Institution:
University of Cambridge

Unit of Assessment:
UoA10

Title of case study:
Cosmological Constants

1. Summary of the impact (indicative maximum 100 words)

This case describes the impact of Professor John D. Barrow's research into the value of the cosmological constant and the constants of physics. The impact occurred through extensive engagement with the public via talks and public lectures, online talks and articles, newspaper and magazine articles, books and radio broadcasts. The engagement led to widespread public interest and increased public discourse in the UK and beyond, the impact being especially strong in Italy. The research has inspired young people, teachers and the general public internationally to follow cosmological developments.

2. Underpinning research (indicative maximum 500 words)

The Nobel-prize winning discovery of the acceleration of the Universe in 1998, and its attribution to the presence of a non-zero cosmological constant in the law of gravity, led to an effort by cosmologists to understand its very unusual small value (10^{-121} in natural 'Planck' units). This is the biggest problem in fundamental physics. The best effort before this to 'explain' it was the anthropic bound, first found by Professor Barrow (Professor of Mathematical Sciences, University of Cambridge Department of Applied Mathematics and Theoretical Physics since 1999) in 1986, long before the observation of the cosmic acceleration, which showed that a value larger than about 10^{-120} would have prevented the formation of galaxies and stars in the past. Barrow's work provided a new way to understand the unusual observed value for the cosmological constant. More importantly, it also precisely predicted the expected sign and value of the parameter that determines the fraction of the energy density in the universe that contributes to the curvature of space. This is a consequence of the prediction of the value of the cosmological constant's value and takes into account the small variations in the curvature of space created by the presence of galaxies and clusters. This numerical prediction remains consistent with the detailed Planck satellite mission data first announced in April 2013, with further detail expected in the next 12 months.

This research was the first to make a definite prediction of the value of the cosmological constant. It was able to do this by a small modification to the process which derives Einstein's equations of general relativity by a variational principle. It includes only variations that are causally connected to us in space and time. This creates an extra constraint equation, in addition to Einstein's classic equations. When evaluated in our universe, allowing for the presence of galaxies, it leads to a numerical deduction of the allowed value of the cosmological constant as the reciprocal of the square of the age of the universe in Planck units (10^{-121}) and also predicts the curvature parameter of the universe to -0.0055.

Barrow and collaborators have followed a long programme of observational and theoretical work in the period from 1999 to the present which has used observations of quasars to establish, first in 1998, the strongest limits on any allowed time variation of certain constants of nature, and then in 1999 and 2001, to find the first evidence for a very slow variation of the fine structure constant. This variation was too small to be detectable in any laboratory experiment. This research has led to the development of a whole field of astronomical study of varying constants that did not exist beforehand. It showed how astronomical observations can give more precise information about fundamental physics than laboratory experiments. This is possible because of the enormous time that light has spent travelling from distant quasars to our telescopes. In effect, we can observe what the laws of physics were like more than ten billion years ago. There is an important link between this work and the study of the cosmological constant and the observed acceleration of the universe because it was found in this work that there cannot be a time variation in the fine structure constant after time when the expansion of the universe starts to accelerate.

This research in 1999 devised a new way to compare the separations between the wavelengths of particular pairs of spectral lines that appear in the spectrum of light from distant quasars with the

separations found when the same spectrum is observed in the laboratory. This can be done with unparalleled sensitivity using astronomical detectors and the shifts in the separations for many pairs of lines can be compared with detailed computations of what the separations will be if tiny differences in the value of the fine structure constant exist between the time when the light left the quasar and its reception on Earth. This work has consistently found a relative shift of five parts in a million over about 13 billion years from the observation of hundreds of quasars and more than 1000 spectral lines using different detectors and different telescopes.

3. References to the research (indicative maximum of six references)

J.D. Barrow 2007 A Strong Constraint on Ever-Present Lambda, Phys. Rev. D 75, 067301, DOI: 10.1103/PhysRevD.75.067301

*D.J. Shaw & J.D. Barrow 2010 A Testable Solution of the Cosmological Constant and Coincidence Problems, Phys. Rev. D 83, 04351, DOI: 10.1103/PhysRevD.83.043518

*J.D. Barrow & D.J. Shaw 2011 New solution of the cosmological constant problems, Phys. Rev. Lett. 106, 101302, DOI: 10.1103/PhysRevLett.106.101302

*H. Sandvik, J.D. Barrow, and J. Magueijo, 2002 A simple varying-alpha cosmology, Phys. Rev. Lett. 88, 031302, DOI : 10.1103/PhysRevLett.88.031302

J.D. Barrow, H. Sandvik and J. Magueijo, 2002. The Behaviour of varying-alpha cosmologies, Phys. Rev. D 65, 063504, DOI: 10.1103/PhysRevD.65.063504

* References which best represent the quality of the underpinning research.

4. Details of the impact (indicative maximum 750 words)

The impact has been the communication of new discoveries and theories about the structure of the universe to the public and young people beyond the academic world. These include (i) the discovery of the acceleration of the universe and Barrow's research to explain it, and (ii) Barrow's work on the evidence for very slow variations in the fine structure 'constant' of physics over billions of years and his research to describe this. The impacts listed are entirely the results of Professor Barrow's research and its dissemination.

Publication of this work on the cosmological constant was the main scientific news story of the week in Nature, online publication 23/2/11 http://www.nature.com/news/2011/110223/full/news.2011.105.html.

This quest to understand the expansion of the universe, the cosmological constant, and the evidence changing constants of Nature has been widely presented from 1999-2013: in talks, radio broadcasts (BBC, RAI), interviews, newspapers (Daily Telegraph, La Repubblica) and magazines (Standpoint, Scientific American) and books (*Cosmic Imagery*, 2008 and *The Book of Universes*, 2011*)*. These included 24 public lectures in London 2008-11 during Professor Barrow's appointment as Gresham Professor of Geometry, and his lectures at the British Science Festival as President of the Physics-Astronomy section (2009) and of the Mathematics section (2012). Both Presidential Lectures (*The Origin and Evolution of the Universe* and *Expanding Minds and Expanding Universes*) covered Barrow's cosmological research. *Expanding Minds and Expanding Universes* was rated 'excellent' by all audience survey respondents and highlighted as 'informative and entertaining' [1]. The audiences included school students, general public, teachers, journalists, and amateur astronomers.

Barrow talked about his research at many events around the world for paying audiences, including Hay (2011 capacity audience 500+), Frome (2012 capacity audience), Lichfield (2012), Ilkley (2011 capacity audience), World Science Festival, New York (2009 capacity audience + online transmission), Edinburgh (2008 capacity audience), Cambridge (2011), Genoa (2012 capacity audience 600+), the Royal Institution London (2011 x 2), Bath Scientific and Literary Society (2013).

Professor Barrow's BBC radio 4 appearance on *In Our Time* 'Mathematics and the Universe' on

11/2/10 reached 2.2 million listeners and 30,000 online listeners [2] (it is still listened to a few hundred times per week). Downloads from the BBC Podcast archive occur at 24,000 per annum for this programme.

Professor Barrow is the only scientist awarded the Faraday Medal of the Royal Society (2008), the Kelvin Medal of the IOP (2009) and the Christopher Zeeman Medal of the LMS and the IMA (2011) for the public communication of science, physics and mathematics. He is the only person since 1652 to have held two Gresham professorships in different subjects ('Astronomy', 2003-7, and 'Geometry', 2008-12).

The Italian edition of Barrow's book *Cosmic Imagery* received the Merck-Serono Prize, the principal Italian literary prize for non-fiction, July 2011, and *The Book of Universes* received the 2012 Antica Pignolo Literary Prize at La Fenice, Venice, Italy in November 2012.

On 6/3/12 Barrow made a joint presentation on *La Musica del Vuoto*, talk plus performance about the vacuum in cosmology and physics, its role in explaining the acceleration of the universe and the musical analogues of silence and timing, with the leading Italian contemporary pianist, Ludovico Einaudi, at the Auditorium Parco Musica, Rome on 6/3/12 selling over 1000 tickets, and over 150,000 views on the dedicated webpage [3].

Articles by Barrow and article-interviews about this research have appeared in the online e-publication PLUS (www.plus.maths.org) for the general public, media, teachers and age 16+ school students: *A Matter of Gravity* (1/3/06 – 6647 page views) *What is dark energy?* (24/08/09 – 5287 page views), *Are the constants of Nature really constant*? (31/5/09 – 4252 page views), *What happened before the big bang?* (23/3/09 – 29,221 page views), *Does infinity exist?* (2/7/12 – 21,035 page views) [4].

The Book of Universes (2011) is translated into Hungarian, Turkish, Italian, German, French, Chinese, Czech, Polish, US, and Japanese and *Cosmic Imagery* (2008) into Spanish, Italian, Chinese, Russian, Czech, Japanese, Korean, and US [5].

Barrow's Gresham public 24-lecture series of which four were in period, attracted capacity audiences of 240 at the Museum of London plus 11,149 online views [6].

Barrow co-authored an invited Scientific American article *Inconstant Constants* about the work on varying constants in June 2005. This was also selected for inclusion, in extended form to take into account new work, in a special Scientific American issue entitled 'A Matter of Time', Spring 2012 [7].

On 27/5/13 Barrow gave the two opening talks on the *Cosmological Constant* at the Stockholm International Workshop for Science Writers organised by George Musser (Senior Editor, Scientific American magazine) to inform science writers about cosmology [8].

5. Sources to corroborate the impact (indicative maximum of 10 references)

1) Audience feedback from 'Expanding Minds and Expanding Universes', the British Science Association Mathematics section Presidential Lecture at Aberdeen provided by the section recorder
2) Listening figures for BBC Radio 4 In Our Time provided by Producer
3) Information on Professor Barrow's event *'La Musica del Vuoto'* provided by Director of Etcaetera Consulting
4) Data on articles and article-interviews in the online e-publication PLUS (www.plus.maths.org)
5) Information on book translations provided by Foreign Rights Manager, Random House
6) Gresham website downloads information provided by Gresham College IT support
7) *' A Matter of Time',* Scientific American (volume 21, no.1 pp. 70-77), Spring 2012
8) 27/5/13 two opening talks on the *Cosmological Constant* at the Stockholm International Workshop for Science Writers: http://prime-spot.de/ww13/index.html.