Student questions: Don Brownlee colloquium on “What Samples of a Comet Tell Us About the Origin of the Solar System”

2/22/17

Note: These questions were answered on a plane so please forgive typos ☺ - Don

Question 1: Is there any drinkable water on a comet?

Ha- good question. There is no liquid water but lots of ice. You could melt the ice and drink it but only if you figured a way to keep all the other stuff out. If you melted it very carefully you could probably separate hydrogen cynaide, methanol and other deadly ingredients from the liquid water. If you had to do it you could certainly make it work.

Question 2: What is the most important thing about studying the comets? Would that tell us new facts about our universe?

The study of comets tells about the planet building materials that were in the cold regions of the early solar system. Among other things, this tells about bodies that delivered some of the water and carbon to Earth.

Question 1: What elements make up the dust particles?

Mostly O, Mg, Si, Fe and C with lesser amounts of Na, Al, S, Ca, Cr, Mn and Ni. All the other elements are less that 1% abundance. The composition is similar to that of the Sun for rock-forming elements.

Question 2: How and why is Ti + V + nitride so rare?

It is rare because Ti and V are very rare and only form the nitride at extremely high temperature in an odd gas that has a C/O ratio of nearly 1 - twice as high as the Sun.

Question 1: What materials and elements falls under the “standard” mix of nebular solids?

Mostly O, Mg, Si, Fe and C with lesser amounts of Na, Al, S, Ca, Cr, Mn and Ni. All the other elements are less that 1% abundance.

Question 2: What explains the traces of meteoritic materials found in the comet without being able to fall into any class of meteorites?

We believe the difference is that comets contain materials from many different regions of the early solar system while meteorites are dominated by locally made materials that retain regional properties. The comets contain a wider mix of materials.

Question 1: Do any of the comet samples contain carbonate and silicate rocks that could suggest any terrestrial life as there is here on earth?

Lots of silicates but we did not see any carbonates. Comets probably do contain carbonates that formed in other bodies or regions of a comet where liquid water existed long enough to alter silicates and make carbonates and other secondary minerals. Carbonates are common in some meteorites but very rare (at best) in the comet that we sampled. Carbonates in meteorites were made without any help from life.

Question 2: Is there any way to determine the origin of comets, that is, what celestial body they are derived from?

Generally comets are considered to be planetismals that larger bodies were made from. There might be some comets that are fragments of larger bodies but none of the visited comets appear to be fragments of much larger bodies. There are many bodies >100 km orbiting beyond Neptune and some comets are probably fragments of collisions of them.

Question 1: With all the types of comets out there, what type of comet would you find most intriguing and exciting to actually set foot on and why?

All comets are exciting. They are so hard to get to that any active comet is a great place to visit. I'm not sure that anyone would happy to set foot on a comet. You can see what happened when the European spacecraft Rosetta tried to land on a comet. The g force is practically zero, it is a very rough surface and you could easily be blown back into space by escaping gas.

Question 2: What do you think of Space X being able to land rockets now on ocean and land platforms and how do you see this impacting our ability to conduct research in space for the future?

I am not sure. Landing the first stage might (or might not be) be a money saver for missions putting things in low earth orbit, but probably not for a high-energy trajectory needed for a comet mission. On such a mission there is an unbelievable emphasis on keeping the mass down. Two things are needed for the future- affordable reliable rockets and larger ones.

Question 1: Is it possible to define a comet based solely on composition or is a comet defined by a combination of composition and behavior?

Comets are often described by their orbits (long and short period) and also by the composition of their volatiles. There should be a range of comets because they could formed over a broad range of distance from the Sun – beyond the snow line to the edge of the solar system. Many comets may have formed in the warmest ice-bearing regions and these are of interest because they plausibly could have delivered water to Earth with the right ratio of D/H.

Question 2: Is it possible to have a body that is somewhere between the accepted definition for a meteor and a comet, and what would it look like and how would it behave?

Meteors officially are things that glow in the sky as they enter the atmosphere. Most meteors seen in the night sky come from comets while most rocks that survive atmospheric entry to become meteorites (defined as rocks that hit the ground) come from asteroids. This strange result is related to selection effects. Most comet particles are weak and break up in the atmosphere while many of the asteroid rocks are strong enough to survive atmospheric entry.

Question 1: It was mentioned that the Stardust mission samples contained structures that may never be found in meteorites because they are destroyed during reentry. Can small rocks be found orbiting earth, not in any quantity like a ring but nonetheless present?

Amazingly enough there are rocks that do get trapped into orbits around Earth but they don't last very long before they they are perturbed elsewhere. They don't form a ring but they are there. Most of these are probably chunks of asteroids and not comets.

Question 2: Would they contain the same structures that are not present after reentry?

When rocks enter the atmosphere, their surfaces melt to form a thin fusion crust of glass but the interiors are usually not heated because there wasn't enough time for the heat to soak in. A good analogy is "baked alaska" a dessert that is melted on the outside but has ice cream on the inside.

Question 1: What was the process of choosing the Si aerogel for the capturer like, were there other capture options (/materials) and if so what made the Si aerogel the most appealing option?

We tried a number of things but silica aerogel won out because it was clear and was microporous on an incrediably fine scale. It was also very stable in space. It was a huge amount of work to make it the right size to fit into the collector. Another material we tried was a nanoporous polymer ring foam but it was not transparent. We also tried aerogel made from other materials.

Question 2: From the sounds of it Wild 2 was a target of opportunity. Are there future comet sample-return mission plans, possibly to comets that are non-Jupiter family comets like those out by Neptune?

Wild 2 was a great target because we could get to it with a Delta 2 rocket and back in less than 7 years. It also turns out that this comet is considered to have the youngest (less processed) of all the comets that have been visited. It would be great to have a sample return from beyond Neptune but this would be very expensive and take a very long time with launch vehicles that are presently available. The Pluto mission (New Horizons) is going to fly past some of these bodies but it cannot come back.

Question 1: If comets formed in the inner solar system environments, how could they have distinctly-made materials in their composition?

Comets formed in the outer solar system where ices such as water and CO could condense. Evidence from Stardust suggests that the rocky components were formed in the inner solar system where high temperature environments existed. The comet solids appear to be a sampling of many different inner solar system environments.

Question 2: If comets got transported outwards, why wouldn't we see asteroids transported as well to the outer solar system?

The comet rocky components were transported outward – we don’t know too much about the comets themselves. Some models suggest that comet could have been deflected over wide regions of the solar sytem. It is certain that some asteroids, those that have close encounters with planets, can be ejected into the outer solar system. When the planets formed, many planetismals should have been scattered – some out of the solar system entirely. An asteroid stored far from the Sun, would not be considered a comet if it was deflected close to the Sun because it would not contain ice.

Question 1: Is it possible for there to be some space debris that is within the ice of a comet that could also contain old rocket fuel, which could enhance a meteorite impact?

Comets spend most of their lives in the outer solar system and they are isolated from Earth, rockets and almost everything else. Another important property of comets is that they are self cleaning. Because they are losing so much mass to space, they are constantly exposing subsurface material that has been buried since the solar system formed.

Question 2: Since asteroids and comets orbit the sun, could there be any sediment that may have been captured by one of these small bodies from an ancient large meteorite impact or volcanic eruption?

Possible but unlikely because of the ans to question 1.

Question 1: Could the lack hydrated silicates be from the impact heat generated when the samples slammed into the aerogel?

This is always a worry but we shot hydrated silicates into aerogel at 6 km/s and they survived along as they were larger that a micron or so. Some of the most primitive meteorites contain large amounts of hydrated silicates but they appear to be rare in comets at best. The most primitive IDPs are dominated by anhydrous phases. A likely explanation for the difference is that ice in comets is lost by sublimation (direct ice to gas) while in asteroids, some original ice melts and the liquid water produced alters the original silicates.

Question 2: Could there be a more gentle way to capture comet tail samples, so they don't explode when they hit the aerogel?

The only way that I can think of is to use lower density aerogel. It is imaginable that you could charge the particles and use an electric field to decelerate them but I doubt that this would ever be practical. If you used low density gas, the particles would actually vaporize because all the energy would go into them. With aerogel, particles build up a shell around them that protects them to some extent.

Question 1: You mentioned that the silicon-based GEMS were glass with embedded metal and sulphides, and that collecting them with the aerogel damaged the samples. Has a new material been developed to capture GEMS without damaging them?

It would definitely help to use an aerogel made of something other that silica and use the lowest possible density. This is a tough problem and the best solution is just to collect them at lower velocity- a much more expensive mission.

Question 2: You mentioned that MnFe Olivine, Wild 2 Olivine, is formed over numerous environments, not just locally formed. What type of environments allow the formation of this type of Olivine?

Great question. Mn/Fe varies due to a number of nebular processes. One is that if a lot of the iron goes into metal then there is less to go into olivine. Mn only goes into the silicates, not metal, so the silicates that form will have higher Mn/Fe. Another factor is condensation, Fe condenses at a higher temperature than Mn so different regions of the early SS should have somewhat different Mn/Fe ratios in solids. Any processes that effects Fe differently than Mn will change the Mn/Fe ratio.

Question 1: Why are comets' orbits more unstable than other bodies in the solar system?

The are not so unstable when they are orbiting beyond Neptune but when the get perturbed on to planet crossing orbits they are very short lived. There are no stable orbit locations between Mercury and Neptune except for the regions that contain asteroids. Planet-crossing orbits are unstable and active comets that come into the inner SS are usally kicked out of the SS by close encounters with Jupiter. Active comets usually lose most of their volatiles after just a few hundred orbits which is even much shorter than their dynamic lifetimes limited by gravitational ejection..

Question 2: How much did it cost for the stardust fly by?

The entire mission was limited to 200 million in 2000 dollars. It would cost about 350 M if done today.

Question 1: How are the conditions for the inner and outer regions of the disk determined? Are the conditions based mostly on theory?

The conditions are based on theory, observation of protoplanetary disks around other stars and studying samples of the early solar system such as meteroites, interplanetary dust and samples returned from comets and asteroids.

Question 2: Do comets lose some of the volatile material as they get close enough to the sun? How would this affect the comet as it leaves the region?

Inside the orbit of Jupiter, comets lose great amounts of dust and gas. There is considerable discussion about the evolution of comets after many passages around the Sun. There is also interest of why many comets behave differently on the way out than they did on the way in. A complicating factor is that comets are spinning a one pole may be exposed to direct sunlight for months on the way in and then the other pole is exposed on the way out. Results from the Rosetta mission suggest that volatiles from solar heated regions can migrate to less active regions and recharge them.

Question 1: Would it ever be possible to mine a comet for rare minerals?

It is possible but comets are unlikly to contain many minerals that you would like to mine. They could be good for water or organics to be used in space projects but unlike planets like Earth, comets never had processes that could concentrate ores like copper, gold, iron, lithium, lead etc. Life on earth only reached the level of civilization that we have now because of terrestrial processes that made great concentrations of coal, oil, copper, iron etc. It would be much easier to mine an asteroid rather than a comet because of their more circular orbits. Many also contain metallic iron and contain percent levels of carbon and water (in hydrated silicates).

Question 2: What is the oldest mineral we have found from outer space?

The oldest minerals are isotopically anomalous presolar grains that are older that the 4.5678 by age of the solar system. The largest of these are SiC and they occur in sizes larger than 10µm.

Question 1: Does the composition of the comet sample you obtained support the general theory that Earth's water was delivered to Earth from comet impacts, or does the concentration of water in comets suggest that there might be something missing from this theory?

We collected rocky materials but no ice or even “water bearing” hydrated silicates. Comets certainly do deliver water and organics to Earth but the main argument that they are not the major source is the D/H ratio of observed comets is higher than Earth’s. It is likely that there was a class of warm-ice comets that formed near Jupiter and had D/H ratios similar to primitive meteorites and Earth.

Question 2: Is it possible that the sample that you showed (where no grain survived capture, but there was a large cavity present), is a consequence of sublimation from the heat of the impact? And if this is not possible, then how could you rule this possibility out?

The large cavity formed because the particle came apart and generated a lot of power at the top of the track. The energy actually melted the huge hole and is lined with silica that melts at about 1800C. I does contain many small grains that survived but it also contains comet stuff that dissolved into molten silica. It either contained a large fraction of submicron grains or material that was unstable to impact – perhaps organic material, fine grained hydrated materials or tiny glass fragments.

Question 1: I don’t understand how the comet starts way out there beyond the ice layer then comes into the solar system. Is it gravity? What pulls them in to the inner solar system?

They slowly orbit the Sun and their orbits change slightly due to gravitational tugs from planets or even the plane of the Galaxy if they are really far from the Sun. When they pass close enough to a planet they get major perturbations to larger or smaller orbits. Comet Wild 2 started beyond Neptune and most likely reached its present orbit between Mars and Jupiter after multiple perturbabtions by several of the the outer planets.

Question 2: You said that there is a super rare mineral that is found on the comet–what makes it rare? Is it the environment that allows this to form? A special element? Why does it form there and not here? Can we replicate it in the lab?

It is TiN and it contains titanium and often some vanadium – both rare elements. It forms at very high temperature (1800 K) but only in nebular envronments with C/O that is twice the solar value. Such a hot C-rich could exist close to the Sun where organic-rich materials had been vaporized to increase the C/O ratio.

Question 1: How does your understanding of electrical engineering guide you towards different conclusions in your research compared to other research and other PIs?

Engineers generally have a stronger focus on getting things like missions done on buget and schedule than scientists do. My Engr background certainly helped me interact with the engineers on the project who often have a somewhat dim view scientists that they consider to be undisclipined and constantly try to add complications to missions. From my balloon days, I had a fair amount of experience with hydrazine, explosive actuators and electronic controls – a this helped quite a bit.

Question 2: If you had to list complex life into stages from one to ten, with Earth's ribosomes and nuclei as ten, what stage of biogenics were discovered on Wild 2?

Wild 2 told us much about the rocky components of comets but only a little about the organics and nothing about ices. I think that the major input into making life-bearing planets is the finding that major solar system materials were mixed over great distances and that most presolar materials were destroyed. If the early solar system made something that was essential to life it was probably delivered to all the planets.

Question 1: You said during the talk that the original mission of Stardust was to collect interstellar dust and that the mission changed once people realized that there was a comet that one could travel behind. Are such mission changes common?

This change occurred before we sent out the original proposal. It is very rare to try to make major changes after a mission is proposed and selected. It takes a major problem for this to occur. Adding new initives is usually frowned because it usually leads to cost increases and increases in risk.

Question 2: Are all meteorite samples checked for presolar grains? It seems like that would be the best method to find such rare particles.

There are actually tens of thousands of meteorites and many are never actually analysed at all. People try to find the most primitive well preserved ones and search for presolar grains. Most presolar grains are submicron and usually found with a ion microprobe doing automated searches.

Question 1: What is the success rate of the aerogel catchement system? Do they ever fail?

It worked very well for 6 km/s solid silicate or suflide materials that were larger than about a micron. Smaller particles often were melted because heat had enough time to soak into the interiors. This capture process work better at lower velocity and poorer at higher veloctiy.

Question 2: The silica melted, what about the impacting material?

Often the outside of particles was coated with either melted or compressed aerogel. The magic of the capture process is the the crust of material picked up of the particle exteriors protected the interiors. Some small impactors were competely melted.

Question 1: Could you melt or somehow dissolve the AeroGel away to get a more thorough look at what was captured in it?

We have used hot HF vapor to remove aerogel in some situations. HF reacts with $SiO2$ to form $SiF4$ which is a gas and a little bit of water. If you heat the aerogel to its melting point you also hurt the samples in it because it takes temperatures >1800 to melt silica.

Question 2: Could there be some kind of contamination from the compounds in the Aerogel that somehow got disassociated from the Aerogel?

This is an issue. The aerogel has tiny bits of contaminant particles in it but usually they do not get in the way of the analysis of capture tracks except for trace elements. The aerogel contains a few percent carbon and this was a problem that we had to deal with.

Question 1: What is the difference in chemical element distribution between the early solar system and the current solar system?

The bulk composition of the solar system probably has remained the same except for radioactive isotopes that decay with time. The early SS contained 26Al that decayed within a few million years. Earth originally contained plutonium, and much more uranium, potassium and thorium that presently heats our interior.

Question 2: What are the phenomena that destroyed isotopically anomalous materials in the early solar system?

Most meteorites were heated in the early solar system and the abundance of presolar grains inversely correlates with the level of heating and transformation. Even presolar SiC can be destroyed by these processes.

Question 1: What effects can solar radiation have on the composition of bodies coming from out of the solar system?

They produce tracks in minerals that can be seen in electron microscopes, they produce isotopes and implant noble gas inside solid materials. All of these effects are used to measure radiation exposure.

Question 2: Is it possible to find in comets unknown material or minerals than those already found in Earth or meteorites?

Yes – many new minerals have been found in meteorites and interplanetary dust. Some of these form in environments that do not exist on Earth. We believe that the (Ti,V)N that we found in the comet has not been observed before.

Question 1: What would it mean if you had found hydrated silicates in the tracks?

It would be evidence that, like the parent body of carbon-rich meteorites, the comet had had liquid water inside it that altered anhydrous silicates to form hydrated silicates.

Question 2: What made your team choose aero gel to catch samples?

It was the only transparent material that could capture small partilcles at 6 km/s.

Question 1: What is your theory on why inner solar system materials where found in the comet? Is it similar to other scientists?

They are in the outer solar system because they were transported over great distinces either in the disk or above it. This is generally accepted although some have suggested that there might have been high temperature environments in the outer solar system that might have produced the high temperature materials that we found.

Question 2: Why is the surface of the comet Wild 2 different than that of other known comets?

We think that is because Wild 2 has spent less time in the inner solar system than the other visited comets. It has the roughest surface and it does not have large regions of "sediments" that are seen on other comets and probably are related to surface erosion.

Question 1: Mr. Brownlee discussed the difference between asteroids and comets. I have heard about the idea of asteroid mining for valuable minerals and volatiles. I was wondering, is comet mining a possibility?

Good question – it was answered in a previous question ☺

Question 2: Mr. Brownlee discussed calcium aluminum inclusions and the common minerals in them. What are some unexpected minerals that have been found in CAI'S?

We found most of the classical minerals common in CAIs. We also found tiny TiN and platinum nuggets that exist in meteorite CAIs but are rare.

Question 1: You mentioned that comets are surviving members of 30 Earth sized masses in the early solar system. Have the compositions of the comets been correlated, and how was that determined?

There is no bulk measurement of a comet compostion but for sure they are orders of magnitude richer in water, N and C than Earth. If there was 30 earth masses of icy-planetesimals then comets were the probably the most common solids in the early solar system.

Question 2: So, if I understand correctly, if we find a meteorite and determine it contains no evidence of hydrated silicas, we should not assume it never contained them because it is possible they did not survive the high speed entry to Earth?

Meteorite interiors are usually protected from atmospheric entry heat and hydrated silicates are well preserved. Most primitve meteorites contain hydrated silicates. Heating on the asteroidal parent body can destroy these phases. In some cases, parent body heating melted all the original phases.

Question 1: What would cause comets to be formed from a large array of distant materials compared to asteroids forming from regionally local materials?

Comet can form in any parts of the ice-bearing parts of the disk – beyond the snowline. This includes the mid region of the asteroid belt all the way to the edge of the disk. Asteroids formed close to the hot regions where rocks could form but comets formed in regions that were always cold. Formation of early solar system rocks required high temperature environments where original presolar grains could vaporize and dusk clumps could melt to form chondrules.

Question 2: What can the compositions of comets tell us about the early formation of the solar system?

The first generation solids (interstellar grains) were largely destroyed and solids were transported over great distances.

Question 1: The gel material is capturing small particles and leaving an entrance trail, but how is this trail (and the entire cell of gel) not smashed upon re-entering Earth? The payload supposedly was going faster than any other payload entering earth due to it coming from such a far distance, so upon impact the data should have been completely ruined. How can we trust the geometry of the gel's particle entry paths?

Aerogel is fragile but it can survive hundreds of g's acceleration – much greater than anything experienced by the sample return capsule. It was traveling past but slowed down fairly slowly. Unless they are cracked, the interiors of the aerogel tiles are prefectly preserved.

Question 2: It appeared as though only a few particles were even captured, so are we seeing the rarest material? How many particles would we need to capture on average to see this rare material?

We captured about a thousand particles. We have many small particles but we would like to have to have more larger ones – up to millimeter size- the size of chondrules and CAIs. This would take a much more expensive mission than Stardust.

Question 1: You mentioned that the payload's shield protected it from incoming fast moving particles, so I am wondering how the gel is able to easily stop the material when it is such an non-dense material, but the shield needs multiple layers and is penetrable.

The shield has a front hard material that breaks up projectiles. There is a space and then layers of ceramic fabric plus a back plate that stops surviving debris. The impact of a cm projectile at 6 km/s blasts a softball sized hole in the fabric sheets. The tests done were pretty impressive!

Question 2: Does the presence of olivine and pyroxene confirm a hydrous environment upon formation?

They are easily altered by liquid water and their survival indicates that they were stored in a dry environment. There was lots of water but it was ice that does not react with silicates and there was no liquid water.

Question 1: Why do comets have such unstable orbits?

See a previous answer. It is because active comets pass near planets and they are perturbed into orbits that hit planets, the sun or escape from the SS.

Question 2: Do you only analyze grains for oxygen isotopes, or are there other isotopic signatures that are used in comparing commets?

People have also measured D/H, 15N/14N, Cr, Mg, S and a few other elements. Oxygen is the most abundant element in rocks and it has very iteresting isotopic variations.

Question 1: How rare are cometary meteorites?

Some people think that there are no cometary meteorites, others have suggested that a few could be from comets. The strength of typical comet rocks – measured by the fragmentation of cometary meteors – is much smaller than any meteorite.

Question 2: In your talk you mentioned Jupiter-family comets. Are there other planet-family ones?

Yes but the main distinction is the difference between short period comets (6 yrs and usually go close to Jupiter) and long period comets. The long period comets usually come from the Oort cloud while the short period comets are most commonly believed to be derived from a distributing bodies orbiting just beyond Neptune.

Question 1: You mentioned that you couldn't get too close to the comet during your flyby in order to avoid damaging the spacecraft. Roughly how close is “too close”, and why?

The probability of hitting a rock larger than 1 cm that could destroy the spacecraft scales inversely with the flyby distance. It is safer to pass at greater distance but you get less sample. We probably could have flown as close as 150 km but with more risk. Even if we had flown much further away we could have been unlucky and hit a cm rock. Comet high speed flybys are a very risky business complicated by flares and jets of rocks and dust.

Question 2: Can you elaborate on the properties of the silica aerogel you used in the capture mechanism? For instance, how is it that such a low-density material is able to dissipate energy from 6km/s impacts?

Silica melts at the interface and most of the energy actually goes into the molten thin silica film flowing around the particle. The process is totally different from slowing down in a gas. The film of compressed and melted aerogel helps insolate the particle to some extent.

Question 1: What physical properties of aerogel allow it to slow such fast moving particles so quickly when the density of the material is so low?

The main thing is that is very low density and that its solid pieces are only a few atoms across.

Question 2: With the low particle densities of space how sure was the Stardust team that such a small collector would catch any particle of interest at all?

We modeled the dust emission from the comet as well as we could and we also scaled from actual measurements made at comet Halley in 1986. There was quite a bit of uncertainity in what the enivronment would be but we flew as close as we though that we could without major impact damage.