Institution: University of Portsmouth

Unit of Assessment: 9 Physics

Title of case study: Impact of Baryon Acoustic Oscillations research on the European Space Agency Euclid Mission

1. Summary of the impact

Euclid is a new M-class satellite selected by the European Space Agency (ESA) to study the dark universe, which will exploit fundamental "Baryon Acoustic Oscillations" research originally performed at Portsmouth. The construction of Euclid is underway, overseen by Portsmouth scientists, with several millions of pounds already spent on research and development within UK university laboratories and industry (e2v), already with economic impact. By the time Euclid is launched, 606 million euros will be spent across UK and European industry (Thales, Astrium) providing significant economic impact as well as societal impact.

2. Underpinning research

In 2011, three astronomers were awarded the Nobel Prize in Physics for their discovery (in 1999) that the expansion rate of the Universe was accelerating, contrary to all expectations. This amazing discovery has revolutionised physics, leading to the possibility that the Universe is full of a mysterious repulsive substance called "Dark Energy" (DE), or that Einstein's great theory of gravity, General Relativity (GR), is incomplete on cosmological scales.

Since the discovery of DE, cosmologists have worked hard to improve the measurements of the expansion rate of the Universe. One of the most important new measurement techniques developed to tackle this problem are *"Baryon Acoustic Oscillations"* (BAO); primordial sound waves created in the early Universe that are frozen into the distribution of galaxies as the Universe expands and cools, thus providing a "standard ruler" throughout the Universe. The concept of using BAO to measure the expansion rate of the Universe is directly linked to the pioneering work done by Prof. Bob Nichol and Prof. Will Percival as part of the Sloan Digital Sky Survey (SDSS) and the 2dF Galaxy Redshift Survey (2dFGRS). While at the ICG, Bob Nichol was part of the research team who made the first robust detection of the BAO signal in the distribution of SDSS galaxies in 2005 [1]. Since then, both Will Percival (at ICG since 2006) and Bob Nichol (at ICG since 2004), have been at the forefront of BAO research improving this technique [2] - including new BAO results [3] - for use in the coming decade to obtain more precise measurements of the accelerated expansion rate of the Universe and better understand the DE that appears to be driving it.

Cosmologists now agree that such measurements are best obtained using a combination of techniques, but especially including the BAO technique, as described in the "*Dark Energy Mission Figure of Merit Science Working Group"* report commissioned by NASA & ESA, which includes Bob Nichol as an author [4]. The strategy outlined in this report laid a foundation for new missions like Euclid; a new European Space Agency (ESA) satellite [5] that will be launched in 2020. Euclid is a medium-class mission selected as part of ESA's *"Cosmic Visions 2015-2025"* programme and is specifically designed to exploit a combination of dark energy probes, including the BAO technique, to map the expansion rate of the Universe over 70% the age of the Universe, and over a third of the sky. Such a dark energy measurement is only possible from space.

The scientific case for Euclid was built upon key research performed by cosmologists at the ICG and, in collaboration with others, they have helped design key aspects the satellite [5]. Percival and Nichol were instrumental in drafting the official Euclid *Science Requirements Document* (SciRD), which is the key reference document used by industry and engineers to specify the Euclid mission hardware [6].

3. References to the research

*[1] *"Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies"* by Eisenstein et al., 2005, *The Astrophysical Journal*, 633, 560. DOI: 10.1086/466512. Bob Nichol is a major author on this paper, listed as 6th of 48 authors, in the top tier of the author list. His contributions to the writing of this paper were undertaken at the ICG Portsmouth. (1624 citations on Thomson Web of Knowledge)

*[2] "*Measuring the Baryon Acoustic Oscillation scale using the Sloan Digital Sky Survey and 2dF Galaxy Redshift Survey"* by Percival, W., et al. 2007, *Monthly Notices of the Royal Astronomical Society*, 401, 2148 (DOI: 10.1111/j.1365-2966.2007.12268.x). *Will* Percival and Bob Nichol are key authors on this paper (first and fourth respectively) (428 citations on Thomson Web of Knowledge).

[3] "*The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: baryon acoustic oscillations in the Data Release 9 spectroscopic galaxy sample"* by Anderson et al. 2012, *Monthly Notices of the Royal Astronomical Society*, 427, 3435 (DOI: 10.1111/j.1365-2966.2012.22066.x) presents the latest BAO results from the BOSS survey. The author list for this paper is purely alphabetical but ICG researcher Percival was a lead author of the paper in his capacity as BOSS Working Group Chair and oversaw both the research and writing of this paper. (42 citations on Thomson Web of Knowledge by October 2013)

[4] *Dark Energy Mission Figure of Merit Science Working Group* report (http://arxiv.org/abs/0901.0721), including Bob Nichol as an author (pure alphabetical ordering).

*[5] "*Euclid Assessment Study Report*" (2009; http://tinyurl.com/9wj2vxu) and the "*Euclid Definition Study Report"* (2011; http://arxiv.org/abs/1110.3193) were submitted to ESA by the Euclid Consortium (EC; http://www.euclid-ec.org) and ESA Euclid Science Teams as part of the ESA "*Cosmic Visions 2015-2015"* selection process. Percival and Nichol are main co-authors

[6] Euclid Science Requirements Document used by designers and engineers to design and construct satellite http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42822#

ICG researchers are underlined and asterisk highlights the three references for assessing the quality of the underlying research

4. Details of the impact

The selection and design of Euclid by ESA is a direct impact of the BAO research done at the ICG over the last decade. As outlined above, ICG researchers have established BAO as an important technique for measuring dark energy. The importance of Euclid goes beyond academia, with major economic and societal impact. This case study highlights such impact so far until August 2013), while also highlighting the direct involvement of ICG researchers in the present and future development of Euclid.

Euclid is a 1.2metre telescope satellite mission built through a partnership of ESA, industry and the Euclid Consortium (EC) [1]. In total, the whole mission hardware will cost over 600M euros [2], funded by European governments via their subscriptions to ESA, with a further 400M euros from the national funding agencies for the Euclid instruments and the Science Ground Segment (SGS), or data processing, both performed by the EC [3]. UK industry is expected to receive approximately 16% (100M euros) of this total mission hardware funding [4] as part of the "juste retour" from ESA. Such space science projects are part of a growing sector of the UK economy, now worth over £7.5 billion [5].

Euclid was born from two *"Cosmic Visions 2015-2025"* proposals (DUNE & SPACE); ESA then

instigated a *"Concept Advisory Team"* (CAT) in early 2008 to study merging these two concepts, and Bob Nichol was one of the 12 European scientists involved in the CAT [3]. The CAT recommended (in May 2008) the first concept of Euclid, concluding: "*all members of the CAT agreed that a combined mission which involved probes of both weak lensing and baryon acoustic oscillations offered a superb mission whose combined strengths were very significantly greater than either of them separately*." This conclusion was based in part on the BAO research performed by ICG researchers [9,10].

The first industrial studies of Euclid started in late 2008 (for one year) with initial ESA contracts granted to two European companies (Thales-Alenia Space and Astrium). These assessment studies were then followed by two definition phase studies (from 2010 to 2012; 18 months) by the same two companies. These contracts were worth a total of nearly a million euros for each company [3]. These industrial studies were managed by ESA but with scientific oversight from a series of official ESA science teams (namely *"Euclid Science Study Team"*, "*Euclid Optimisation Advisory Team"* and *"Euclid Interim Work Study Team"*), which all included Bob Nichol from the ICG. He was the only scientist in Europe with an unbroken involvement in this series of science teams and had significant input into official *Science Requirements Document* [6] used by industry to design Euclid. Also, since May 2009, Will Percival has been one of only four Science Coordinators responsible for organizing the scientists within the Euclid Consortium [9].

On June 20th 2012, Euclid was official adopted by ESA, and on June 27th 2013, Thales-Alenia were selected as the prime contractor of the satellite with a cost of 322.5M euros [7] (the Euclid payload has been assigned to Astrium SAS). Bob Nichol remains part of the ESA oversight of this mission [9,10] (including industrial contractors) as a member of the official *"Euclid Science Team"* (EST), which includes only 12 scientists from Europe and USA. His official title on the team is *"BAO Scientist*".

Euclid has entered the final design phase with the successful selection of all the major industrial and university contractors with design reviews schedule for mid-2014. For example, the Euclid visual camera (VIS) will be constructed in the UK by UCL/MSSL at a total projected cost of approximately £7.5M, and includes scientists and engineers at Open University and e2v to design and test new detectors [8]. This work is already underway and employs a number of people in UK industry via grants from the UK Space Agency (UKSA) and ESA e.g., e2v will receive over 30M euros directly from ESA to purchase the final detectors [4]. Since the initial studies in 2008, and including current commitments, UK funding agencies (STFC, UKSA) will have spent £7.455M by 2015 [4].

Finally, the Euclid Consortium is responsible for the instrument operation and data centres (Science Ground Segment, SGS), which is a major computational challenge (costing over 150M euros in total across Europe). The SGS will be designed and implemented in laboratories and universities across Europe, and in the UK [10], we are planning £17M investment in new computing hardware for this work. The SGS provides an investment in UK businesses as well as significant training opportunities for software engineers, students and scientists. At the ICG, Will Percival's prominent role in Euclid and BAO research has resulted in a European Research Council (ERC) Starting Grant entitled *"Cosmology from Next Generation of Galaxy Redshift Surveys"* for a total of 880k euros (07/2008 to 07/2013). Moreover, Percival and Nichol have also received funding from the UKSA for SGS and Euclid science management work packages totalling £395k to 2015.

5. Sources to corroborate the impact

[1] Euclid Consortium website at http://www.euclid-ec.org

[2] See the published recommendation of the ESA Science Programme Committee (SPC) from June 12th 2012 (reference ESA/SPC(2012)16) which quoted 606M euros as the 2012 equivalent cost.

[3] Private communication from Euclid Project Scientist, ESA/ESTeC

[4] Private communication from Head of Space Science, UK Space Agency

[5] *"The Size and Health of the UK Space Industry"*, October 2012, BIS UK Space Agency (UKSA), http://www.bis.gov.uk/assets/ukspaceagency/docs/industry/size-and-health-report-oct-2012.pdf At the ESA Ministerial Council in November 2012, Euclid development was confirmed between 2013-2017 and UK ministers approved an additional £1.2 billion to ESA, via the UKSA, over this period; a 30% rise in funding making the UK the third largest partner behind Germary and France (http://tinyurl.com/ak4oh3t)

[6] Public link to the Euclid *Science Requirements Document* can be found at http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=42822#

[7] Thales Alenia Space press release, http://www.thalesgroup.com/en/worldwide/space/press-release/thales-alenia-space-wins-prime-contract-europes-euclid-cosmology

[8] *"Charge-coupled devices for the ESA Euclid M-class Mission"*, Endicott, J., et al. 2012 *Proc. SPIE* 8453, High Energy, Optical, and Infrared Detectors for Astronomy V, 845304 (September 25, 2012); DOI: 10.1117/12.926323. Also, see press release from e2v highlighting the Euclid contract to develop new detectors for Euclid VIS (http://tinyurl.com/9d8o74k)

[9] Private communication from Euclid VISible Instrument Scientist, Mullard Space Science Laboratory

[10] Private communication from Euclid Programme Manager, UK Space Agency