Institution:
University of Cambridge

Unit of Assessment:
UoA10

Title of case study:
Stephen Hawking

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

The research underpinning Stephen Hawking's books, TV appearances and lectures has shaped public attitudes towards frontier research in cosmology. It attracts large audiences to learn about his research, and he is the most well-known scientist in the world. Highlights include the publication of his 2010 popular-science book *The Grand Design*, and the Discovery Channel series *Into the Universe with Stephen Hawking.* Further evidence of the impact of Hawking's research was the award of the 2009 Presidential Medal of Freedom (America's highest civilian honour) and his role as narrator in the 2012 Paralympic Opening Ceremony watched by over 11M UK viewers.

2. Underpinning research (indicative maximum 500 words)

Stephen Hawking (Lucasian Professor of Mathematics from 1979 to 2009 and Director of Research from 2009 to present, University of Cambridge Department of Applied Mathematics and Theoretical Physics [DAMTP] and 2006 Copley Medallist of the Royal Society) has made historic contributions to our understanding of the possible origin and evolution of our Universe and the properties of black holes. Hawking is responsible for many important and interlinked breakthroughs in cosmology, black holes, and quantum gravitation. He developed new mathematical approaches to joining the study of quantum fields to gravitating systems governed by general relativity. Most dramatically, this allows the quantum theory to be applied to the study of entire universes [1-6].

Hawking's highlighted researches, refs. [1]-[3], between 2008-12 are in collaboration with James Hartle, (UC Santa Barbara) and Thomas Hertog, (KU Leuven). Hawking has provided new geometrical and topological ideas about the problems of initial conditions and inflation which his collaborators have then developed and helped prepare for publication. The research has focussed on mathematical ways of defining the likelihood (or 'measure') for different types of universe (including a simplified version of the one that we observe today) to arise from a particular quantum prescription near its initial state in the distant past when boundary conditions are placed on its quantum wave function. This is difficult because the size of infinite collections of possibilities depends upon the way they are counted. An important example of a possible quantum initial state is the famous Hartle-Hawking 'no boundary' condition, introduced first in 1982-3. It introduces an imaginary time coordinate so that, in the quantum limit of the early universe, time becomes another dimension of space. This was described in the best-selling book *A Brief History of Time* (1988) but has remained a focal point of research into quantum cosmology by Hawking and others. In refs [1]-[3] and [5]-[6] it was extended by Hawking in a new way to include the introduction of a 'string landscape' of possible cosmological vacuum states into the theory. Hawking has also studied whether the most likely quantum initial states subsequently lead to inflationary expansion in the early universe [5] and, if so, what the resulting form of inflation is likely to be, and what the observational signals in the microwave background radiation of this form of inflation should look like. This also included the unusual new possibility of inflation with a negative cosmological constant [1].

In ref [2] Hartle and Hawking also introduce a further new consideration into quantum cosmology by asking what constraints are introduced on the probability distribution of outcomes for the universe by the fact that we exist in a low-density environment after the universe has expanded for more than 10 billion years [2]. Hawking continues to develop the mathematical framework for calculations of the wave function of the universe; for example, investigating the relationship between inflation and the cosmological constant [1].

In a much-cited work (ref. [6]) carried out with Neil Turok (Professor of Mathematical Physics (1967) from 1996 to 2009, DAMTP), Hawking also showed that an 'open' (i.e. negatively curved) universe could be created without invoking a special type of inflationary expansion.

Hawking has also studied the longstanding problem of information loss in the process of black hole formation and subsequent 'Hawking' evaporation into radiation, [4], which he first predicted in 1975. This problem has important implications for the quantum theory of gravity and the extent to which a theory of space and time can be created using the concept of 'information'. His recent

work on this information loss problem, from 2005 to the present [4], has led to significant high-profile scientific exchanges about Hawking's research on quantum information loss [4] with Kip Thorpe (Caltech) and Leonard Susskind (Stanford) that were reported in Susskind's best-selling popular book*, The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics* (2008).

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

[1] **Inflation with Negative Lambda.** James B. Hartle. S.W. Hawking, Thomas Hertog. Jul 2012. 4 pp. [LANL archive: arXiv:1207.6653]

[2] ***Local Observation in Eternal inflation.** James Hartle (UC, Santa Barbara), S.W. Hawking (Cambridge U., DAMTP), Thomas Hertog (APC, Paris & Intl. Solvay Inst., Brussels). Sep 2010. 4 pp. *Published in Phys. Rev. Lett. 106 (2011)* DOI: 10.1103/PhysRevLett.106.141302

[3] ***No-Boundary Measure of the Universe.** James B. Hartle (UC, Santa Barbara), S.W. Hawking (Cambridge U., DAMTP), Thomas Hertog (APC, Paris & Intl. Solvay Inst., Brussels). Nov 2007. 4 pp. *Published in Phys. Rev. Lett. 100 (2008)* DOI:10.1103/PhysRevLett.100.201301

[4] ***Information loss in black holes.** S.W. Hawking (Cambridge U., DAMTP). DAMTP-2005-66. Jul 2005. 5 pp. *Published in Phys. Rev. D72 (2005)* DOI:10.1103/PhysRevD.72.084013

[5] **Why does inflation start at the top of the hill?** S.W Hawking, Thomas Hertog (Cambridge U., DAMTP). Apr 2002. 21 pp. *Published in Phys. Rev. D66 (2002)* DOI:10.1103/PhysRevD.66.123509

[6] **Open inflation without false vacua.** S.W. Hawking, Neil Turok (Cambridge U.). Feb 1998. 10 pp. *Published in Phys. Lett. B425 (1998) 25-32* DOI:10.1016/S0370-2693(98)00234-2

This work has been supported continuously during this period by STFC rolling grants (now consolidated grants), the latest of which is entitled, *Fundamental Physics and Observational Cosmology*, 2011-14 (ST/I002006/1 amount £1,138,424, PI Shellard). Previous STFC/PPARC grants supporting Hawking's work have been
ST/F002998/1 (01/04/2008 – 31/03/2011, amount £1,227,537, PI Hawking)
PP/C501676/1 (01/04/2005 – 21/03/2008, amount £634,294, PI Hawking)
PPA/G/O/2001/000476 (01/10/2002 – 31/03/2005, amount £442,363, PI Hawking)
PPA/G/O/1999/00603 (01/10/2000 – 30/09/2002 amount £366,791, PI Hawking).

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

Since 2008 Hawking has created several books and TV series that bring the new developments in physics and cosmology arising from his research since 2003 on information loss, the no boundary condition, and the inflationary universe to a general audience. They provide access to ideas whose sophistication would normally preclude coverage in the mainstream media. Hawking places research in a wider cultural context. This deepens public understanding of research in physics and cosmology, produces widespread media interest, and reiterates the worth of these fields to society.

Books:
Building on the phenomenal success of *A Brief History of Time* with over 10 million copies in print, in more than 45 languages -- the follow-up volume *A Briefer History of Time* explaining the no boundary proposal [3] has sold 580,000 copies since 2008. The book *The Universe in A Nutshell describing cosmological aspects of the no boundary condition and black holes* has sold 823,000 copies since 2008.*The Grand Design*, co-authored with Leonard Mlodinow, has sold 1.43 million copies since publication in 2010 (all data supplied by Random House [8])**.** In *The Grand Design*, the authors discuss Hawking's own research since 2003 on cosmology, particularly the no-boundary proposal [3] and its implications for inflation and initial conditions for the expanding universe [2,3]. A selection of the many national and international press reactions can be seen from reports in *The New York Times* (20/09/2010) [15] and the *BBC News* (02/11/2010) [16].
Hawking also co-authored two books for young children with his daughter Lucy Hawking: *George's Cosmic Treasure Hunt* (Corgi 2009, sales 75,692) and *George and the Big Bang* (Corgi

2011, sales 27,185). These titles completed a trilogy of children's books begun in 2007 with *George's Secret Key to the Universe* (sales 176,220). Sales figures provided by Transworld Publishers [11]. These books introduce children aged 8 upwards to physics and cosmology, harnessing their fascination with the universe, space travel and alien life, as well as the search for the frontiers of knowledge. They introduce science through engaging adventure stories and communicate what motivates scientists in their quest to understand the universe.

TV series:

Hawking also participated in high-profile TV series about his research and on cosmology and physics more generally. These programmes had high impact, as can be seen from the viewing figures [9] (which will continue to grow dramatically when the series are reshown or dubbed into foreign languages and released in DVD format). The fact that such programmes are commissioned and broadcast also provides evidence of the very considerable impact that Hawking's previous work has had upon the world of the media and the general public.

Most recently, Hawking's major TV impacts have occurred through the series *Into the Universe with Stephen Hawking* (2010, Discovery Channel), *Genius of Britain* (2010,Channel 4 had 901,400 viewers for the 5th programme in the series, which featured Hawking), *Brave New World with Stephen Hawking* (2011, Channel 4, four-programme series had 892,100 viewers), *Stephen Hawking's Grand Design* (2012, Discovery Channel 4, the 3 episodes had in total 3.14 million viewers, *Into the Universe with Stephen Hawking* (2010-11, Discovery Channel, the 6 episodes had in total 5.9 million viewers), and *Stephen Hawking: Master of the Universe* (2008, Channel 4, the 4 programmes had a total of 1,399,900 viewers [9]).These last three series encourage the public to explore cosmology and physics. Each series draws on Hawking's recent research, including eternal inflation (refs [2, 5]) and the no-boundary proposal in the context of the string theory landscape (ref [3]).

A film entitled *Hawking*, directed by Stephen Finnegan, has been made by Vertigo Films in collaboration with PBS/Channel 4 (duration 89 mins) and was shown at the Cannes Film Festival, 15th -26th May, 2013 and the Edinburgh Film Festival 19-30 June 2013 [13]. Its UK Gala Premiere is at the Cambridge Film Festival on 19 September 2013 (Hawking will also open the Film Festival) [13]. It will be released in cinemas across the UK on 20 September 2013 and shown by Channel 4 later in 2013.

Paralympic Opening:

Hawking's impact as one of the best-known scientists in the world was notably demonstrated when he was chosen for the role of narrator for the 2012 Paralympics Opening Ceremony watched by a peak of 11.2 million UK viewers (and many more overseas) [14]. This was the largest ever Channel 4 audience. While championing the cause of those living and competing in the Games despite disabilities, Hawking urges his listeners to believe there are no boundaries to human endeavour, In his narration Hawking mentions explicitly his cosmological research on the no boundary condition for the universe: "There ought to be something very special about the boundary conditions of the Universe, and what can be more special than that there is no boundary?" [10]. Anthony Faiola for the The Washington Post (29 August 2012) reported: '*London raises curtain on Paralympic Games "*With an ode to science, human perseverance and the disabled physicist Stephen Hawking … Performers with disabilities soared in the air on zip lines as Hawking, arguably the globe's most celebrated living scientist, used his trademark voice box to deliver a metaphorical message: "Look up at the stars, and not down at your feet."[12]'

In recognition of the enormous impact of his work, in 2009 Stephen Hawking was awarded the Presidential Medal of Freedom, America's highest civilian honour, by President Obama. The citation states [7]:

'Persistent in his pursuit of knowledge, Stephen Hawking has unlocked new pathways of discovery and inspired people around the world. He has dedicated his life to exploring the fundamental laws that govern the universe, and he has contributed to some of the greatest scientific discoveries of our time. His work has stirred the imagination of experts and lay persons alike. Living with a disability and possessing an uncommon ease of spirit, Stephen Hawking's attitude and achievements inspire hope, intellectual curiosity, and respect for the tremendous power of science.'

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

[7] Presidential Medal of Freedom citation: http://www.whitehouse.gov/the-press-office/background-medal-freedom-ceremony

[8] Book sales data from Bantam Random House (supporting statement available)

[9a] TV viewing figures from Senior Legal and Business Affairs Executive, IWC Media (supporting statement available)

[9b] TV viewing figures from The Discovery Channel (spreadsheet available).

[10] Transcript of Paralympic presentation: https://twitter.com/gemgemloulou/status/241438450061045760

[11] Sales figures for children's books from Transworld Publishers (statement available)

[12] The Washington Post (29 August 2012) http://articles.washingtonpost.com/2012-08-29/world/35492460_1_martine-wright-ludwig-guttmann-paralympic-games

[13] 'Hawking' film 2013: Edinburgh International Film Festival http://www.cine-vue.com/2013/06/eiff-2013-hawking-review.html

[14] Paralympic Opening Ceremony viewing figures and analysis: http://www.theguardian.com/media/2012/aug/30/paralympics-opening-ceremony-8m-viewers

[15] *The New York Times* (20/09/2010) http://nyti.ms/bkLyZS

[16] *BBC News* (02/11/2010) http://www.bbc.co.uk/news/uk-11161493