

Institution: Lancaster University		
Unit of Assessment: 9, Physics		
Title of case study: Impacts on creativity, the arts and culture from Lancaster research in cosmology, biological oscillations and experimental particle physics		
Period when the underpinning research was undertaken: 2000 to 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Dr Kostantinos Dimopoulos	Reader	01/07/2004 to present
Prof. Roger WL Jones	Professor	01/03/1996 to present
Prof. Aneta Stefanovska	Professor	01/03/2006 to present
Period when the claimed impact occurred: 2015 to 2020		
Is this case study continued from a case study submitted in 2014? N		
<p>1. Summary of the impact</p> <p>Research from the Physics Department at Lancaster University has been used to bridge the divide between science and the humanities, identified by C. P. Snow as 'The Two Cultures'. This includes inspiring and co-producing new artistic works, generating new ways of thinking that influence creative practice and enhanced cultural understanding through learning and participation. Cosmology provided the inspiration for the generation and national exposition of 56 new works of art, and for cultural discourse. Non-autonomous, dynamical analysis of biological signals formed the basis for original works of music by pioneering composer Prof. Nigel Osborne MBE, performed live to audiences of 7,000 and broadcast on television. Particle physics provided the vision for embedding the communication of science into cultural festivals, most prominently leading to the World of Physics at the World of Music, Arts and Dance (WOMAD) festival. At least 30,000 people worldwide have been directly impacted through leading cultural events in the UK, Croatia, the Czech Republic, Denmark, Slovakia, and the USA, with approximately 14.7 million people reached through associated media coverage.</p>		
<p>2. Underpinning research</p> <p>The impact is underpinned by research in cosmology, biological oscillations and particle physics, all of which explore grand challenges and far-reaching ideas that capture the imagination.</p> <p>2.1. Theoretical particle cosmology (2004 to 2019)</p> <p>Current models of the universe suggest that 95% of its content is unknown. Primary exploration of this fundamental mystery rests in two major areas of study within cosmology: dark matter and dark energy. Dimopoulos has investigated a direct relation between dark energy, thought to constitute 70% of the content of the present Universe, and cosmic inflation. Cosmic inflation set up the initial conditions of Big Bang cosmology, and generated the primordial perturbations that seeded density fluctuations, leading to the formation of structures such as galaxies. In Dimopoulos' work, a single substance called quintessence, originally introduced to explain only dark energy, was posited to be potentially responsible for both dark energy and inflation [3.1]. He also proposed that the primordial curvature perturbations, which led to density fluctuations and structure in the Universe, could be due to a vector boson field. This is similar to the (massless) photon field of electromagnetism, but with mass [3.2]. This novel idea supplements the use of scalar fields (e.g. Higgs boson) typically employed in inflationary cosmology. The mechanism directly links cosmological observations of the microwave sky with collider experiments at CERN searching for new vector bosons, thereby revealing the deeper nature of reality.</p> <p>2.2. Living systems as coupled non-autonomous oscillators (2006 to 2020)</p> <p>Obtaining a detailed mathematical model of living systems is a major challenge, but it is characteristic of life that almost every measured parameter oscillates, and Stefanovska's work shows that it does so in complex ways [3.3]. In particular, the frequencies and amplitudes of biological oscillations vary in time, mainly because of their mutual interactions. For decades these oscillations were largely ignored, and the focus was placed on averaged quantities, e.g. heart rate, or systolic and diastolic blood pressures. Yet there is an enormous amount of information contained within these oscillations and their variations. Using a novel vision of living systems as collections of coupled non-autonomous oscillators, Stefanovska and co-workers have developed a mathematical and physical framework based on non-autonomous dynamics for describing such systems, with focus on interactions and temporal coordination as core</p>		

features of life. The oscillations are detected by conventional physiological measurements such as electrocardiogram, respiration, laser-Doppler blood flow, electroencephalogram (EEG) and blood oxygenation by near-infrared spectroscopy. The novelty lies in the analysis of the resultant time-series data using specifically-designed software developed by Stefanovska and colleagues since 2006 [3.4]. The work has shown that the physiological state, and even the emotional state, of a human can be characterised in terms of oscillator parameters.

2.3. Experimental particle physics (2000 to 2020)

The goal of the ATLAS experiment at the Large Hadron Collider is to unravel the mysteries of how matter and forces behave at the highest energy densities yet achieved. Having discovered the Higgs boson, ATLAS is being used to explore its nature and seek any partner particles it may have. It is searching for new physics beyond the standard model, including supersymmetry and the origins of matter/antimatter asymmetry, and testing the standard model in new, extreme conditions, and with exquisite precision. Jones has been a crucial contributor to the ATLAS experiment. In addition to the Higgs discovery and measurements of its properties [3.5] (where he worked most closely on the momentum scale and decays to taus), specific research contributions involve leadership in the study of B and light states, and investigations of matter-antimatter asymmetry [3.6], as well as new particle searches and quantum chromodynamics studies. Jones has led the computing and software research for ATLAS in the UK since 2002, serving as ATLAS UK Computing and Software Co-ordinator and ATLAS UK Upgrade Software and Computing work package leader, and also chaired the ATLAS International Computing Board (between 2003 and 2009). The Lancaster group, including Jones, also played an important role in the development and operation of the ATLAS Semiconductor Tracker.

3. References to the research

- [3.1] K. Dimopoulos, "[Can a vector field be responsible for the curvature perturbation in the Universe?](#)", Phys. Rev. D **74**, 083502 (2006). 93 citations (Scopus).
- [3.2] J. C. Bueno Sánchez and K. Dimopoulos, "[Trapped quintessential inflation](#)", Phys. Lett. B **642**, 294-301 (2006). 28 citations (Scopus).
- [3.3] A. Stefanovska, "[Coupled oscillators - complex but not complicated cardiovascular and brain interactions](#)", IEEE Eng. Med. Biol. Mag. **26**, 25-29 (2007). 72 citations (Scopus).
- [3.4] D. Iatsenko, P. V. E. McClintock and A. Stefanovska, "[Extraction of instantaneous frequencies from ridges in time-frequency representations of signals](#)", Signal Process. **125**, 290-303 (2016). 69 citations (Scopus).
- [3.5] The ATLAS Collaboration (incl. R. W. L. Jones), "[Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC](#)" Phys. Lett. B **716**, 1-29 (2012). More than 5,000 citations (Scopus).
- [3.6] The ATLAS Collaboration (incl. R. W. L. Jones), "[Flavor tagged time-dependent angular analysis of the \$B_0 \rightarrow J/\psi \phi\$ decay and extraction of \$\Delta\Gamma\$ s and the weak phase \$\phi_s\$ in ATLAS](#)", Phys. Rev. D **90**, 052007 (2014). 38 citations (Scopus).

Quality indicators:

The Wellcome Trust, 074437/Z/04/Z, "Nonlinear dynamics of congestive heart failure", GBP206,300.00, (2004 to 2010) [3.3]
 EPSRC, EP/100999XI, "Physics of non-autonomous systems in the life sciences", GBP448,323.00 (2010 to 2015) [3.4]

4. Details of the impact

The underpinning research in Section 2 has provided the inspiration for artists, composers, actors and musicians, led to the production of new artistic work, influenced leading figures in the art and culture sector and brought an enhanced cultural appreciation of physics research to new audiences, bridging the divide between 'The Two Cultures'.

4.1. Dark Matters: Original art, film and discourse inspired by cosmology

Dimopoulos' research [3.1, 3.2] was the inspiration for an artistic and anthropological exploration of the concept of 'radical imperceptibility', with Dr Rebecca Ellis (anthropologist) and Dr Sarah Casey (artist). It drew on his research activity in cosmic inflation and quintessence, and on the role of the theoretical cosmologist in revealing the imperceptible. For one year, between 2014 and 2015, Dimopoulos, Ellis and Casey met weekly, engaging in deep discussions on the nature of (im)perceptibility. Dimopoulos explained how imperceptibility is addressed by theoretical

cosmology and his own research. Insights and deeper understanding generated through these discussions led to multiple interdisciplinary and cultural impacts [5.1].

- **Art exhibitions:** 56 original pieces were created by Casey with Dimopoulos providing texts and source material derived from his research, including photographs of his papers. The texts were purposely elusive (they did not attempt to teach cosmology) to contribute to the intangible sense of the art. The exhibition was originally staged at the Peter Scott Gallery, Lancaster University from 15th December 2015 to 14th January 2016, and was subsequently presented at the 2016 Being Human Festival, billed as 'the UK's national festival of the humanities', where it was viewed at the Blyth Music Centre and the Blyth Library, Imperial College London, by over 900 people [5.1]. Two of the drawings were also displayed in the exhibition 'Beyond Perception' (Aberdeen, 2nd April 2015 to 4th April 2015).
- **Short documentary film:** This 17-minute film was produced by Daniel Morell and Robert Potts in 2016. The film, which was largely based on Dimopoulos' research (and in which he was substantially featured), explored radical imperceptibility drawing on art, social anthropology and physics. It was first shown in the Peter Scott Gallery and then at the 2016 Being Human Festival, and has been viewed over 460 times online [5.2]. It was one of five documentaries among hundreds shortlisted by the AHRC for the 2017 Best Research Film of the Year [5.3].
- **Public talk:** Dimopoulos presented a talk on '*Comics, Theoretical Cosmology and the Nature of Reality*', at The Lakes International Comic Art Festival in Kendal (11th October 2019 to 13th October 2019) to an audience of about 100.

4.2 Impacts of non-autonomous dynamics on the performing arts

4.2.1. Theatre performances of '*The Bacchae*' in Croatia

Stefanovska's research was used to explore the effect of emotion on physiological oscillations and the ability of professional actors to 'get into' character. For example, when acting anger, the actor may (really) feel angry and their physiological response may change accordingly. Recordings were made in Zagreb on eight female actors in repose and while playing the emotions of, for example, anger, pain, love, hysteria or sadness. Their respiration, heart rate and EEG were continuously monitored. When analysed, using techniques developed by Stefanovska [3.3, 3.4], they were found to be distinctive of the different emotional states. In collaboration with innovative composer Prof. Nigel Osborne MBE, the recorded data were then 'sonified' (turned into sound) to provide the basis for musical accompaniment for the classical Greek play '*The Bacchae*', which involves all human emotions. The sonification of each emotion used the extracted instantaneous frequencies from the analysis to modulate carrier signals in the form of pure tones. The play was performed to critical acclaim at the prestigious Ulysses Theatre in Veliki Brijuni, Croatia, which lists Angelina Jolie, Ralph Fiennes and Vanessa Redgrave among its patrons, between 28th July 2018 and 30th July 2018, 17th July 2019 and 20th July 2019, and 1st August 2019 and 2nd August 2019. It was also performed at the ZKM Theatre in Zagreb, between the 17th January 2019 and 20th January 2019, 10th May 2019 and 2nd June 2019. Audiences totalled about 7,000 [5.4].

Excerpts were also broadcast on Croatian, Serbian and Bosnian television, with a reach of approximately 7 million people, and the performance was reviewed in all Croatian national newspapers and portals (e.g. *Jutarnji List* (31st July 2018, circulation 42,974, readership 450,000), *Scena* (10th January 2019), and *Novi List* (4th October 2019, circulation 30,000, readership 250,000)) [5.4]. The play received critical acclaim, including with respect to the physiological basis for the music. "*The music is composed on the basis of material obtained from medical measurements of the emotional states of actresses - heart rate, breathing and brain activities. With this approach, viewers will be immersed in all senses in the external representation of the interior of their human nature, in a common longing for (un)achievable freedom*" (*Scena*). *Novi List* commented: "*Through the anthems of Dionysus and the musical listening to the mysterious "howling" of recorded brainwaves of performers, which is a musical research contribution to the play, these Bacchae become Greek goddesses of revenge...*" [5.4].

4.2.2. Playing in harmony?

The cardio-respiratory and brain oscillations of two pianists were recorded simultaneously whilst performing together, and whilst at rest, to investigate whether these oscillations synchronize [3.3, 3.4] during the performance. The sonified physiological oscillator recordings were then used to generate a new musical work, 'A Short History of Polish Philosophy', by Osborne, under commission of the Donaueschingen Festival [5.4]. Founded in 1921, it is one of the oldest and most important contemporary music festivals in the world, with typically 10,000 attendees and broadcast to around 25 million people across Europe by, for example, Sudwestrundfunk (Germany), BBC, RAI (Italy) and RF (France). Concerning this work, Osborne commented *"It is an honour to play at this festival, and therefore I was delighted to be able to work with you [Stefanovska] again and use your research to compose a piece of music for performance there. The composition is the first to use intersubjective data from brain activity and physical measures of performers to modulate the sound of the performance itself. In other words, the thoughts and emotions of the performers directly control aspects of the music that listeners hear."* [5.4].

4.3. Impacts on major cultural festivals

The communication of physics is now included in a context, *i.e.* cultural festivals, that was previously entirely artistic, even to the extent that physics is treated on a par with conventional cultural activities such as music and dance. The inception of this impact came from ground-breaking research on the ATLAS experiment at CERN [3.5, 3.6], which attracts large numbers of interested visitors, some of whom are greeted by Jones. Amongst these was Mike Large, Chief Operating Officer of WOMAD Limited and Real World Operations Limited, founded by musician Peter Gabriel. During discussions Large and Jones identified the lack of science in cultural festivals, and resolved to address this, leading to the impacts described below [5.5].

4.3.1 World of Music, Arts and Dance (WOMAD)

In 2016, Jones instituted the Physics Pavilion at the World of Music, Arts and Dance ([WOMAD](#)) festival, publicised as 'The World's Festival', and held annually in Wiltshire. The Physics Pavilion, billed as 'Where Ideas Collide', was an instant success; over the three days of the festival, it achieved a footfall of 4,000, going beyond the capacity of the tent, which had to have a side removed to accommodate all the visitors. In 2017, pavilion attendance was 5,500, and, by 2018, Jones had expanded the venue to include a workshop area, walk-by discovery centre, planetarium and 'accelerator in the sky' (footfall 6,500). In 2019, the Physics Pavilion became World of Physics, on a par with the Worlds of Music, Dance, Food and Children, achieving a footfall of 8,000 (one quarter of all attendees at the festival) [5.5]. There have been numerous contributions from Lancaster physicists to WOMAD, not least Jones, who has run small, hands-on, 'cloud chamber', 'aurora detector' and 'collider in your pocket' workshops (capacity 40,700 participants per festival), and talked about topics including Higgs and new particle searches and matter/antimatter asymmetry, as well as the spin offs and wider impacts of particle physics. Many of the 'physics' expositions were cross-cultural. Some of the many notable highlights of the Physics Pavilion/World of Physics since 2016 include: regular performances on the theremin from Dorit Chrysler (composer, producer and singer) [5.6]; Steven Moffat OBE (writer and producer) discussing science and Dr Who; Helen Arney (physicist, presenter, stand-up comedian and musician) of the Festival of the Spoken Nerd; Robin Ince (comedian, actor and writer) on comedy and science; Jim Al-Khalili OBE FRS (physicist, author, broadcaster) on fiction and science; and Mark Lewney ('The Rock Doctor') discussing the physics of rock guitar and playing 'in 11 dimensions'.

Anecdotally, the objective of crossing the cultural divide and communicating science to sections of society that would not otherwise engage with it has been achieved. According to the BBC, an artist attendee said *"I know nothing about physics and wouldn't have come to such a thing if it hadn't been at a festival"*, while another 'non-scientific' audience member commented: *"Sometimes there's a feeling that science is a bit dry and separate from the rest of life. They're making it really accessible to us. It's interesting, understandable and quite beautiful."* [5.7] It has also had an impact on performers. For example, Dorit Chrysler found that *"the Physics Pavilion and World of Physics at the WOMAD Festival...stimulated my art through exposure to the research you [Jones] and your colleagues have been undertaking"* [5.6]. The resulting *"deeper connection with CERN"* felt by the artist led to its choice as location for the production of the film

[‘Electric Storm: 100 Years of Theremin’](#) (more than 8,000 views), with music *“inspired by the research conducted there, not least your own [Jones]”* [5.6]. Due to COVID-19, WOMAD 2020 was replaced by an online version offering ‘the essence of WOMAD’, including contributions from the World of Physics, but the full event is scheduled to return in 2021.

4.3.2 International Impact

In 2018 the Big Bang Collective was formed, based on the ‘collective’ concept that is widely used in the arts, with a vision to *“bring physics and particularly particle physics to music and cultural festivals”*, with Jones as one of the ‘core’ members [5.8]. This gave the impetus for taking the concept global, starting with the successful inception of the Big Bang Science Fair at WaterFire in Rhode Island, USA in 2018, which ran for a second time in 2019 [5.9]. In Europe, the Big Bang Collective started the Science Pavilion at the Roskilde Festival, Denmark (between 27th June 2019 and 4th July 2019), which at 130,000 is one of the largest music festivals in Europe, and attracted 3,750 visitors to the Pavilion. This event was followed by Magical Science at Pohoda Festival, Slovakia (between 11th July 2019 and 13th July 2019; 3,500 visitors) and the Big Bang Stage at Colours of Ostrava, Czech Republic (between 17th July 2019 and 20th July 2009; 4,000 visitors). Plans are already established to export the World of Physics model to WOMAdelaide and WOMAD Auckland in 2021.

4.3.3 Media coverage

The impact has been recognised in the UK media, for example in dedicated BBC News pieces from 2016 and 2018 on science at music festivals [5.7]; the former of which described the Physics Pavilion at WOMAD as *“the brainchild of Roger Jones, a professor of physics, and Mike Large, WOMAD’s chief operating officer.”* Events in Roskilde and Pohoda have been particularly widely reported in their respective national media. Examples for Pohoda include pieces in the most popular breakfast show, midday news, national newspapers and websites with a combined reach of approximately 6.7 million people [5.10]. Similar examples for Roskilde include a Danish podcast and the coverage from the Roskilde and Science Pavilion websites reaching approximately 354,286 people [5.10].

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5. Sources to corroborate the impact

[5.1] [Outputs from the ‘Dark Matters Project’](#). Link to website shows examples of outputs created. A report from Lancaster University to support the REF2 submission for UoA32 is also provided, which again includes examples of the artwork resulting from this project and corroborates the 900 attendees at the Being Human Festival.

[5.2] [Dark Matters film online](#) (copy held at HEI).

[5.3] [AHRC shortlist](#) of the Dark Matters film, showing it in the top 5 films for the award.

[5.4] Testimonial from Prof. Nigel Osborne MBE, composer and musician. Dated 15th January 2021 and corroborating impact of Stefanovska’s research on performances and international media coverage.

[5.5] Testimonial from the Chief Operating Officer of WOMAD Limited and Real World Operations Limited. Dated 29th October 2020 corroborating impact of Jones’ research on the WOMAD Festival.

[5.6] Testimonial from Dorit Chrysler (Kreisler), thereminist, composer, producer, and singer. Dated 29th October 2020 and corroborating impact of Jones’ research on her music.

[5.7] BBC News articles (a) [‘Womad: Bridging the gap between science and music’](#) and (b) [‘The Festivals mixing music and science’](#) corroborating media coverage and Jones’ contribution to the Physics Pavilion at WOMAD.

[5.8] Information on the [Big Bang Collective](#), showing Jones as one of the “core” members.

[5.9] WaterFire Web pages corroborating (a) [inception of the Big Bang Science Fair](#) (2018) and (b) [subsequent event in 2019](#)

[5.10] Report on Danish and Slovakian media coverage of the Science Pavilion at the Roskilde Festival and Magical Science at the Pohoda Festival. Dated December 2020.