Face to Face

This section features conversations with personalities related to science, highlighting the factors and circumstances that guided them in making the career choice to be a scientist.

The Celestial Sphere that Bounced Back to Space

Sir Harold Kroto talks to Prasanna Venkhatesh V

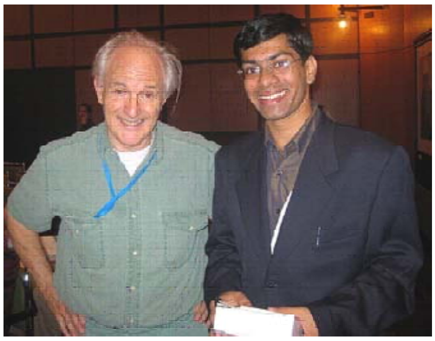
As is often the case in research, personality is more of a factor than sheer brilliance, and it needs doggedness of pursuit and tenacity of will.

– Francis Crick

Carbon is the backbone of the life on Earth and it forms the structural basis of all life forms. Carbon when combined with hydrogen, oxygen, nitrogen and phosphorus in different quantities and geometric arrangements, results in an immense potpourri of materials with enormously different properties. It is this unique feature to readily engage in the formation of chemical bonds with many other atoms and to itself that makes carbon the chemical basis of all known life. Structures as diverse as the cell membrane, proteins, sugars, and DNA are all carbon-based compounds. The likelihood that life throughout universe is carbon based is probably because of the fact that carbon is the fourth most abundant element in the universe by mass after hydrogen, helium, and oxygen. Occurrences of carbonaceous meteorites stand to testify our understanding of the organic-rich origin of our solar system.

During the late 70's, surprisingly long carbon chain molecules were discovered in the cold dark clouds of interstellar space by radio astronomical studies. This led to the subsequent studies which aimed at investigating the source of such carbon-based molecules. The results indicated that these carbon molecules were being blown out of red giants, carbon stars. This interested not only astronomers but also many chemists who where galvanized by the fact that space presented them a plethora of exotic molecules in a wide range of physio-chemical environments. During 1975–1978, Kroto along with Canadian astronomers discovered HC_5N, HC_7N and HC_9N molecules in the interstellar space. This was totally unexpected and it remained unclear at that time as how such species came to be present in the interstellar medium. The role of red giants in carbon-chain molecules became clear when IRC+10216, a spectacular infrared object which

Box 1. Sir Harold Walter Kroto



Photograph:
Left: Prof. Sir Harold Kroto
Right: Prasanna Venkhatesh

Harold Kroto was born in 1939 in Wisbech, Cambridgeshire, UK. He received his PhD in 1964 from University of Sheffield in Electronic Spectroscopy of free radicals and unstable intermediates in the gas phase. Subsequently he moved to Canada for his post-doctoral research at the National Research Council, Ottawa. In 1966 he moved to the Bell Laboratories in USA, where he studied the liquid phase intermolecular interactions by laser Raman Spectroscopy. In 1967 he was offered a faculty position at the University of Sussex and he became a Professor in 1985. He was elected Fellow of the Royal Society in 1990 and Royal Society Research Professor in 1991. He was knighted for his contributions to chemistry in 1996, and later that year, together with Robert Curl and Richard Smalley of Rice University, Houston, Texas, received the Nobel Prize in Chemistry for the discovery of C_{60}. In 2002 he became the President of the Royal Society of Chemistry and he is a foreign associate of the National Academy of Sciences (USA). Harry Kroto is currently Francis Eppes Professor at the Department of Chemistry and Biochemistry, Florida State University.

Besides his scientific accomplishments Prof. Harry Kroto is well known for his extraordinary thought-provoking popular lectures and he is an ardent advocate of Science Education. In most of his talks he gives great emphasis on scientific attitude among people and sustainability. He likes graphic designing and loves to interact with young children and students about science. In 1995 he founded the Vega Science Trust with an objective to preserve the scientific cultural heritage by recording scientists who have not only made outstanding contributions but also are outstanding communicators.

pumped vast quantities of chains and grains out into the space, was discovered. This later gave insights about the formation of carbon at the heart of second and subsequent generations of stars (*Figure* 1).

It was during 1984 that Prof. Richard Smalley of Rice University (one of the co-recipients of the 1996 Nobel Prize in Chemistry) developed a powerful laser vaporization cluster beam apparatus that vaporized the solid refractory target using a powerful pulsed laser in a helium-entrained plasma. This technique allowed studying the cluster of atoms generated in the plasma using a mass spectrometer. For more than six decades, astronomers and spectroscopists were puzzled by the famous Diffuse Interstellar Bands – a set of absorption features. It was believed that long carbon chains might be the carriers of the Diffuse Interstellar Bands. To prove this hypothesis one needed to simulate the exact conditions present in a carbon star and the technique developed

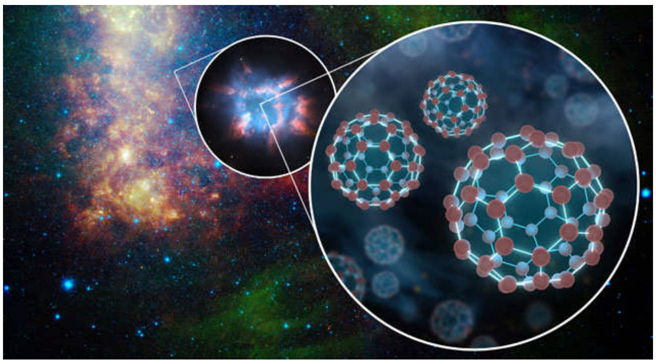


Figure 1. Fullerenes could have been formed in a planetary nebula, and then drifted out into space. Adapted from 'Buckyballs give clue to space mystery', RSC Publications. 22 July 2010. Image Copyright © NASA/ JPL-Caltech/T. Pyle (SSC). Hubble image copyright NASA

by Richard Smalley was ideal. Then in 1985 Harry Kroto collaborated with the Rice group to study the mechanism by which carbon nucleates under such conditions by using graphite as the target for the laser. When they carried out the experiments they did see carbon clusters as expected, but they noticed something unusual about the peak at 720 amu which went off the scale under various conditions. The peak corresponding to 720 amu is a cluster of 60 carbon atoms. When they did several experiments carbon preferred the 'Magical Number – 60' and a small fraction of 70 was also observed (*Figure* 2).

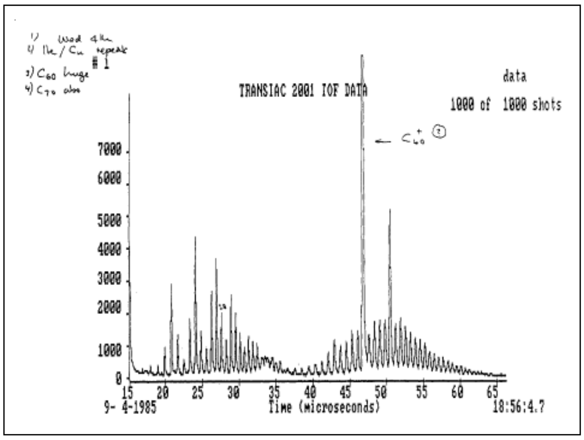
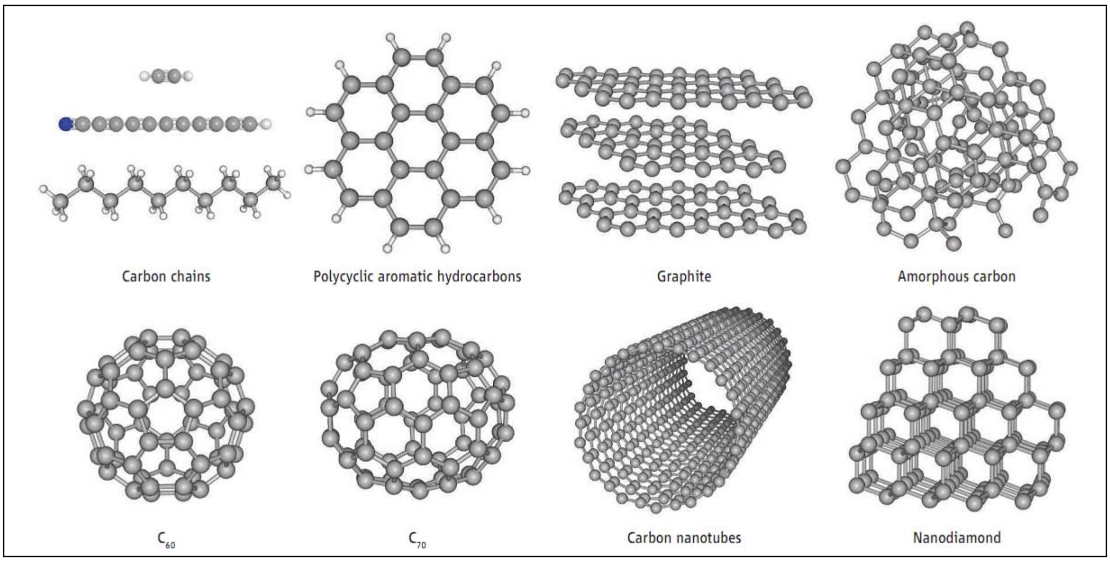


Figure 2. The time of flight mass spectrum of carbon clusters produced by laser vaporization of graphite. Reprinted with permission from H W Kroto *et al*. Copyright © 1991, American Chemical Society.

"What on earth could C_{60} be?" What kind of 60 carbon-atom structure might give a super-stable species? The Rice team and Kroto came to a consensus that it must be a caged molecule, like some sort of spheroid. Kroto's vivid memory about his visit to Buckminster Fuller's geodesic dome at EXPO '67 in Montreal helped him use the geodesic dome concepts to arrive at a solution for the C_{60} puzzle. Meanwhile Rick Smalley also concluded that C_{60} must be a soccer ball structure by constructing a paper model. They suggested that C_{60} must be a truncated icosahedron a polygon with 60 vertices and 32 faces, 12 of which are pentagonal and 20 hexagonal. They named it 'Buckminster Fullerene' and the results appeared in *Nature,* November 1985. Thus the quest for a rational explanation for the dominant line in the mass spectrum reached a climax, but it led to an outburst of sudden interest on C_{60} chemistry among the scientific community. Since these experiments were done on the gas phase, there was not a clear way to make C_{60} in large quantities to test its properties.

Five years after the discovery, in 1990, two astrophysicists (not chemists!) Wolfgang Kratschmer from Max Plank Institute für Kernphysik and Donald Huffman from University of Arizona came up with macroscopic quantities of fullerenes for experimental study while attempting to produce the analog of the interstellar dust in the laboratory. Thus a new field of carbon chemistry emerged from the discovery of $C_{60.}$ Scientists all around the world began to explore the immense potential of C_{60} in various fields ranging from superconductivity to polymers to electro-active materials. Researchers have spent 25 years exploring the remarkable properties of fullerenes and its cousin carbon nanotubes (discovered by Sumio Ijima). Most recently yet another form of carbon called 'Graphene' – a one-atom-thick flat sheet of carbon (essentially an unrolled nanotube), was recognized with the 2010 Nobel Prize in Physics (*Figure* 3). Ever since they had been discovered in 1985, it was hypothesized that C_{60} molecules might be present in space. What is more interesting is that J Cami and coworkers from Canada have found C_{60} and C_{70} molecules in young planetary nebulae using the Spitzer space telescope. Now that we know that bucky balls also exist in space, it opens a lot of opportunities for further research. As Harry

Figure 3. Different known forms of carbon allotropes. From Pascale Ehrenfreund and Bernard H Foing. Science, Vol.329, No.5996, pp.1159–1160, 3 September 2010.



Kroto noted, “It is the celestial sphere that fell to earth now bounced back!” The rich and exciting chemistry of bucky balls still continues to grow even after 25 years of its discovery.

What follows is an interview with Prof. Sir. Harry Kroto where he answers a wide range of questions posed to him.

PV: This year 2011 is being celebrated as the ‘International Year of Chemistry’ to commemorate the advancements in chemistry and its contributions to the well-being of humankind. ‘Chemistry is our life, our future!’ Your views on it?

HK: The whole modern world is dependent on chemistry and material sciences, materials engineering and all aspects of chemistry – from plastics and polymers to silicon chips, life-saving drugs and all other things of that nature. In the future it is going to be more vital because more and more issues that we address like sustainability and survival will require technical advances if we are going to survive. It will not be possible to maintain the present standard of living without major advances in materials and the development of new technologies. I think chemistry will be vital in those areas. We are so dependent on oil. As oil starts to become more and more difficult to obtain, we have to have major breakthroughs for the generation of energy from sources other than oil.

PV: What do you think of the cross fertilization of ideas in interdisciplinary sciences?

HK: Well I think that physics, chemistry, biology and engineering have been taught as separate subjects for far too long. People in university departments of engineering, for example, did not have sufficient overlap with people in chemistry and physics and biology. However, I think today there is more of an overlap, which is starting to break down the barriers between these disciplines. So we are seeing the overlap between biology and chemistry, biology and physics, biology and engineering. If you look more carefully, chemistry is often the bridging subject. Particularly, as we move towards the bottom-up assembly approach to make new materials, we see that nanotechnology, which I define as “atom by atom, molecule by molecule assembly of a complex and/or functional system”, is going to be the chemistry of the 21st century.

PV: In one of the interviews you have mentioned that it is good to change the traditional departmental structure from chemistry, physics, biology and engineering to a more overarching infrastructure by dividing them into molecular science (which subsumes molecular biology and condensed-matter physics) and atomic science (which includes high-energy physics and astrophysics).

HK: Absolutely. When I started with University of Sussex in 1967, there was a School for

Molecular Sciences; it was way ahead of its time in recognizing the importance of molecular/ condensed matter research as the basis of the technologies of the next century. As we become more and more proficient in creating more and more complex molecules, molecular sciences will become even more important. I think that the next generation of molecules will be sophisticated systems, in particular if we are focusing on molecular biology and medicine. We see that the enemies (viruses and bacteria) are complex systems and if we look at what we use against them in the hope of defending ourselves, they are relatively simple molecules. I think in the future as we become more and more proficient at building more and more complex molecular machines, we shall develop systems which are as sophisticated as the enemy.

If we look at catalysis in the body, it is not just a simple process. Enzymes which carry out catalysis in the body are more like complex molecular factories. We in the future can develop "catalysts" of that kind which are as sophisticated as enzymes. I think here is where the tremendous advance in the chemical sciences will be helpful. I think it is an exciting time which should be realized and we must definitely use it for the benefit of mankind and not for its detriment.

PV: Will we be able to answer questions on the origins of life on earth?

HK: I have no idea, but the more knowledge we have, the more likely that we will be able to understand how life started off. Now at least we know when it started approximately and what chemical systems were available at that time. I do not see why we shall not be able to understand that. But, as a scientist I am always aware that we cannot know everything exactly, we must always leave room for deeper understanding or else the human race cannot advance. I think it should be possible one day to find out crucial details of the origins of life in terms of chemistry. As we learn more and more, the better are the chances that we should be able to answer this question.

PV: You have been advocating about the scientific attitude of people. And you frequently mention, "It is worth reflecting on the fact that improvement was brought about by scientific/ technological advances based on doubt and questioning – evidence-dependent philosophies totally at variance with the belief-based concepts that underpin all mystical societal attitudes". Could you tell us something about that?

HK: Science is about evidence and without evidence anything goes. I am an atheist and humanist – I guess I prefer the term Freethinker – and I believe in secular humanitarian values. I think it's vital that in the future secularity defends the right of the individuals who do not believe in mythical or mystical entities. I see a clear conflict between science and belief. Science is about evidence and I think it is the only philosophical construct on which we can rely to determine TRUTH. We should always make a really careful analysis of the evidence on which certain claims are made. Children should not be educated in faith-based schools and I think young people deserve to be taught to recognize what is true and what is false. If they are not taught that way they will be misled and that is mostly the case at present. Most of them are misled on the basis of dogma and religious belief. I think this is dangerous, and we see every day the danger caused in some part of the world in the name of religious dogma.

I am working hard to inculcate the scientific attitude among young people. Obviously the language of science is not everything. Religious people see secularism as a threat to their authority. Well, some parents also think that many of the ethical values come only from religious education, but that's totally untrue. If you look you will find that many people who are involved in humanitarian work are atheistic. That does not mean that religion does not have any positive aspect. On the other hand we must not be blind to the dangers that religious dogma often poses. We see that most of the suicide bombers who blow themselves up justify their actions on some religious grounds. I really don't understand it. I am concerned about the negative aspects of religion, when they impinge on political issues as they do in many countries today. I am fairly comfortable with religious people who focus on humanitarian issues but will certainly argue strongly against those – 'holier than thou' individuals – who frequently maintain that religiosity is necessary for an ethical and humanitarian perspective.

PV: What can be done to create interest in science among young children?

HK: The interest and curiosity is already there! Several other problems have arisen now, as today's children are subjected to a world in which complex things like computers, CDs, DVDs, i-phones, i-pads and digital cameras and other new technologies abound. It is not possible for most young people to understand how these technologies work – they are too complex. If I look back on my own youth at the age of 9–10, I had a camera which I could open up and see almost everything. I could see through the lens, I could actually use chemicals to develop the photographs and I had the hands-on feel as to how they worked. Today we all have mobile phones, but most people who use them every day have no idea as how they work and indeed unfortunately few care. Even if the youngsters are curious, they cannot figure out how a mobile phone works when they open it up. You learn by fixing things with your hands, but the sad fact is that you can't fix anything nowadays. If the telephone did not work forty years back, you did not throw it away and get a new one. You opened it up and checked why it was not working, I did those things. In fact when I was young I made my own radio. I wanted a radio so I made it. Now that there are chips and ICs, it's not easy to work out what is going on and so there is a big problem. Of course some kids get through it but far too few. We have to work a lot harder in education and try to ensure that more can.

There is another big problem; the language of science today is mathematics – in particular algebra and it was only in the 16th and the 17th century that algebra was recognized as the language of science. So it is rather vital that all children get a good mathematical training and especially in algebra. This is very important. If you want to understand the culture of science you have to learn the language in which the Universe speaks and learning a new language is not easy. When you are young you learn a language very easily but as you get older it becomes more-and-more difficult. It is also true with mathematics. I think we probably have to work harder at getting young people to be fluent in mathematics particularly algebra at a very young age. However, it is not easy to see how we can improve the numbers of young people who know algebra well enough to understand and appreciate the beauty of the way the Universe works and so gain some intellectual benefit from the revelation.

PV: Is it like 'Math First – Biology Top' as Prof. Leon Lederman propounds?

HK: Yes, biology is very complex and it has been a major subject of deep scientific value since the development of molecular biology, particularly the discovery of DNA, X-ray crystallographic structures of hemoglobin and other molecular machines.

We now know how complex it is and our chemistry is still in the Stone Age. What I mean is that our chemistry is primitive because we are not able to develop a complex chemical system such as a single living cell. We do not have the technical ability to create molecules and systems that are as complex and sophisticated as those found in nature.

Take the example of hemoglobin; it's an amazing machine that is perfect for the transport of oxygen around the body. It captures oxygen in the lung and delivers it to where it needs to be released. We have not even started to build anything like that. We are even conceptually behind in creating any drug with that level of sophistication.

Think about penicillin which has saved many lives and made massive contributions to society; it is such a simple molecule by comparison, even though it was quite difficult to determine its structure and synthesize it. In fact, it is much simpler than many of the systems present in the body. The point that I am trying to make is that we are only at the first step; chemistry at the nanoscale is the next step for producing molecules that occur in Nature. I think the future of chemistry and nanotechnology in the medical area is to start to develop systems as complex as the enemies of the body.

PV: Could you please tell us about the story of "The Celestial Sphere that Fell to Earth"?

HK: I can tell you my part of the story. In the mid 70's, I was studying some carbon chain molecules in the laboratory with my colleague David Walton who was the world expert in creating these molecules. About the same time I started to take an interest in molecular radio astronomy and, together with Canadian astronomers, used radio telescopes to try to detect these carbon chain molecules in the space between the stars. About the end of the 70's and early 80's infrared radio astronomy had advanced and a number of interesting objects were observed in space; these were carbon-rich red giant stars which emitted radiation in the infrared and microwave regions of the spectrum. When radio astronomy was used to study these red giants, it was discovered that carbon chain molecules were being ejected. The element carbon is created inside a star by the triple alpha process in which three helium nuclei are squeezed together gravitationally to form a carbon nucleus and these stars basically blow them into space. I proposed the idea that carbon chains that we were seeing in the interstellar medium were actually produced in the stars and ejected and then spread out in the space where they were observed. This idea was not really accepted as a viable hypothesis at that time but I was certain that it was worth serious consideration.

Around the mid 80's I was visiting Bob Curl at Rice University (a friend of mine) and he told me to talk to Rick Smalley, as he was doing something interesting. When I saw Rick he explained how he was vaporizing metals and silicon and producing clusters using a laser. It struck me that if we could use this apparatus to study the vaporization of graphite, we might be able to see carbon chain molecules that come off the plasma. I could then use that as a justification for my idea that the carbon chains were made in stars. It is like simulating the conditions found in a carbon star. I went to Rice University to do the experiment in September 1985 along with the Rice University team, hoping to see carbon chains. In fact we did see carbon chains, but to our immense surprise we also detected the C_{60} molecule. We proposed that it should have a soccer ball structure. 'The Celestial Sphere that Fell to Earth' is a sort of a metaphor that we discovered it on the earth but I wanted to understand what was going on in space. That was 1985 and in 1990 it was proven to be a correct hypothesis as it indeed did have the soccer ball structure. In 1996 Bob, Rick, and I were awarded the Nobel Prize for that discovery. What is exciting is that just a few months ago astronomers have shown that the C_{60} molecule is actually coming out of some of these stars. One could say it fell to earth and bounced back again into space! That's very exciting.

PV: Most of your talks focus on sustainability and survival. You also mention that our only hope for survival rests on the shoulders of those who take survival and sustainability issues seriously – and do something about it.

HK: Obviously if you look at the problems that we face in sustainability and survival, things do not look very good. It now appears that our technologies may well have also catalyzed a mindless mass-production-driven plundering of the planet's resources. The evidence, such as

GHG effect and global warming, is disturbing. Many people do not seem to believe it or accept it and I think that we will have lots of problems in the future as far as sustainability is concerned.

We cannot be entirely sure but on the basis of what we know today things do not look promising. The evidence is pretty worrying; it is not conclusive as the situation is extremely complex but there is not too much doubt that we will have serious problems in sustaining the life-style that we have at present. Our children are facing problems; we need to now work on every possible front, on our social attitude – our political attitude – and I feel the only group which is taking these issues seriously is the scientific community. They are trying very hard to find alternative sources of energy and trying to harvest solar energy in a useful form. Whether there will be a technical solution I do not know – we can only hope as I do not see that society as a whole is taking these issues at all seriously. It's a massive problem for us to change our habits.

PV: You show dung beetle on Earth as a logo for sustainability and indicate that people could learn few lessons from the small creature that recycles the waste. Could you please elaborate on those lines?

HK: The 150,000 refrigerators I show dumped in a field is a very good example as how different our way of life now is from that before the technical revolution. In nature, recycling happens all the time. I showed the dung beetle as an example. I use it as a logo, indicating that we should now start to recycle our own waste like refrigerators, mobile phones, computers, etc., which are almost impossible to recycle. We have got to think in these terms and develop technologies which can allow us to recycle much more easily than is possible at the present time.

I am not very involved in green chemistry research, but I am very much involved in spreading awareness about the problems that we face. There is a limit to what I can do so I am focusing on education more than anything else. I am trying to explore the way in which the Internet can help improve the education of our young people. To some extent my message about sustainability is a part of that educational purpose.

PV: Your views on Education Policy?

HK: Far too many people who are in responsible positions do not understand science and technology; only a few of them do. My contribution is to try to improve education. What I am doing with the Internet is targeting teachers and trying to create a cache of educational material distributed all around the world and accessed globally through the Internet. I think it is possible and the idea here is to capture the genius of all the brilliant teachers in the world. It builds on the idea of the Wikipedia example. It's fantastic that all these people are altruistically giving their knowledge to the world through Wikipedia. Wherever there is a school, we should be able to give teachers access to the global cache of educational information.

PV: What about the data quality?

HK: Reliable quality has always been an issue. But this is a solvable problem. For the sciences, chemistry, physics and mathematics, the Wikipedia material is very good. You know bad books have always been written since time immemorial. The point is that there are ways of reviewing these sites and in the interest of society we can always have them checked for the data quality and information.

The way we can ensure a level of reliability is by working with the best universities and other accredited educational institutions[1]. I see websites everyday and I am in a position to asses them, but at the same time we have to teach our young people to be careful and not to be misled by some of the sites that give them false information.

A fairly obvious one is the debate in the US about the 'Origin of Species and Evolution'. If you think about it more carefully, Darwin's theory of evolution and discovery of fossils and carbon dating of these, made it impossible for one to believe in Genesis as it is written in the *Bible*. Life has been on earth for a long long time and it has evolved over a period of several billion years. Darwin was very well aware of the problems and was very careful in whatever he wrote. Many religious organizations believe that our knowledge about life on earth is completely inconsistent with all explanations of the origin of human beings based on science.

You should also note that it is in the interests of the religious institutions to insinuate that science is not reliable or has limitations. So you will find organizations such as 'The Discovery Institute' producing a website which looks like a scientific website, but as you read through it you realize that it says many things which are not correct. It is basically trying to systematically undermine science, not just evolution. If we progress further and further in science, we can see how immense our universe is and how miniscule we are in it. Science is a massive threat to the authority of the church and other religious institutions. You have to realize that the biggest business on the planet is religious industry; it is like a multi-national company with all its different facets. The religious people can only save their livelihood by claiming that science does not totally undermine the religious point of view. There are some scientists, very few good

[1] Prof. Kroto has been exploring the possibilities of teaching with the Internet, through a program called Global Education Outreach for Science Engineering and Technology (GEOSET). The key aim of this program is to catalyse the creation of a global network providing materials to the local and global need for much improved SET education. (www.geoset.info)
Also, to promote the popularity of science and to make information about science and scientists more available, Prof. Kroto has set up the Vega Science Trust; it contains many valuable lectures and interviews. (www.vega.org.uk)

ones, who claim they do not find a conflict between science and their belief. This is a personal view which conflicts with the general views of the vast majority of top scientists. Careful studies indicate that nine out of ten Fellows of the Royal Society, nine out of ten Members of the National Academy of Sciences and nine out of ten Science Nobel laureates are atheists/ freethinkers/agnostic. There is thus a massive conflict between religion and science in the minds of the top echelons of scientists. Just because 5% of them claim not to see a conflict does not mean there is none – in this case a democratically held view by those with real expertise in the field of deciding what is true is that the conflict is irresolvable. So science deeply undermines all religious doctrines – which of course are mutually undermining anyway. In fact, all that has happened now is that some of the religious groups say, "Ok, ok... God did not do it 5000 years ago; He did it before the Big Bang". Well, you know they had no evidence before and they have no evidence for this either.

A problem in the United States is that 92% of the top scientists are free thinkers/atheists and 99% of congress men and political leaders claim to be religious. The group that created the modern world with all the science and technology are the scientists. These technologies are the outcome of the philosophy of understanding what is true, but people in the government take the decision as to how to use the technology and so it is the politicians who become the policy makers in these areas. This is extremely disturbing. It's a problem in the way people think. If they accept something like religion on the basis of no evidence, the question is what else will they accept? For instance, are they going to accept that there are weapons of mass destruction in Iraq on the basis of no evidence as seems to have been the case? So a decision-making philosophy which requires no evidence is very disturbing. It is not that evidence will always ensure good decisions but that ignorance of evidence is certainly not good for those in positions of authority.

PV: What do you think is the coolest thing about science?

HK: I think the coolest thing about science is the discovery of something totally unexpected which is beautiful. That was the case with the C_{60} discovery. We certainly did not expect to see C_{60} and it was beautiful and it told us something new about our understanding of carbon chemistry.

PV: Science is …..

HK: Science is the only philosophy that the human race has created to decide with any degree of reliability as to what is true and what can be true; everything else is wishful thinking.

PV: Greatest source of inspiration?

HK: My close friend and Sussex University colleague and Chemistry Nobel Laureate Sir John (Kappa) Cornforth has been a great influence. Nothing has had a more profound influence on me than his deeply penetrating perspective – both positive and negative – on science and scientists! In his article 'Scientists as Citizens'[14], his concise penetrating comments, advice, humor, and culture appreciation make it mandatory reading not only for young scientists but everyone, particularly those with responsibility in the 21st century. It is the collected wisdom of a man who, though deaf since a teenager, was awarded the Nobel Prize. He is not only an iconic example for young people on how to triumph over severe disabilities but for all of us as it confronts scientists, and non-scientists, with our humanitarian and societal responsibilities. On communications and attitude and scientific thinking, I think Richard Feynman – whom I only saw in videos – was quite influential, particularly as to how to present ideas.

PV: What should be the attitude of a scientist towards a scientific investigation?

HK: My 4/5 rule is that when we make an observation that interests us which we are curious about, then we should make a hypothesis and that hypothesis should indicate several other avenues of investigation. If you follow those and 4/5 of the investigations confirm the hypothesis, then you are almost certainly right. And if only 1/5 is correct you are almost certainly wrong. If you take for instance classical mechanics, it is good enough to get us to the moon, but it is not good enough for GPS location as this needs Einstein's relativistic corrections. Therefore 4/5 is good enough in general. Let the 5th one be open and watch it as it may lead us to an advance. The important aspect of science is that it differs from all other philosophies like politics and religion in which the dogmas are closed and not open to any sort of further refinement. But science is always inherently open to refinements and it has a self-corrective feedback mechanisms. To leave yourself always open to question, to always have some doubt in your mind even when you think you are sure; you must be aware that in many cases you can't be absolutely certain and that there might be something that has been overlooked. That is Science!

PV: Scientists as explorers, scientists as problem solvers?

HK: Scientists are more than problem solvers; they solve problems but also seek to understand the physical world. Problem solving to a large extent is common sense. If you have a problem in the car you fix it and for that you don't really need to know how things work. But scientists look deeper into solving these problems in order to understand more about how Nature and the physical world work.

PV: Your message to young people.

HK: My message for young people or anyone, not just scientists, is that they should never do anything half-heartedly. If you are going to do an assignment, do it to the best of your ability. If you do not feel that you want to do it to the best of your ability, you should find some other area where you are prepared to apply yourself to the best of your ability. And if you have this attitude you will almost certainly be successful. My second message is to believe nothing and recognize that nothing can be considered to be true without evidence.

PV: That's really very kind of you to have alloted sometime for me. Thank you very much for the brilliant answers.

HK: Oh thanks, that's my pleasure.

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Suggested Reading

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