotopes have nearly identical chemistry, they are picked up in the same ratios by all the minerals in the rock, so all the samples have the same proportions of the different isotopes. Hence, all of these minerals have the same Lead-206 and the Lead-207 content, relative to Lead-204, so if we made a plot showing the ratios of different lead isotopes, all the minerals would give points that fell in the same place, as shown below.

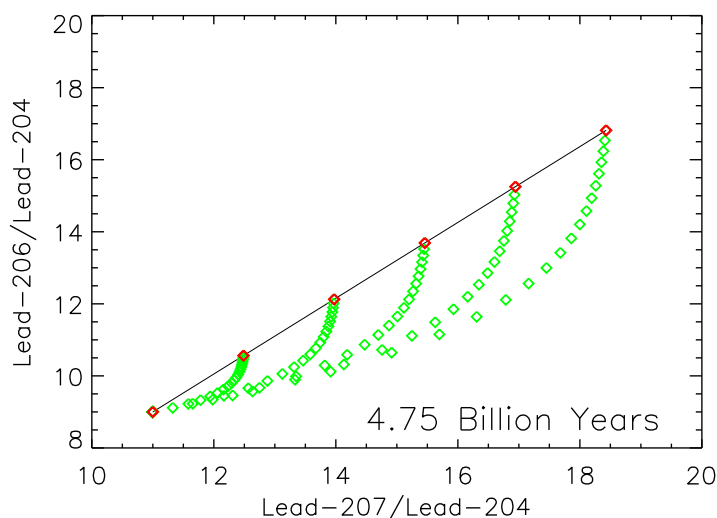


Similarly, these different minerals would have the same relative amounts of the two types of Uranium. However, each of these samples contains different amount of Uranium relative to lead, and as time goes on, the Uranium decays and alters the proportions of different types of lead.

Say we looked at the minerals 1 billion years after they formed. Then we would get a plot like this (again, the light gray points show how the samples have changed over this time).



These minerals fall along a line with a fairly shallow slope. This is because the Uranium-235 has a shorter half life than Uranium-238, so the relative amount of Lead-207 increases faster than the relative amount of Lead-206. However, as time goes on, the line becomes steeper as more and more Uranium-238 decays. For example, after 5 billion years, the minerals would give data that would produce a line like the one shown below.



Just as with the Rubidium-Strontium system, the slope of the line on these plots provides a way to estimate the age when the rock formed.

The reason this method can yield more precise results than the Rubidium-Strontium method is because the relevant half-lives are shorter. Also, since we only have to determine the relative amounts of isotopes of the same element, the measurements of the various ratios have smaller experimental uncertainties. (For example, with the Rubidium-Strontium system we have to worry that the procedure which extracted the Strontium from the samples might be less efficient than the procedure that extracted the Rubidium. This is not so much an issue when all we care about is extracting the different forms of lead.)

Using this method, some researchers have managed to extract age measurements of meteorites which have spectacular precision. First, in 1992 an achondrite was measured to have an age of 4558 million years, with an uncertainty of only 500,000 years. Then in 2002 another team measured the age of chondrules from one chondrite as 4564 million years and the age of two CAIs from another chondrite as 4567 million years, in all these cases the uncertainty is significantly less than one million years.

These results confirm the previous finding that CAIs formed a couple of million years before the chondrules, and that the achondrites appeared somewhat later. If these results are correct, they imply that millimeter scale objects were being made for a long time before they were assembled into chondrites. This means that there were likely repeated heating episodes which could melt and form chondrules. Also, these small particles needed to be stored and mixed before being put together into larger objects. However, it is important to realize that only a few objects have been dated with this level of precision. More data on more objects is needed to confirm that CAIs are consistently older than chondrules. Also, it will be interesting to compare individual chondrites and CAIs from the same meteorite. Such additional data will further clarify the sequence of events and illuminate how the solar system formed.

From the birth of the solar system, we will now turn to the death of stars. In the next lecture we will see how to determine the age of stars by carefully studying their color and brightness.

6 References

For a nice introduction to meteorites, see

- Harry McSween *Meteorites and their Parent Planets, 2nd ed* (Cambridge 2000)

Also useful are the relevant chapters in:

- Beatty, Petersen and Chaikin *The New Solar System, 4th ed* (Cambridge 1999)
- Weissman, McFadden and Johnson *Encyclopedia of the Solar System* (Academic Press 1999)

For more advanced technical introduction, try Volume 1 of the *Treatise on Geochemistry* (general editors Holland and Turekian, volume editor A.M. Davis, Pergamon 2004)

For details of the Park Forest Meteorite, try

- S.B. Simon et al “The fall, recovery and classification of the Park Forest Meteorite” in *Meteoritics and Planetary Science*, Vol 39 (2004) Issue 4

For more details on isochron plots and radiometric dating, look at textbooks on Geochemistry such as

- A.H. Brownlow *Geochemistry, 2nd Ed* (Prentice Hall, 1996)

For the latest High-precision age estimates using the Uranium-Lead system:

- Lugmair and Galer “Age and isotopic relationships among the angrites...” *Geochimica et Cosmochimica Acta* Vol 56 (1992) 1673-1694
- Yuri Amelin et al “Lead Isotopic Ages of chondrules and Calcium-Aluminum-rich Inclusion” in *Science* Vol 297 (2002) pp 1678.