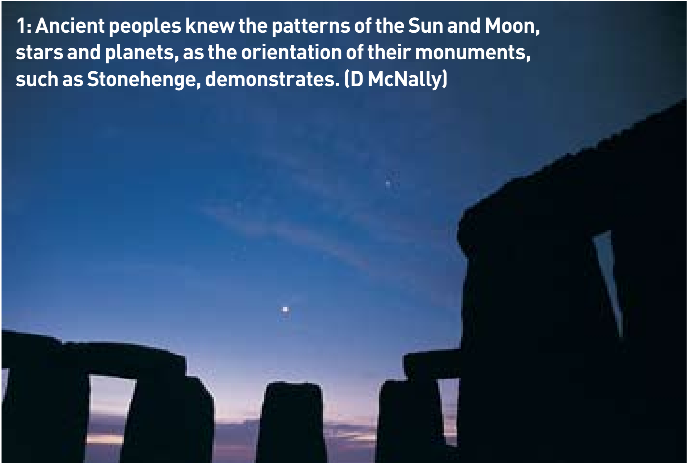


1: Ancient peoples knew the patterns of the Sun and Moon, stars and planets, as the orientation of their monuments, such as Stonehenge, demonstrates. (D McNally)

The impact of astronomy

Andy Fabian assesses the variety and scope of the impact astronomy has on science, technology and society – and why it is so hard to measure – in his Presidential Address 2010.

2: Glorious starry skies, as seen here at Gemini North, are now a rarity for most people. (Gemini Observatory)

During my Presidency of the Royal Astronomical Society I've had to deal with several different issues related to the impact of astronomy: the tensions between the scientific, societal and economic worth of what we do are the focus of this Presidential Address. I will outline the impact astronomy has had on our society historically, and at present, in terms of cultural, technological and economic benefits. I will also discuss why these benefits are so difficult to quantify in terms of the contribution made by basic science. I hope I will show that we all need to do what we can to promote the worth of our work in the wider world, at this difficult time for public spending.

Astronomy had a major impact on ancient peoples and it's pretty obvious why whenever you look up at a starry sky. Modern cities and lighting mean that few of us have a view of the dark sky (figure 2), so most people are not as aware of the night sky now as they used to be. The monuments that ancient peoples left behind stand as proof of their interest in, and knowledge of, astronomy (figure 1). Astronomy stimulated science in ancient societies. The cycles of the heavens, the predictability of the planets and the regularity of the motion of the Sun in the sky inspired people into thinking about time, about changes and ways to predict them, and started them thinking about simple physical laws – and about things which weren't so obvious, such as comets. I'm not going to talk about other sorts of impact in astronomy – when astronomers have something like an impending collision with an asteroid to tell the public about it can be very significant, but it's not what I'm talking about here.

Astronomy has driven important contributions to science and knowledge throughout history, from Copernicus dethroning the Earth from the centre of the universe, with Galileo taking that idea further, through Kepler's work on orbiting bodies, leading onto Newton, whose work was largely inspired by astronomical observations. There is also the obvious economic impact of astronomy in its role in navigation. Captain Cook's first voyage was an astronomical expedition, funded by the Royal Society, and was a major science project to make Transit of Venus observations from Tahiti. When the Admiralty got wind of it they put in some money that enabled the ship to be made a bit bigger and reminded Cook to look out for the postulated southern continent – Australia. Joseph Banks travelled on that voyage, much as Charles Darwin did on the *Beagle*, documenting the flora and fauna from Australia and Pacific islands. Astronomy was the first quantitative science (see "Astronomy: the master science" page 3.26).

Basic science

In the 20th century, Arthur Eddington's observations from Príncipe during the 1919 total solar eclipse made a huge contribution towards getting Einstein's new physics accepted and appreciated – and, in a sense, astronomy contributed indirectly to a lot of Einstein's work. Spectroscopy and nuclear fusion were also largely stimulated by astronomical studies. For example, the concept of electron degeneracy and complex ideas important in solid-state physics were first derived by Ralph Fowler for white dwarf stars, some years before they were established in solid-state physics.

Basic science continues to be useful in current times. The best source I can point you to is an article by Chris Llewellyn Smith on "The use of basic science" (http://www.jinr.ru/section.asp?sd_id=94). This is an excellent exposition of the reason why basic science matters. In it he says: "I shall argue that the search for fundamental knowledge motivated by curiosity is as useful as the search for solutions to specific problems. The reasons we have practical computers now and didn't have them a hundred years ago is not that, meanwhile, we have discovered the need for computers, it is because of discoveries in fundamental physics which underwrite modern electronics, developments in mathematical logic and the need of nuclear physicists in the 1930s to develop ways of counting particles." He cites many interesting examples. Many of you will know that the chairman of IBM in the 1950s thought that there was no need for more than six computers in the world, and that Rutherford thought that there was no

Astronomy: the master science

Astronomy is the oldest of the sciences in a simple taxonomic sense – such as recording eclipses, comets, or elongations of Venus for astrological purposes, as in Babylon and ancient China. But, more importantly, it was the first science to develop a mathematical and geometrical foundation and was also the first science to develop sophisticated instrumental procedures – using quadrants, armillary spheres and projection techniques within the 360° circle. This gave astronomy a firm basis for the collection and verification of precise data. Greek mathematical astronomy had its origins in the sixth century BC, while Hipparchus to Ptolemy (second century BC to second century AD) based theoretical astronomy upon observations made with instruments using 360° scales. This provided a valuable foundation for a public verification or falsification procedure for observational accuracies.

This geometrical and observational foundation would become crucial in creating (a) a public standard of credibility and (b) a clear relationship between instrumentation and mathematics. No other classical science – medicine, botany, natural history, animal studies, etc – had such a foundation, as they were based on visual taxonomy alone.

Medicine had its four-humour pathology, but therapeutics were still rooted in rule of thumb. And it stayed there to the 19th century. By 1846, Adams and LeVerrier could both calculate the position of Neptune, yet no-one had any realistic idea regarding what caused cholera or typhus! Chemistry was the first to develop a verifiable mathematical basis after Lavoisier, Dalton, Berthollet, Mendeleev, etc over the period 1785–1860 brought forth the ideas of atomic weights and the Periodic Table. Medicine began to develop a foundation with Virchow's Cellular Pathology (1858), Pasteur and Koch working on bacteria (1865–1880) and developed rapidly thereafter in tandem with organic chemistry. But not until Crick and Watson's geometry of the double helix of DNA in the 1950s did the biomedical sciences develop a comparable mathematical foundation.

I have described astronomy as the "master science", which created a procedural basis that the other sciences took 2000 years to catch up with.

Allan Chapman

use for nuclear physics, but there's also a very nice quote from a Director of Fermilab who was asked by a US governmental committee how much he thought Fermilab would contribute to the defence of the US. His response was that he thought it would contribute little to the defence of the US, but would contribute a lot to the reason why the US was worth defending. I strongly recommend this article.

The coming impact

A lot of the issues that have been concerning me stem from just four years ago, and the 2006 statement from the Department of Trade and Industry entitled "Increasing the economic impact of research councils". The issue of economic impact looms very large in British scientific life at the moment and it has generated a lot of tension. Many parts of this report consist of statements that everybody would agree with: "Science and innovations underpin the UK's position in the global economy … The UK needs to maintain its position as a world leader in high-value-added industries to ensure growth in our prosperity and quality of life." But elsewhere in this report, the position of our research councils is made clear. "Research councils have pivotal roles. They are increasing their emphasis on knowledge transfer and the economic impact of their work. They must increase that emphasis further without sacrificing the research emphasis for which we are rightly admired." It continues: "Chief executives of each research council are now responsible for the economic relevance of their programmes and for the impact of their spending." In other words there's a strong push from government and the Treasury down to the research councils to quantify their worth in terms of economic impact. Over the past couple of years we have managed to include societal and cultural impact as well as economic impact in these measures, but these are terribly difficult to quantify. What the government is really talking about is economic impact because this is something they think they can measure.

In 2008 Geoff Broomfield wrote in *Nature* (**453** 1150) on "Payback time" in which he looks at the changing landscape of science funding in Britain. "British scientists have never had it so good as in the last decade. Since 1998 government funding for the nation's seven research councils has nearly doubled in real terms to around £3bn and the boost has made the UK an attractive country for science … there's a growing concern in the research community that the increases are coming with a cost, that the Treasury is using its influence to erode the independence of the research councils which fund the majority of basic science in the UK. …the latest round of research council documents are littered with Treasury catchphrases such as 'economic competitiveness' and 'social impacts'. Some councils have begun favouring government initiatives over investigator-motivated projects and at one in particular, the Science and Technology Research Council, deep cuts have been made to fundamental fields in part to protect more commercially appealing programmes … The one council where subtlety is most lacking and where the Treasury's influence may be most damaging is the STFC which oversees large facilities for physics and astronomy." In other words, the pressure for economic impact was already there in 2008.

You will recall that we used to be in a research council with particle physics called PPARC which in 2007 was combined with the CCLRC which looks after all the large facilities. We were bunged together to form the STFC: a research council that was not properly funded to start with, then received a disastrously low amount of money in the Comprehensive Spending Review in 2007. We've never recovered the previous funding level because soon afterwards the UK and much of the world slipped into recession.

Shortly after the 2007 CSR announcement, the Chief Executive of STFC Keith Mason told researchers working in the more fundamental fields – that is, astronomy – that they needed to work harder to prove their economic worth. When we're told to do that, some of our colleagues say: "I think astronomy's worth doing, because it is really important to me, it's an important subject and therefore I don't need to prove its worth." Be that as it may, in the funding regime I have outlined here, we do have to establish the worth of our basic research.

An emphasis on economic impact matters to the average astronomer in the university research community because, when we are told that the money is going to be focused on areas that are going to be of most benefit to the UK economy, we struggle to explain how our work is going to change, say, the price of bananas. In part this is because our work seems distant from most people's everyday life. Even if we talk about something major, like an exploding star or a continental rift, it happens far away. If it took place in London, maybe people would listen. It is frequently stated that the emphasis on economic impact is not meant to detract from basic research. The documents always say that it will not disadvantage basic research, or stifle research creativity or scientific discovery – "of course, we're not going to change what's going on here, but we're also going to focus on these especially valuable things". There's a tension in all this that is difficult to resolve.

It's not a uniformly gloomy picture. One area where it is possible that things are going to be okay, even in the UK, is the space sector. At the moment the UK space industry is worth an estimated £6bn and we have a national strategy to grow it to £40bn. Even better, it turns out that the space sector has been completely unaffected by the recession. That's good news for space science, although quite how space research fits into that booming economy is not so obvious. But the potential for growth in UK space industries is clear, especially when looking at government spending on space in European countries and the US budgets. France has an enormous space programme, Germany also has a large one, Italy has quite a large budget – and the UK is lying next to Belgium, at the low end of the scale. This is an area where there is certainly large potential for expansion in the UK.

1: Research outputs in space science (inc. astronomy) 1999–2009

country	papers	citations	citns/ paper
USA	53561	961779	17.96
UK (not NI)	18288	330311	18.06
Germany	16905	279586	16.54
England	15376	270290	17.58
France	13519	187830	13.89
Italy	11485	172642	15.03
Japan	8423	107886	12.81
Canada	5469	102326	18.71
Netherlands	5604	100220	17.88
Spain	6709	88979	13.26
Australia	4786	83264	17.40
Chile	3188	57732	18.11
Scotland	2219	48429	21.82
Switzerland	2821	46973	16.65
Poland	2563	32362	12.63
Sweden	2065	30374	14.71
Israel	1510	29335	19.43
Denmark	1448	26156	18.06
Hungary	761	16925	22.24
Portugal	780	13258	17.00
Wales	693	11592	16.73

Data comes from ISI Thompson via Sciencewatch.com.

But there's another league table that is rather more worrying. This is a measure of national research success, shown in table 1, using data from May 2009 from the company ISI Thompson. The table shows countries ranked according to citations per paper, including the number of refereed research papers in space sciences (including astronomy) per country, together with the citations to those papers, aggregated over 10 years. An unfortunate thing about an American company like ISI Thompson is that they're not especially sensitive to the rest of the world and treat Wales, England and Scotland as separate countries – but that's good for Scotland, as they come top in terms of citations per paper! If you look at the list superficially, it gives a poor impression of us, especially as it came out initially ranked in terms of numbers of papers, with the USA first. But if you look at the figures in terms of the number of citations, the US is still at number one, with Germany second, and England at number three. If you add together England, Wales and Scotland (Northern Ireland was not included), we sit in second place, ahead of Germany. This means we are really number two in the world in space science, which here includes astronomy.

> "I cannot imagine that a comparable table for this decade, in 2019 or even 2014, will still have the UK as number two"

Unfortunately, with the cuts that are happening now, with the grants line cut by more than a third, and so on, I cannot imagine that a comparable table for this decade, in 2019 or even in 2014, will still have the UK as number two. We are being left behind by our scientific rivals, because Germany, France, Canada and others are putting a lot of money into their basic science. It is the UK that has chosen to leave basic science by the wayside.

Some spin-offs from astronomy

I also want to cover the issue of spin-offs. Does astronomy have spin-offs that one can talk about in terms of economic benefits? The answer is yes. Take CCDs. Astronomers did not discover CCDs: they were discovered serendipitously by people designing memory storage devices. They wanted to store electrons in each pixel, as we would put it, and the charge coupling was a way of shunting them around quickly in order to read the memory. What they found was that these devices worked rather differently depending on whether you had the light on or not: they had produced very sensitive light detectors. The early devices would have been useless in a camera, because they had all sorts of faults and quirks, but it was astronomers who spotted their potential and developed them. Now they are widely used, in the sense that almost everyone has a CCD in their phone. But astronomy tends not to get the credit for that development work.

And then there's wi-fi. An Australian astronomer, John O'Sullivan, who received the Australia Prize last year, discovered the methods we use to access wireless computer networks as part of his work as a radio astronomer, and the patent on this arose from his work. In another example, terahertz technology for security scanning uses ideas and techniques from submillimetre astronomy.

Active optics technology and ultra-sensitive detectors over the whole electromagnetic spectrum are two more areas where astronomy has led the development of more widely applicable techniques. Some of the most sensitive detectors come from astronomy because, to paraphrase Craig Mackay, astronomers usually can't do anything about the brightness of their source, so if they want to make the best images, they can't do what you would do in the lab – simply turn up the brightness of the source. The only way to improve the image is to improve the efficiency and properties of the detectors, or change the size of the telescope. Well, we push the size of telescopes as much as possible, but having got a telescope, you then have to go and push the detector. That's why, in terms of detectors, astronomy leads the world.

I could go on and on. There's a lot of radio signalling and radio communication technology that owes its background to astronomy, there are companies working on statistical inference, using techniques derived from astronomy, through data handling, image processing, etc. But very often you find that the astronomers never went into that field in order to make the economic impact. And if you had told them to do so in the first place, they probably wouldn't have done it. It's not why or how we do what we do.

You can do this analysis for your own subject area, any field in astronomy or any other basic science. In my area, X-ray astronomy was initiated by Riccardo Giacconi, and it won him a Nobel Prize. He was working at the company American Science and Engineering at the time. His biography on the AS&E website (http://www.as-e.com) concludes: "Giacconi's groundbreaking work on X-ray detection laid the foundation for AS&E's proprietary technology for counter-terrorism and security applications." Back in the 1970s it was very common to see AS&E printed on the security scanners that you put your bags through at the airport. Now you find that the X-ray detectors that scan whole trucks are made by AS&E. A lot of this successful spin-off came from the enormous synergy between X-ray astronomy and the techniques needed to develop these machines, to get the very best way to detect X-rays.

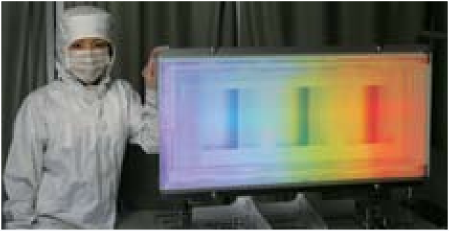
The Chandra X-Ray Observatory carries not only very fine telescopes but also an impressive set of gratings. Its high-energy transmission grating based on gold nanostructures was designed by Claude Canizares and Mark Schattenberg, and it produces very fine X-ray spectra. What these guys did in the 1980s and 1990s was to work out how to build very regular replicated structures that were able to diffract X-rays. Chandra's wonderful spectra eventually came out of that work. The spin-off from this is that Schattenberg now has his own company, as well as being a research astrophysicist at MIT. He's won awards and prizes and has gone on to develop a "nanoruler", the world's most precise grating patterning tool, which his company has used to make the world's largest diffraction grating. Their products are used in laser fusion, for example, and there are a variety of other applications that you can see on their website (http://www.plymouthgrating.com).

There are all sorts of examples of spin-offs from our science. The University of Leicester also takes X-ray detection seriously and makes lots of detectors, among them large-area high-resolution detectors with high efficiency and low background. If you go to the dentist nowadays, you often find that the dentist will put a CCD camera in your mouth. Dental X-ray imaging is connected with the techniques developed for astronomy – they don't use exactly the same techniques, but there's a synergy there, and this is one area developed by e2v (http://www.e2v.com). Medical imaging generally has a lot in common with astronomical imagery – apart from the scale. In general you don't want to make the X-ray source so intense that the sample is damaged (figure 4). The MPE team at Leicester also helped to build the high-resolution camera for Chandra and a spin-off from that which is used in the medical centre at Nottingham. They also make mini gamma-ray cameras. The team at Munich that was working on XMM-Newton, producing the pn detector, got another spin-off: out of designing and making that detector, they now have a company called PN Sensor (http://www.pnsensor.de) which makes radiation sensors for a wide variety of applications.

I'm pulling out these examples just to emphasize how common this is. If you go to any branch of astronomy, you will find there are many such examples. It's not why we do the astronomy in the first place, it's a spin-off, and although the benefits of this technology are clear to see, the cost of the work contributing to its development would be extremely difficult to determine.

And then of course we have direct applications of a lot of solar–terrestrial physics research (figure 5). In the next few years as the Sun ramps up in its cycle, solar activity could cause problems for satellite navigation and other technologies as we move towards solar maximum. There's a direct connection there between astronomy in the solar–terrestrial connection and things that will happen in people's own homes and lives.

I also want to emphasize one enormous impact that astronomy has – and here's today's *Metro* newspaper to highlight it. It's got a big picture of Saturn on one page, and a few pages further on there's a whole section about astronomy. There are very few sciences which are treated so well by the press as astronomy and that's because the public interest in astronomy and its role in society and in culture is one of our major impacts. But I have no idea how you quantify that impact. How do you put a number on a child reading today's *Metro* and being inspired to study science?



3: The High Energy Transmission Grating on the Chandra X-Ray Observatory (left) uses gold nanostructures to produce fine spectra. Developing this instrument led to a host of other detectors, and the nanoruler for making the largest high-precision gratings, such as this 91×42 cm grating made for laser pulse compression at Osaka University (above).

Can we measure impact?

The RAS has tried to consider economic impact seriously and we combined with the Institute of Physics to see if we could measure it. We wanted to connect a decision to put a pound into astronomy research with the pounds that later appear elsewhere as a result. We planned 12 case studies, starting with a pilot study of three, and commissioned a company, Oxford Economics, to carry it out. They attempted to trace three important technologies back to the underpinning scientific knowledge.

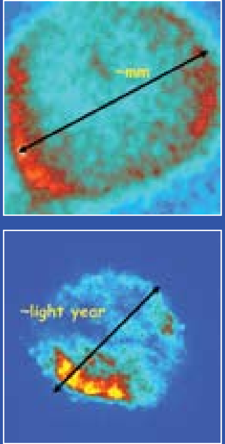
As a result of the pilot study we have concluded that we can't do it. More than that, we don't think it is do-able; Oxford Economics doesn't think it is do-able, either. So we're not continuing with the study. The problem is that one has to unravel a rich network of inter-relationships. It's very rare that somebody makes a discovery in the lab or on the bench and rushes out with it, crying "Eureka", directly to a company which then makes it straight into something that we are all willing to pay for. That is so extremely rare that it probably never happens. What does happen is that every scientific advance is part of an enormous international network. If you try to isolate the UK node in the network, you may isolate what you think is the UK contribution to the work, but you might miss out the fact that you've got to be part of the network to contribute and do the work in the first place. It is extremely difficult – we concluded impossible – to do such an analysis and have it mean anything at all. In addition, much of the way in which astronomy makes a contribution is very long term, for very basic science, and how you trace it through the decades is difficult. (Similar issues in the humanities are discussed by Stefan Collini in the *Times Literary Supplement* 13 Nov. 2009).This problem is very difficult to get across to government and the people who are insisting on changing the way in which we do our work. After a meeting with Science Minister Lord Drayson, one of his staff stressed to me the importance of quantitative measures of what we do. Impressing our peers in astronomy is not the important issue for the government. It is interested in getting products out of astronomy that the public want. This does happen but, as we've found, it is very difficult to quantify and, in general, happens on a much longer timescale than governments typically consider.

I think this is in part because how we do science is not understood. I'd like to outline how I think we do sciences – and I know that every scientist has their own ideas about this, but these are mine.

How astronomy works

First, I think that serendipity plays a very important role in discoveries in many sciences, including astronomy. Roberts (Roberts R 1989 *Serendipity: Accidental Discoveries in Science* Wiley, New York) writes on serendipity in science and argues, for example, that all important chemicals were discovered serendipitously. He mentions one important process, for synthetic indigo, in which the catalyst is mercury. The role of mercury was discovered because someone broke a thermometer while measuring the temperature, mercury was released, and the reaction went much faster. It's a wonderful book, full of such stories, and the same pattern is there in astronomy.

The trouble is, serendipity sounds like luck. Worse, it sounds like gambling, which is what banks do. We're not like that! We are much more directed, but we benefit from serendipity and the mental equivalent of averted vision. If you want to see the Andromeda Nebula, you'll struggle to see it if you look at it directly. You need to use averted vision, to look off to one side where your retina is more sensitive. You need to do that with your mind if you want to solve a



4: A 10^{19} difference in scale. (Top): 27 keV X-ray emission from a ^{125}I-labelled mouse tumour approximately 1 mm across, in the lab. (Institute of Cancer Research) (Bottom): 0.2–3.5 keV X-ray emission from the supernova remnant RCW103, roughly 1 light year across, taken by ROSAT's HRI camera. (University of Leicester)

5: A Yohkoh X-ray image of the Sun at 3–45Å from 1991. As we move away from solar minimum, flares and coronal mass ejections will become more frequent and powerful, putting at risk our satellite-based technology such as satnavs. (ISAS/NASA)

problem: keep it in your head and play around with it, keep coming at it from different directions, and suddenly the answer will become apparent. A certain amount of pressure from grant-writing, observing time proposal writing, reviewing papers and so on is helpful; I think it focuses the mind to have to set out priorities. But if you have to do enormous amounts of this, writing many many grant proposals because the success rate is very low, it becomes the enemy of thought – it becomes just a grind. We're getting towards that state now.

I suggest that the pressure to obtain economic impact from our work is going to have disastrous consequences for our international competitiveness in basic research. And I'm going to say something contentious, because I think it may be true. Why have there been no Nobel Prizes in physics to UK-based physicists for the past 30 years, since Neville Mott's award? I know that a UK physicist working abroad has won, and that a Nobel Prize has gone to someone working in the UK at the time of the research, but not to UK physicists working in the UK. I think that this is because in the Thatcher era there was an enormous emphasis on economic impact in physics, and many people I know in physics have one or two companies. None of them are driving round in Porsches, but none of them have Nobel Prizes either. I think if you are to do work of the quality that wins Nobel Prizes, which is admittedly rare and takes a very special person, then there's a low probability that the identical person will be successful as an entrepreneur. It is a very very low probability that one person would have the qualities to achieve both. Such people do exist but they are very rare. I think that too many physicists in the UK have been distracted by the drive to pursue work of economic impact. That's my theory, and it's not been tested, but it is based on observation.

I also want to wonder why we do astronomy? Why am I passionate about doing astronomy? Why have I and so many others devoted our careers to astronomy? It's not for economic impact – and certainly not for the economic impact on our individual lives! The mathematician GH Hardy has something to say on this. I read that, as a child, he used to spend time in church factorizing the hymn numbers, so he was certainly unusual. In later life he worked on the theory of numbers and he sounds to have been rather arrogant. "I have never done anything useful. No discovery of mine has made or is likely to make, directly or indirectly, the least difference to the amenity of the world." And yet we all know that digital security for credit cards is based on factorizing and prime numbers, just the field GH Hardy felt was so lacking in utility in his lifetime. None of his work was done with the direct intention that it would be useful – quite the opposite! And that's one thing worth bearing in mind in terms of how to motivate scientists: telling them they have got to do things that are economically impactful is not effective.

Serendipity

We tend to find things through serendipity. The term dates from Horace Walpole in 1754, in a letter where he mentioned a Persian fairy-tale about the three princes of Serendip who happened to stumble on odd things. It was defined then as "accidental sagacity", but the way I like to regard it comes from Pasteur in 1854, who said: "Chance favours the prepared mind." There are lots of things found serendipitously that could have been discovered by other people, but the person with the prepared mind – the person who is thinking about it properly – is the person who actually makes the discovery. A more modern summary by Glashow, a particle physicist, is: "Does science evolve through blind chance or intelligent design? Do you think before you look or look before you think?" (Glashow S L, http://tinyurl.com/glashow).

I want to use the idea of serendipity, plotted on axes of luck, preparedness and aim – although I have no idea what the units are and I'm not going to use a scale! Nevertheless, figure 6a shows some key points. The circle represents the conventional idea of discovery, the sort of thing you're taught at school where you're highly prepared and have a very definite aim, and as a result you find something out. I would put serendipity somewhere up along the luck–preparedness axes, and it's got the shape of the three-dimensional solid, because it does depend on aims as well as luck and preparedness. Most of the time in astronomy the astronomer has an aim, a reason to be looking in a particular direction, and it might even be related to what they discover. But they then stumble onto something, perhaps not completely unknown or completely different. It's a complex thing, but that's how a lot of discovery takes place in astronomy.

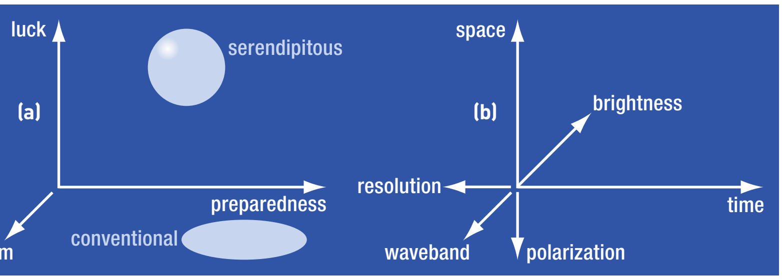
I also want to recommend a lovely book by Martin Harwit, which introduces the concept of discovery space I've used here (Harwit M 1981 *Cosmic Discovery: The Search, Scope, and Heritage of Astronomy* Basic Books, New York). I've represented six dimensions so I've used three at the top and three below in figure 6b, to show how astronomical discoveries are made. You can discover things in astronomy by looking deeper in space, by looking at fainter objects, by looking for longer times – or even shorter times if you want to discover pulsars – you can look in finer detail, with better spatial or spectral resolution, you can use other wavebands, such as X-rays, gamma rays, TeV, or polarization, and so on. That's how we tend to discover things, overall, although there are of course many ways to go about astronomy.

Much of my work is related to X-ray astronomy. X-rays were discovered serendipitously in 1895 by Roentgen, and they're called X-rays because the X means "I don't know what it is". In much the same way, we currently call dark matter "dark matter", and dark energy "dark energy", because we don't know what they are either. Most people are more familiar with X-ray absorption images, which are widely used in medicine, security and manufacturing, while emission images are more familiar in astronomy, for example in images of the Sun.

X-ray astronomy started entirely serendipitously. In 1962, Giacconi used a rocket to launch a detector to look for X-rays from the Moon and did not find any. Instead he and his colleagues found a much brighter source, Sco X-1, which started the field. We can compare the optical sky with the X-ray sky and they are very different. Most of the objects in the X-ray sky are accreting black holes, so we're seeing processes that we can't pick out from optical images. Pulsars were discovered serendipitously, as were magnetars. In 2004 an eruption on a magnetar produced an enormous flash of energy, the brightest thing that has ever been detected in astronomy, and the oscillations that followed the outburst ionized the Earth's atmosphere in a periodic manner, which led to the Earth's magnetic field oscillating. This object exploding on the other side of the galaxy twanged our whole magnetic field – in terms of impact, this is where astronomy can have an impact. If astrologers really wanted to prove that there was some connection between the stars and us, they really should be doing X-ray or gamma-ray astrology.

Astronomy has lots of examples of surprises recognized while observing other targets. Gravitational lenses were discovered by Dennis Walsh, Bob Carswell and Ray Weyman back in 1979. The first extrasolar planets were found by Michel Mayor and Didier Queloz, and here's an image by Marcy and Butler of a four-day period "hot Jupiter". Who expected to find an extrasolar planet with a period of four days and the mass of Jupiter or more? Fred Chaffee, the first Director of the Keck Telescopes, made a list of the most important discoveries made by the Keck telescopes in their first decade, and noted that none of them was part of the case for building the telescopes in the first place. Serendipity remains a key element in astronomical research. I certainly hope that the James Webb Space Telescope does not just do the work that was set out in the case for building it. I hope it makes lots of serendipitous discoveries – and I expect that it will. I hope the same for the enormous ground-based telescopes currently being planned.

6: Discovery space.



Real research for students

But one of the largest roles astronomy has is in inspiring students. The physical sciences don't appeal to everybody. Astronomy is a pure science with no societal impact, which means that it is also no threat to society – students can just concentrate on understanding the science. It tackles some of the largest and the most profound questions of all. In undergraduate degrees in physics, maths or astronomy, we are teaching students problem-solving, which can be applied in a wide variety of areas. We're making the prepared minds that Pasteur recognized. A major output of teaching and researching astronomy in universities is the body of students that pass through and into other areas where their scientific background contributes in so many ways.

We deal with both the fundamentals of the universe and its complexity. We're trying to find ways to understand that complexity, yet the subject still has a "small science" side. A graduate student can make a discovery or two during the research for their PhD. Many of our graduate students can do exciting and interesting research and I know from being in a graduate college, Darwin College at Cambridge, for nearly 30 years, where there are regular talks from graduate students in many disciplines, that in most other sciences the students are not making discoveries at the same rate as in astronomy. Here are four examples from my students in recent years – and I know that everyone who teaches PhD students will have similar examples.

Helen Russell, in her final year, discovered an odd-shaped cluster of galaxies in Chandra data; it's a bullet cluster, one of the most energetic events in the universe where two clusters of galaxies have collided and moved through each other. That's why it has such an unusual shape, with all the shocks that Helen observed. And the important thing about bullet clusters is that temporarily, you get the ordinary baryonic matter separated from the dark matter, so that you can learn a lot more about dark matter. This is the third such cluster discovered and Helen discovered it. She will work in Canada next year.

Becky Canning, a student in her second year, has been looking at NGC 1275. It has been known that there are star clusters 500 million years old in the centre of this galaxy; what Becky discovered is that one particular loop of star clusters are only 30–50 million years old. She has discovered something new about this galaxy.

Mary Erlund, working also with Katherine Blundell, was looking at the largest radio quasar in the universe, which has an X-ray hotspot. Mary proposed and was awarded time on the Chandra X-ray observatory to look at the detailed structure of the X-ray region. Combining this with other waveband images she found that the jet finished in a double shock structure – the X-ray hotspot – getting on for a megaparsec away from the core of the galaxy. Mary is now working in the nuclear power industry.

Dan Wilkins is a first-year student working on data from an active galaxy with an X-ray spectrum including a line arising from material swirling into the central black hole, where the extreme curvature of spacetime produces enormous gravitational redshifts. He was able to disentangle the signals to work out how much radiation comes from different distances from the black hole. He has made a pseudo-image – not a real image, of course – of the accretion flow around the black hole at various radii. Dan is the first to map the flow around a black hole in this way.

Conclusions

In summary, the most important thing that we need to get across to people in government is that the impact of our basic sciences is very difficult to measure in a quantitative and objective manner. How do you attribute contributions when they are part of a chain of collaborative work in an international multi-dimensional network, possibly lasting for decades? I don't know how to do it, but I do know that it is extremely difficult. The RAS and IoP tried to do it with professional economists, but maybe we didn't try hard enough. If anyone reading this has a great idea that can help here, please tell us.

But we also need to be clear that economic impact is not the motivating factor for most people in astronomy and space science. Curiously, it is not a major agenda item in most other countries and, in many of those countries, basic science is being boosted. I think that there is a pendulum issue to this; I believe in the cyclical theory of history, so I believe that we've seen it before and we're going to see it again in 20 years' time, so I'm hoping that maybe in 10 years' time impact will not be an issue. In the meantime, we have to do what we can.

So what can we do? We have to have a survival strategy, because I really do think we are at an important time in UK astronomy. We are on the edge of a cliff for funding, and therefore for research activity. We don't know what's going to happen after the general election. We have to continue to argue vigorously for the worth of our science and we have to campaign against it being judged on immediate economic impact. We are doing this, and I think we must continue. But we also have to be pragmatic; we've got to maintain research standards and quality. We have, of course, to continue outreach, getting things into the press as well as talking to schools, making sure that young people and adults can see that astronomy is a good thing.

Funding is shrinking, so the research we are going to accomplish is also going to shrink. How do we make the best of that? I think our peer review system is okay for small changes in funding, and it's probably okay for large upward changes in funding, but in this climate I think it's broken. It can't discriminate at the level we need when tough funding decisions hang on the outcome. We have to concentrate funding and support on projects and groups where we're significantly above critical mass in scientific productivity and leadership, with a healthy lineup of significant projects to achieve. Spreading the money to groups that are subcritical is not a good idea. We need, above all, to maintain intellectual leadership in our research. ●

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