Random questions I have answered via email or on my old blog over the past five years (2009-2013).

Ben Moore, University of Zurich

Origin of water on Earth

“How did water form and end up on the planets and moons in different amounts?”

The origin of the elements on the planets and moons is a fascinating topic. To understand this we need to first understand a little about how the planets arise. The basic idea is that the forming Sun was surrounded by a hot gaseous disk with a mixture of all types of atoms. As this gas disk cooled, different compounds could begin to form. For example, at large distances from the Sun, carbon could bind with titanium or silicon. These larger molecules began to stick together and form clumps, rather like dust. Any atoms that remained in gaseous form was eventually blown away by the solar wind. The clumps collided and grew larger and larger until they began to attract and stick to each other via gravity. Eventually, lots of rocky asteroid and proto-planets formed.

Water can arise on Earth in a variety of ways which are still debated amongst researchers – here are the main ideas: The early solar system was also too hot near the Earths position for water molecules to form. But at the Earth-Sun distance, oxygen could condense with many elements, for example to form iron oxide. Hydrogen rich compounds such as serpentine can also form there. Thus, the proto-Earth would have contained a lot of H and O but locked into other compounds. The early Earth was hot – molten hot from its violent formation and internal radioactive heating – resulting in gases being released from its surface. Late giant impacts, such as that which led to the origin of our Moon, would also melt parts of the planets, heating the rock so hot that it vaporised causing an atmosphere of gases to form. In an atmosphere the temperatures and pressures are such that the H and O can bond together to form water.

At larger distances ices could condense, thus the distant asteroids and comets were ice rich. Some of these end up on eccentric Earth-crossing orbits and collided, also delivering water to its surface. In fact, this is also the most likely mechanism for the origin of carbon on Earth. The relative amounts of water and other compounds on the planets and moons therefore depends an awful lot on where they formed and on a rather chaotic/random collision history.

And to quickly answer the follow-up question: “why does the solvent for life have to be liquid water?”

I think that it doesn’t have to be liquid water. Certainly a liquid gives a medium within which early complex molecules can form – atoms can move around freely and stick together via intermolecular forces. This could also happen in other forms of liquid. Probably the most compelling reason that water is thought to be essential is that the one example of life that we know, relies on liquid water to survive.

Lifetime of black holes

“What is the expected life span of a stellar mass black hole?”

When a massive star ends its life after burning all its fuel via nuclear fusion, the central region collapses into a black hole that has the mass close to that of the Sun. The collapse releases a huge amount of energy – a supernova. A black hole is the name given to something that is so massive that even light cannot escape from its interior.

We don’t know a great deal about the internal structure of a black hole. Gravity has overcome all the electro-nuclear forces that we know hold atoms together, but this doesn’t mean that there is some as yet unknown physical process that prevents the collapse to a singularity.

So, how long does the black hole last? If Stephen Hawking is correct, black holes will slowly radiate away mass through a quantum mechanical processes involving ‘virtual particles’. A stellar mass black hole is expected to exist for a long long time, much longer than the age of our universe. Its difficult to comprehend how long; ~10^67 years compared to the age of the universe which is ~10^11 years.

However, virtual particles are a mathematical construct used to explain the properties of matter and the forces of nature on the smallest scales. This overall theory is very successful, one of the best tested theories that we have in science in fact, but the reality of virtual particles remains to be understood. They have never been directly ‘seen’ in an experiment since they can’t exist for a long enough period of time. If virtual particles are a reality then Hawking may be correct. But until we have a better understanding of quantum mechanics, or a detection of Hawking’s radiation, we can’t be sure that a black hole couldn’t last for eternity.

Planets in the habitable zone

“Finding all those exoplanets got me thinking – how many exoplanets with stable orbits (over millions of years) could there be in the habitable zone of a star? Expanding this question: Does the size/the type of the star change the size of the habitable zone and thus the number of exoplanets?”

The habitable zone around a star is the region at which a planet can orbit without its surface water freezing or boiling away. It’s quite a narrow zone – if our Earth were 10% closer to the Sun our oceans would boil away, if it were about 50% further away the oceans would freeze. However, this doesn’t mean that life could not evolve in other places, such as within Enceladus, the moon of Saturn which lies well outside the habitable zone. The icy surface of Enceladus hosts an interior ocean of warm water that is prevented from freezing by internal radioactivity and gravitational squeezing by Saturn.

Our computer simulations show that almost ever star should have about one planet in the habitable zone. For the details see here: http://adsabs.harvard.edu/abs/2010Icar..207..517M
There is rarely more than one planet in this region since they would be orbiting quite close together and perturb each other over long timescales. Most of the ~50 billion stars in our galaxy have a mass not too different from our Sun, so there should be plenty of life in our Galaxy.

How far away can we detect a 1km object

“I was wondering how close would an object approximately 1 km in length have to be before it could be detected by our most powerful/far-reaching telescope?”

If you are asking, “how far away could you **detect** a 1km object?”, this depends on its brightness, or how many photons it emits or reflects. In principle, you can detect a 1km object at the edge of our visible universe if it is bright enough, although it would appear as a point in space. The edge of the universe is not really an edge, its just the distance that light has traveled in the age of the universe. Since space is stretching over this time (13.7 billion years) the furthest you can possibly detect an object is about 50 billion light years.

If you are asking, “how far away can you **resolve** a 1km object?”, then take the resolving power of the Hubble Space Telescope as an example. It has a resolution of about 0.1 arcseconds, so it could resolve and measure a 1 km object that is about 4 million km away. It could resolve a 100 meter object on the surface of the Moon.

Technically, the answer also depends on the wavelength of the light that you are observing.

Bosons

“I realize that nuclear fusion that happens inside stars is of course due to intense heat and pressure, but are bosons affected by high temperatures (gluons , w and z bosons, or photons)?”

Bosons are subatomic particles that are responsible for transmitting the fundamental forces of nature, such as electromagnetism. They act like messenger particles when ‘normal atomic matter’ interacts. There are five basic bosonic particles: photons, gluons, the W, Z and Higgs bosons. All have been detected in experiments apart from the Higgs. Thats what the Large Hadron Collider is aiming to find!

In order to understand if bosons are affected under the conditions of high pressure and temperature, it is worth looking into the details of nuclear fusion in stars. This is the process that drives the vast energy output of the Sun and the process that creates ‘most’ of the atoms in your body.

One of the important nuclear fusion processes in our sun is the so called proton-proton reaction. This is a series of nuclear reactions that transforms hydrogen into helium. Of crucial importance for the proton-proton reaction is the weak interaction, which is another of the four fundamental interactions in physics, whose force is mediated by the heavy W and Z bosons. The starting point of the proton-proton reaction is the collision of two hydrogen nuclei (protons) that transform into a deuterium atom, plus a positron and a neutrino. (Deuterium is an isotope of hydrogen containing one proton and one neutron. A positron is the antiparticle of the electron.) Only the bosons of the weak interaction permit this reaction to occur. The next reaction in the chain of events is that the deuterium interacts with another hydrogen nucleus to create a light helium isotope and some photons. These reactions gives rise to considerable amounts of energy since the final helium atom has a total mass that is about 1% less than the sum of the individual hydrogen atoms. Einstein showed us that energy and mass are the same thing and that more precisely, energy = mass x a very large number. This is why the sun can shine for ten billion years.

These proton-proton chain reactions are very unlikely unless the conditions are somewhat extreme, for example at the center of a star. Higher temperatures lead to a larger average energy of the particles – they are moving faster. This means that they will collide more often. Furthermore, at higher pressure and densities, there are more particles to collide with. Thus the rate of the reactions mentioned above increases at higher temperatures and pressures. In fact, the reason that the Sun doesn't explode in a single giant fusion explosion is because the temperature and pressure at its core adjust themselves to maintain a stable equilibrium reaction rate.

Now I can finally answer your question! Whilst the rate of reactions would increase at higher temperatures and pressures, the outcome of the reactions that involve the bosons would not change. This is because inside stars, the W and Z bosons exist only as the virtual messenger particles. They appear and vanish during a remarkably small interval of time and they don't care how hot or dense the surrounding material is. This all changes if the conditions are really extreme. By extreme, imagine compressing our Sun into a volume the size of a cup of coffee. Then add into the same cup another ten billion stars or so. Yes, thats our entire Galaxy inside a coffee cup. Now we have something resembling the conditions that really existed a fraction of a second after the big bang occurred. At that epoch in the history of our universe, even bosons are affected by temperature and pressure… but thats another story.

Aliens

"Weird question or two if you don't mind. Do you believe in the existance of Extra Terrestrials? If you do what is one big concept you don't fully understand about them? I don't know who to contact over some freaky dreams of White Owls and Horses…Comment at any time."

I think that 'life' in some form, should exist on numerous other planetary systems, and one of the biggest puzzles to me is why there is no evidence for *any* 'intelligent life' in our Galaxy. One of the research projects we do in our Astrophysics group is to carry out supercomputer simulations to study the origin of the Earth. We find that most stars in our Galaxy should have about one rocky Earth-like planet in the 'habitable zone'. That's the region where the Earth can orbit a star without its water boiling away or freezing solid. Our Galaxy should contain billions of planets on which life can evolve.

We know from experience that intelligent life can evolve on a timescale of about 4.5 billion years, that's how old our solar system is. Intelligence is arbitrary to define, let's say that a species is intelligent when it has the capability to save its host planet from mass extinction from a giant asteroid impact. A true global ecosystem and we are almost there! Our Galaxy is twice as old as that, so if it happened here, there is no reason it couldn't have already happened throughout our Galaxy. It surely can't be the case that all civilisations wipe themselves out when they develop technology such as nuclear fusion – an energy source that could both erase most of the existing life as well as save it? In which case consider the potential of the human race: within 50 years we will have orbiting space missions that can measure the composition of the atmospheres of planets orbiting other stars that are several light years travel away, within a few hundred years we could send people to the nearest star, Alpha Centauri, within a few million years we could populate the entire Galaxy. All with known technology! If you think that is a long time, then compare it to the lengthy 150 million years that dinosaurs were at the top of the food chain.

There isn't any evidence for life beyond our solar system, via radio signals or Galactic restructuring. Neither is there any evidence we have been visited by 'aliens'. It's a shame, because I would have a few questions for them… 🙂
I don't think this helps with your dreams of owls and horses, but it might give you something to think about instead.

Solar Cycles

"I have heard and/or read that the upcoming height of the solar cycle is expected to be unusually strong. Curiously, is that true? And if so, why do we expect it to be so strong? I've wondered if that could be the main reason behind the launching of the Solar Dynamics Observatory."

The magnetic activity of the Sun varies on an average timescale of 11 years which can be measured by counting the number of sunspots. During 2008-2009 the solar activity was very low with a long period with no sunspots. The next peak in solar activity has been predicted to occur in May 2012, but it could be a year earlier or later. Unfortunately, since we don't understand why the solar cycle occurs, we can't really predict how strong the next one will be… but I'm hoping the next one is spectacularly strong since I want to travel see the Northern Lights (Aurora) from Iceland or Norway in 2012! The aim of the solar dynamics observatory is to monitor the magnetic activity of the sun over the peak of the solar cycle. Why is this all important? Because the Earth's climate and our communication systems are directly affected by variations in our Sun.

Intergalactic bean dip

I was asked for my favourite recipe. Here you go, it's a taste of the big bang with each atom guaranteed to have been individually engineered at the centre of a star over 4 billion years ago. A fusion of space and time that can be eaten with absolutely anything, but particularly good on toast or with chips.

5 large fresh tomatoes
equivalent of one tin of refried beans
a ripe avocado
2 large onions
yellow pepper
red pepper
fresh cilantro
garlic
jalapenos

Cut up the onions and peppers, jalapenos and fry them in a big pan with some vegetable oil. Wait exactly three minutes, this is the time after the big bang that the basic elements are created, then and add the garlic. Don’t overcook it – you want some texture left in the veggies. Add the refried beans, chopped tomatoes and half of the cilantro and keep it cooking for about five more minutes. At this point you will have something resembling a volcano, with bubbles erupting on the surface, possibly covering you in a thick brown superheated paste. Don’t panic. This is good. Like a musical composition, this dish evolves as you refine the ingredients and flavours. Add the chopped avocado, ground black pepper and salt. Now you should have something what will pour out of the pan. But it shouldn’t fall out like a waterfall, more like a lava flow. The final step is to cover with the remaining cilantro and enjoy, before all the atoms decay into neutrinos, positrons, pions and photons in about 10^{70} years.

The attraction of the moon

“*What role does the moon play in the evolution of life on Earth? Is the moon drifting away? How fast? How far would it have to drift before there is a noticeable change on Earth?”*

The moon and its significant role in the evolution of our Earth deserves an entire book, but let me summarise some of the most interesting parts:

The moon formed from a collision between a proto-planet (named ‘Theia’) and our proto-Earth about 4.5 billion years ago. The molten rocky debris scattered into orbit about the Earth coalesced into the moon – which is literally made in part from material that was once inside the Earth. This explains why the composition of the moon is very close to that of our planet.

Our moon is responsible for causing two tides in the ocean each day. This is because the pull of gravity from the moon is slightly stronger on the side of the Earth that is facing the moon at any point in time because that point is closer – the moon literally squishes the Earth into a shape like an egg, although we are talking about just a few meters in shape difference from a sphere. The ‘egg shape’ always points at the moon, so as the Earth spins, the entire planet is continuously being deformed and the ocean tides are due to the time difference it takes for the land and water to recover from this time dependent shape change. The water literally ‘sloshes’ over the two bulges on the Earth.

There are a couple of other effects that cause the rate of spin of the Earth to slow down and to cause the distance to the moon to increase with time. Due to a lag in the time it takes for the ‘egg shaped Earth’ to deform back to a sphere, the Earth and moon shapes do not point exactly at each other. There is whats called a ‘torque’ on the spin of the Earth and also a similar back-reaction on the moon. In addition, there is significant loss of energy due to heat generated by the compression and motion of material inside the Earth & the water sloshing over the Earth’s crust. Over time, the day has gotten a lot longer – billions of years ago, the day was just a few hours long! We can find evidence of this in the growth rate of fossilized coral which is sensitive to the length of the day and the lunar month.

The continuous deformation of the Earth’s shape is replicated on the moon due to the similar gravitational force of the Earth on the moon. The spin of the moon has also slowed down over time, so much so that we now only ever see one side of the moon! This is called ‘tidal locking’ in astrophysics language. In the distant future, the Earth will rotate exactly once every lunar month (which will be about 60 days long) so that one side of our planet will always be facing the moon – future generations living on the ‘dark side of the Earth’ may never see the moon for themselves. Don’t worry, this is not going to happen soon but in a few billions of years from now.

The implications for life are fascinating. When the moon formed it was much closer to the Earth – perhaps ten times closer. The moon moves away since the total energy of the Earth-moon system must be conserved. In fact by bouncing a strong laser onto mirrors left on the moons surface by the Apollo astronauts in the 60’s, we can measure the distance to the moon to an accuracy of about 1mm and we know that every year the moon moves about 4cm further from the Earth. The moon will eventually come to rest at about twice its current distance, when both the Earth and moon will be tidally locked, at which time the tides will not be strong enough for surfing, so enjoy the ocean whilst you can

It’s a simple calculation to show that the height of the tides is proportional to the distance to the moon^3, i.e. if the moon was once ten times closer, the ocean tides were 1000 times higher! So in the distant past, when water first appeared on Earth from the icy bombardment of comets, there were tidal waves nearly a km high crossing over the land every few hours. Not a good time for life to crawl out of the ocean!!!

There is another interesting fact about our moon. All the planets without their own moon, or with a small moon, are spinning chaotically. Small perturbations can cause their spin axis to change – dramatically and rapidly. Fortunately, our massive moon stabilises the spin axis of the Earth. Without our moon, on a short timescale, life evolving on the equator would have suddenly found itself at the new ‘North Pole’. Not a good situation for the first immobile life forms to face.

Enjoy our Moon, we wouldn’t be here without it.

Dark matters

“Please explain dark matter, in words that my 14 year old students will understand.”

Astronomers try to measure the mass of the universe through observations with telescopes and space satellites. This is important because (i) we want to understand what our universe is made of and (ii) how the universe evolves in the future depends on the amount of stuff present. We have known since the 1920’s the Universe is expanding at close to the speed of light, but will it ever stop?!

Now we know that everything is made of particles – the atoms in your bodies are made of electrons, protons and neutrons – literally billions and billions of them. But there are many other types of particles that we have detected that are sometimes very strange, but real. For example neutrinos are tiny particles travelling close to the speed of light that are streaming through your bodies and even through the entire Earth all the time! (Most of the neutrinos come from the sun which is a basically a giant nuclear fusion reactor.) They are very hard to detect because they are so small that most of them pass right through the spaces inside the atoms of our bodies! It’s interesting that the neutrino was predicted to exist by scientist Wolfgang Pauli in 1930 yet it wasn’t until 1956 that experiments became sensitive enough to detect them. The story of dark matter is similar…

When we observe the Universe it turns out that there is a lot more mass around than can be accounted for by summing up all the planets, stars and galaxies. We can measure mass in the Universe in many different ways and they all come up with the same result. I won’t go into those details here. We know this mass is not the same form as what we are made of since electrons, protons etc give off photons of light and we would see them. Even your bodies give off a faint glow of light in the infra-red (the heat from your body which we can easily detect). So whatever the missing mass is, it doesn't radiate light – so we call it 'dark matter'.

'Dark matter' is an unfortunate term since it conjures up thoughts of something very mysterious that scientists have made up to give themselves work. Indeed, we don't know much about these particles at all, however there are experiments around the world that are becoming sensitive enough to detect individual particles of dark matter – in a similar way as experiments finally observed the neutrino. It may take another ten years, but most scientists are confident that soon we will know a lot more about our Universe.

now, don't ask me about dark energy…

Life and love

"You are a scientist, what is love to you – just a chemical reaction? isn't there more to life than what we know from science?"

Love is a beautiful thing and a very powerful emotional feeling that can give us the most happiness as well as the most pain… I cannot claim to understand how our feelings work, or how our memories and senses lead to emotions - yet at the most basic level everything that takes place inside our heads is a result of chemical reactions; atoms and molecules storing and transferring information using electromagnetic signals. When we die this process stops and the cells decay and our memories die with us – we can only hope to have left others behind and touched their lives in some way such that their memories of us live on – for a while at least.

Is there more to "life" than just science? This is a good question. We understand almost everything about how our sun works – how it releases energy, how atoms are created via nuclear fusion at its center, yet we are a long way from understanding 'life'. Understanding how a star works is so much easier than understanding the nature of life & consciousness. A star, like our sun, involves well understood physical processes whereas understanding life requires an understanding of 'complex systems'. This is a field of research that attempts to understand how extremely complex behaviour emerges from a physical system that follows a small set of simple rules. Before i would appeal to non-scientific 'mystical' beliefs about souls, spirits or even god, I would have to have exhausted all the scientific avenues for explaining life.

What is the purpose?

"If the universe will end and all life will die then is our only

purpose to enjoy our short lives?”

Tough question. It’s difficult to be certain of anything, but it does seem that life cannot survive forever in our Universe, so it is important to make the most out of our short lives.

but perhaps there is more...

All life on our planet is still evolving, becoming ever more efficient at surviving and reproducing. Humans are no different in this way, however we have apparently become more skilled than many other animals at this process - in particular due to the capacity of our brain for logic and thought. I think that we do have the capability to answer fundamental questions, such as 'why the universe began' and 'how life originated'?

These questions may take another 1000 years to answer but they will give us a deeper understanding of why we are here. So as well as having fun and enjoying our short lives it seems that we have an additional capability & purpose - to understand our universe.

live life!