A beautiful universe?

An Interview with the 2014 Shaw prize winner Professor John Peacock

(Cover photo: John Peacock in the Scottish Highlands: the summit of the 'Five Sisters of Kintail', April 2010)

Prof. John Peacock is a professor of Cosmology at the University of Edinburgh, and a Fellow of the Royal Society and the Royal Society of Edinburgh. He obtained his PhD from the University of Cambridge in 1981, and moved to and stayed in Edinburgh ever since. He won the prestigious Shaw Prize in 2014 for his work on the large-scale structure of the universe; he also wrote a classic book "Cosmological Physics". He is a keen mountaineer and an avid clarinet player. He answered our questions during his first trip to China in Sept. 2016.

1. **How did you get interested in astronomy?**

When I was young, I was interested in astronomy only as part of a general interest in science. I was 13 when Apollo landed on the Moon, and this was a perfect age to be inspired by such an event. I read science fiction, and was also influenced by the factual science writings of Isaac Asimov. But I was honestly more struck by the romance of space exploration than by any desire to spend hours using a telescope in my back garden. At school, I was drawn to chemistry because of the feeling of power in learning about atomic structure and how it generated the periodic table, and I went to university intending to be a chemist. But at Cambridge you study "Natural Sciences", which forces chemists to do a full course in physics in parallel during the first year, and by the end of this I realized I was much better suited to physics and mathematics. At the end of my physics degree, I looked at the available jobs and found none of them inspiring – so I decided to do a PhD. Most of the projects in the physics department seemed rather narrowly specialized, but the work of the radio astronomy group was more open-ended. So I finally became an astronomer, but this was never a goal – and I only became genuinely enthusiastic about this direction after I had chosen it. The key event was reading Michael Berry’s book “Principles of cosmology and gravitation” in the summer of 1977 before starting my PhD. The vision of using mathematics to describe the whole universe inspired me (it still does), and I became determined to find a project related to cosmology.

2. **What did you learn in Cambridge as a PhD student?**

Figure 1: Graduating with a fresh PhD from Cambridge (from left to right: his mother, father, girlfriend (wife since 1982) and John Peacock), taken in 1981.

I joined Martin Ryle’s radio astronomy group, so the focus was very much on understanding how radio interferometers operated. The mathematical basis of this is Fourier analysis (thinking of everything as a superposition of waves), which is of course important in physics anyway, but in radio astronomy all your thought processes are conditioned to use this tool. I think learning to think naturally and intuitively about everything via the Fourier viewpoint was helpful when I later came to work on large-scale structure. The cosmology related work in Ryle’s group was statistical: making surveys of radio sources. So I got a useful grounding in statistics. But really the most useful thing about being a PhD student in that system was the chance to refine and deepen my whole physics education via undergraduate teaching. The Cambridge system is based on the “supervision”, which means a group of perhaps just 2 students spending a few hours per week with an expert. But because there are so many undergraduates, PhD students have to do the bulk of this teaching. So there I was: only a few months after my final exams, having to pretend that I could answer any question about physics from these students. It was hard work, but it left me with much more confidence in my own knowledge.

3. **You made key contributions to the two degree survey that won you the Shaw prize**
    a. **How did the survey get started?**

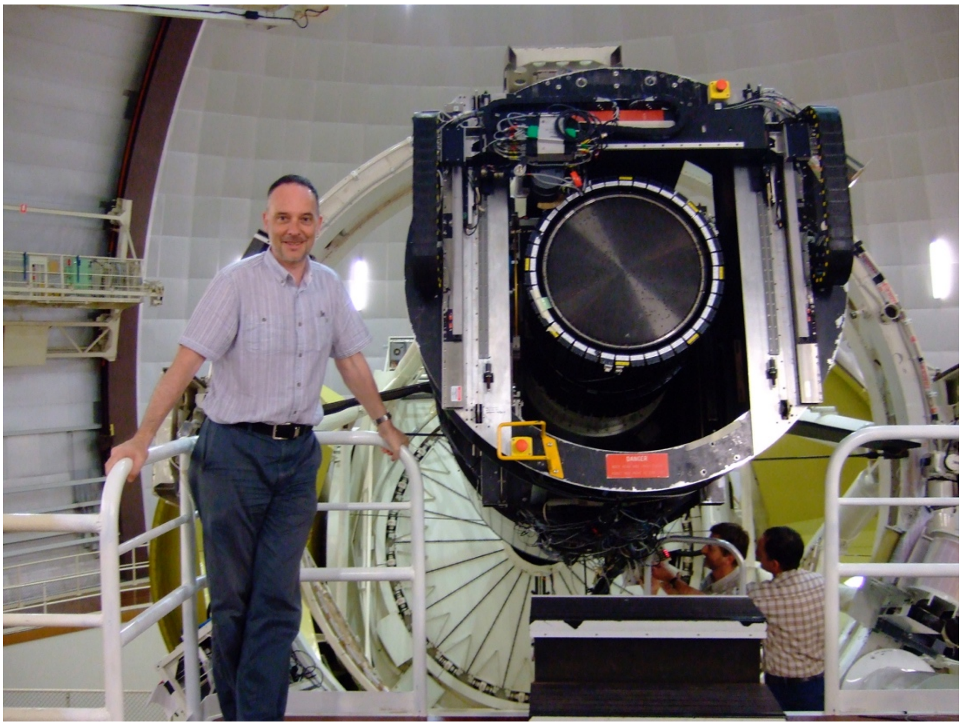

Figure 2: John Peacock with the 2dF fibre positioner at the prime focus of the Anglo-Australian Telescope (taken in 2012). This instrument measures light from 400 objects

simultaneously, opening the door to large statistical surveys of the galaxy distribution.

The 2dF (for acronyms, see the end of this article) Galaxy Redshift Survey started for me in about 1993. But the event that drove it was the decision to construct the 2-degree Field instrument on the Anglo-Australian Telescope. This happened in the late 1980s, and it was driven by the expertise in fibre-optic multiplex spectroscopy that the telescope had developed. It was clear this revolution would benefit from a wider field of view, and a push for this came from the joint UK-Australian Board that controlled the telescope. I later came to be a member of this body, and found it had a great deal of power and capability for independent action. The UK members in the late 1980s were Richard Ellis and Michael Rowan-Robinson, and I think they deserve a lot of credit for getting the 2dF project started. But most astronomers didn’t know what was coming, and the AAT wanted to educate them – so it sent Stuart Lumsden on a tour of the UK to generate interest. Stuart had been my PhD student, so I found out about the 2dF early on, and was able to join the first discussions about forming a survey consortium. This was initially led by Richard Ellis, but I took over Richard’s role in 1999 when he left the UK.

b. **People thought that the photometric accuracy of the photographic plates will be a serious issue for inferring the large scale structure, why was that not an issue?**

It was potentially an issue. The statistical power of a 3D galaxy survey is weakened if the depth varies over the sky in ways you don’t know. When we started out, there was not so much digital data to calibrate the photographic plates. So we relied on overlaps between the plates to try to put the photometry on a uniform scale. But after the survey had started, we realized this hadn’t quite succeeded. The new information came from 2MASS, which imaged the whole sky in the near-IR. Their shortest waveband was 1500 nm, whereas we were working at more like 450 nm, but we could see variations in the average optical-to-infrared colour from plate to plate. But this gave us the information needed to correct our photometry, and Shaun Cole & I put a lot of effort into doing this. So the depth of 2dFGRS is not uniform – but we know the non-uniformities, so we can allow for them.

c. **What have you learned in terms of the large-scale structure of the universe?**

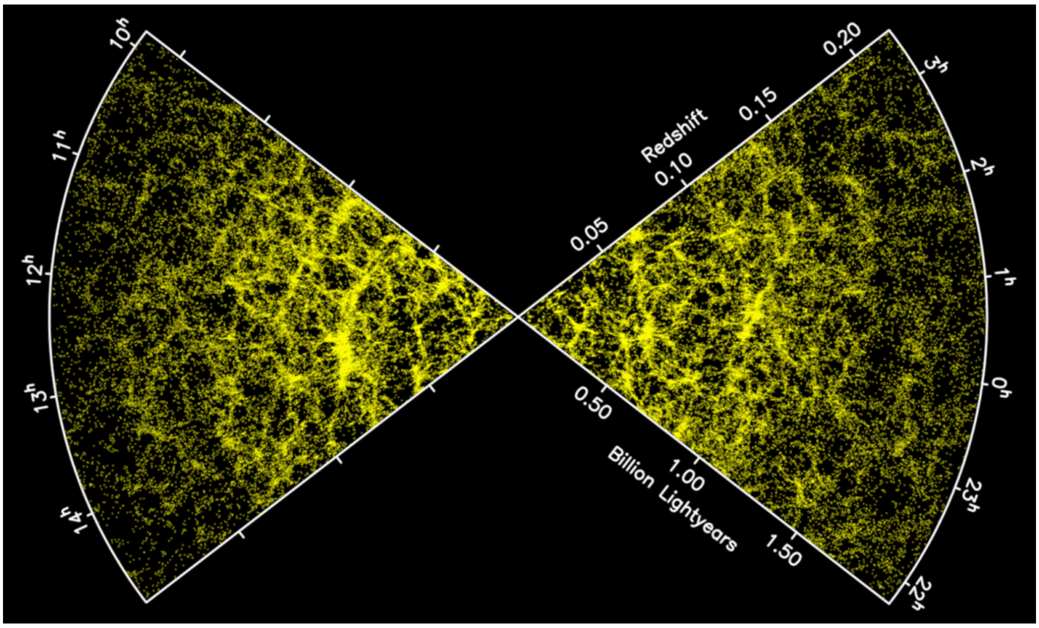

Fig. 3: The beautiful filamentary distribution of galaxies in two fan-shaped volumes as a function of distance (in units of billions of light years), as revealed by the 2dFGRS project, which measured the 3D positions of about 200,000 galaxies between 1997 and 2003. These patterns are the relics of tiny initial fluctuations, probably generated by quantum fluctuations when the whole universe was of microscopic size. Gravitational collapse of these initial seeds generates all complex

structure in the universe – leading ultimately to planets and people.

The 2dFGRS measured many things accurately for the first time. We measured how galaxy bias depended on colour and luminosity (alternatively, we measured how the galaxy luminosity function varies with environment). But the most fundamental impact came from measuring the form of galaxy clustering: the power spectrum and correlation function. The large-scale shape of the power spectrum is sensitive to the total matter density, which was still poorly known when we started. Our first power-spectrum paper, in 2001, combined this with the restricted CMB data of the time (WMAP results did not exist then) to favour the current Omega$_m$=0.3 model. Also in 2001, we published the first evidence for Baryon Acoustic Oscillations. This was very exciting, seeing the evidence for this signature for the very first time. I remember presenting this at the Texas meeting on relativistic astrophysics in December 2000: people were quite skeptical at the time, but we were right. We got an improved measurement in 2005 with our final dataset, at the same time that the American SDSS project detected BAO; a lot of people think that SDSS was the first detection, but that’s not how it happened. In another 2001 paper, we also made the first accurate measurements of Redshift-Space Distortions from the velocities associated with structure formation. These also depend on the matter density, and again favoured a low value. Today, thanks to WMAP and Planck, we know the density very well – but RSD is now used as a probe to tell us if we have the right theory of gravity. So two tools that 2dFGRS pioneered – BAO and RSD – really dominate modern cosmology.

4. **In terms of dark energy research, what do you think will be the main directions for the future? How will the nature of dark energy be revealed?**

I don’t know if it will be that easy to learn the nature of dark energy. We will try to measure if it varies with time, and indeed whether it can support inhomogeneities. So far, such results are null: at redshifts ~1, the dark energy density is the same as today, to within about 10%. If DE is indistinguishable from a cosmological constant, it’s hard to know what that really is: many quantum processes add to a ‘bare’ cosmological constant and you’re left with just one number. Even if we see some dynamics, it may not tell us much: if we saw that DE had declined by e.g. 3% since redshift 1, and we detected that at 10-sigma precision, it doesn’t tell us a lot more about the phenomenon – just that something is going on. I think a lot of people’s prejudice (mine, certainly) is that a cosmological constant will match the data, but it’s good to check. Future experiments will use BAO as a standard ruler to probe the distance-redshift relation and we will measure the growth of perturbations using RSD and gravitational lensing. This will be executed by colossal experiments costing over $100M and with 1000 astronomer participants: DESI, LSST, Euclid, WFIRST. I wish things could be done more simply, but the effects of changes in DE are small, and I don’t know another way to get sub-% precision. But this does feel like the next generation of experiments may be the end of the line – especially if no evolution is detected.

Figure 4: Professor Peacock is a professional-grade clarinet player. On the right he is leading the clarinet section of the Edinburgh Players Orchestra while rehearsing Richard Strauss. He is also a keen mountaineer who has conquered many mountain peaks in Scotland and elsewhere.

5. **I had theorists who swore to me that the matter density has to be critical because that is the simplest and most elegant universe. Now we discover that while the universe is flat, but the matter density is only 30% of the critical value, and the rest may be dark energy. Is our universe really ugly?**

When I first saw papers by Jim Peebles proposing a matter density Omega$_m$=0.3, a cosmological constant Omega$_v$ =0.7 (in 1983), I did indeed think this was ugly. For a long time, I was convinced that the vacuum density should be zero (for reasons explained in the next question). So then Omega$_m$=1 was an attractively simple model; but from about 1990 It seemed that the evidence was really against it. I then felt that a curved low-density model was the most attractive, although there were arguments against that from the lack of CMB fluctuations on small scales. But in those days only a few people had codes for CMB calculations, so it was hard to check these arguments. Things were further confused when the first Supernova papers (in 1996) mistakenly claimed to rule out vacuum-dominated models. So it was only when the Supernova people changed their position (an event they don’t want people to remember) that I decided there was too much evidence in favour of a cosmological constant, and so one had to accept it – this was in 1998. This outcome is, if not ugly, certainly complicated. There is a unique time when the universe switches from being matter dominated to being vacuum dominated, and it is a challenge to understand why this transition is happening now.

6. **What is your opinion of the multiverse? Is empirical test becoming unnecessary as the mathematical beauty may become more and more important?**

Figure 5: an imaginary multiverse
(image from http://msnlv.com/multiverse.html)

As I said above, there are several problems with a cosmological constant, or a non-zero density of the vacuum. The problem is not to understand how the density can be non-zero, but why it is so small. Quantum corrections should induce a physical vacuum density, which diverges if you allow infinitely energetic virtual particles. So new physics must cut this divergence off: at an energy scale of at least 10 TeV, since no new physics has been seen at the LHC. But the energy scale of the cosmological constant is meV – 16 powers of 10 smaller. You can argue that this is just a coincidental cancellation between various contributions to the vacuum density, or that some principle acts to prevent large values. Since we also have to explain why the vacuum is just becoming important as we observe the universe, this is a strong hint that observer selection could be important: so-called ‘anthropic’ reasoning. This argument was set out beautifully by Steven Weinberg in 1987: a large vacuum density suppresses the growth of structure, leading to fewer galaxies and fewer observers. In this framework, one can calculate the probability distribution of the vacuum density seen by a typical observer, and the actual value is consistent with being drawn from this distribution. Thus the anthropic prediction is subject to empirical test – although it is hard to make this test any sharper. Now, does this reasoning require a multiverse? We talk about the probability of a given vacuum density, and the meaning of this is easy to understand if there is an actual ensemble of universes with different vacuua. But Bayesian statistics allow you to discuss probabilities without there being an ensemble: given a fair coin, you can say P(heads)=0.5 without needing to toss the coin even once. So if you believe anthropic reasoning works, it is hard to move from there to say you have proved that a multiverse exists. But with a coin you know heads and tails are both possible. So in the same way, there must be physics that permits different values of the vacuum density to exist. The challenge will be to find and explore this physics – which can be done in this universe, whether or not other universes exist.

7. **Any major impact on your research in terms of the UK’s decision to leave the EU?**

Figure 6: UK voted to leave the EU in a referendum on June 23, 2016 (image credit: http://www.bbc.co.uk/news/uk-politics-32810887).

This is a depressing situation, and not a good advert for democracy. People in the UK were asked to answer a question without really knowing what the implications of a “leave” decision would be. The question should not have been asked in such a vague way, and I hope (for non-scientific reasons) that the issue can be revisited as the implications are clarified. This is not to say I regard the matter as trivial: unrestricted migration does cause a lot of problems, and I think maybe Europe adopted this model too easily. Still, the price of gaining control over migration into the UK may be too high, and people should be allowed to decide what to do once the price is known. But as for science, the direct personal impact on me will be minimal. I have an ERC research grant that runs until the end of 2020, and this money is guaranteed even if the UK managed to leave the EU by 2020 (which I doubt). But the 2nd-order risks are still serious: in future, good EU researchers may decide that Britain is not a country that they want to come to, so we would hire less good postdocs and faculty and our future quality would suffer. In the worst case, our economy might suffer to the point that we could fail to participate in international telescope projects. But the lesson of events so far is that life has continued much the same – so I expect any impact of this vote to arrive slowly and thus be mixed in with many other factors, meaning we may never be sure what effect the vote did have.

8. **What is your general impression of Chinese astronomy so far?**

   I already knew that many Chinese astronomers were highly active in cosmology, and my trip let me meet some of the new generation of young researchers in this field. In the areas of astronomy where I am knowledgeable, it seems that Chinese interests cover all the important areas, with a balance between theory, numerics and statistical data analysis that is not so different from the West, and where the quality of the work being performed is competitive. It’s hard for me to make broader statements, especially regarding fields where I am not active. The balance of interests must reflect access to facilities to some extent, so probably there are proportionally fewer Chinese working on high-redshift galaxies, for example, simply because it is harder to gain access to HST.

9. **Any final thoughts for our Chinese audience?**

   It’s clear that Chinese astronomy is still building up rapidly. I was aware of high-profile observatory projects such as LAMOST and FAST; the latter in particular has received a lot of publicity in the West, and it has impressed people to see China building the world’s leading facility of a given type. I presume that more such projects will follow. Before my visit, I was perhaps surprised that China did not have a more active programme in space astronomy, especially given its presence in manned space exploration. However, I have now heard a lot about new proposed projects, and I can see that this is likely to change. But the most important trend is the simplest: I wasn’t aware of the sheer scale on which China is creating new university faculty jobs. Science advances through the creativity of bright young people, and your investment in these new minds is bound to yield an exciting return in the years to come.

Acronyms used in the text:

- 2dF survey: two degree field survey
- 2MASS: The Two Micron All-Sky Survey
- DESI: Dark Energy Spectroscopic Instrument
- ERC: European Research Council
- Euclid: An optical/IR space satellite by the European Space Agency
- FAST: Five-hundred-meter Aperture Spherical radio Telescope, located in Guizhou province, China
- HST: Hubble Space Telescope
- LAMOST: Large sky Area Multi-Object fiber Spectroscopic Telescope, a Chinese mega-project LHC: Large Hadron Collider
- LSST: Large Synoptic Survey Telescope
- RSD: Redshift-Space Distortion
- SDSS: Sloan Digital Sky Survey
- WFIRST: Wide Field Infrared Survey Telescope
- WMAP：Wilkinson Microwave Anisotropy Probe