Institution: University of Hertfordshire

Unit of Assessment: 9 – Physics

Title of case study: Exoplanetary discovery: increasing public interest in and understanding of worlds beyond our solar system and influencing new space missions

Period when the underpinning research was undertaken: 2004-2020

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:
Hugh Jones	Professor of Astronomy	Jun 2004 – present
David Pinfield	Professor of Astronomy	Sep 2004 – present
Phil Lucas	Professor of Astrophysics	Oct 1999 – present
Mikko Tuomi	Post-Doctoral Researcher	Dec 2010 – Sep 2019
Guillem Anglada-Escudé	Post-Doctoral Researcher	Sep 2014 – Aug 2015
Fabo Feng	Post-Doctoral Research Fellow	Oct 2015 – Oct 2018
John Barnes	Post-Doctoral Research Fellow	May 2006 – Jun 2014

Period when the claimed impact occurred: 2015 – December 31, 2020

Is this case study continued from a case study submitted in 2014? N

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

The search for exoplanets has been one of the most exciting areas of astrophysics over the last three decades. The University of Hertfordshire's Centre for Astrophysics Research (CAR), through its development of novel data analysis algorithms and software, has played a central role in some of the most high-profile exoplanetary discoveries in recent years. Evidenced through traditional media and social media metrics, these findings, including the identification of the 'super Earth' Proxima b in the habitable zone of the nearest star, have inspired ongoing debate in the public sphere about the nature and significance of these new worlds, engaging a global audience in the tens of millions. The effects have been: an increase in public awareness, curiosity and understanding of what lies beyond our own solar system; significant influence over the objectives of three pioneering exoplanetary exploration missions, including a $100m funded initiative; and the creation of new digital and artistic works designed to further fire the public imagination.

2. Underpinning research (indicative maximum 500 words)

The discovery of planets beyond the solar system is widely recognised as having changed the way we view the Universe and our place within it. CAR researchers have played a significant role in shaping this new view using a wide variety of different techniques. Examples from the start of the research period are the pioneering of the precise measurement of polarisation in stars and star forming regions by developing instrumentation [**3.1**] providing evidence for the low albedos of planets such as 51 Pegasi b and for the origin of homochirality in space as well as discoveries of free-floating planets sometimes known as rogue planets. They have published more than 200 peer-reviewed exoplanet-related journal papers. Here we emphasise the impact of CAR researchers in the development of novel algorithmic methods to facilitate some of the most high-profile recent exoplanet discoveries around the closest stars to our solar system.

This area of research entered a new phase in 2004 with the appointment of Jones and Pinfield. Jones had previously co-founded the Anglo-Australian Planet Search, a long-term survey to catalogue planets around 240 nearby stars of the southern hemisphere. This work was funded at Hertfordshire by the STFC [**G1, G2**]. Pinfield led the EU-FP7 Rocky Planets Around Cool Stars programme [**G3**] expanding support for this work and used the 4-metre UK Infrared Telescope to search for potentially habitable exoplanets at, for the first time, infrared wavelengths. Combined, these programmes allowed CAR researchers to develop and refine new algorithms to maximise the sensitivity for identifying exoplanets. In particular, this case study focuses on results from the radial velocity method: the identification of an orbiting planet from the 'wobble' of a star by the detection of small shifts in its spectral features.

Tuomi, Jones and Anglada-Escudé identified initial evidence of exoplanets around two of the closest stars to the Sun – Proxima Centauri and Tau Ceti [**3.2**, **3.3**]. They secured a Leverhulme grant PANDORA [**G4**] to systematically reprocess and combine different high-resolution radial velocity datasets in order to test for signals. Refinement of their analytical techniques led to Tuomi, with Anglada-Escude and Jones, winning an international challenge competition in 2014-15 to push the boundaries of the radial velocity method [**3.4**]. This led to the ground-breaking discovery of a rocky, Earth-sized planet, named Promixa b, orbiting the habitable zone of Proxima Centauri 4.2 light years from Earth. It was published in *Nature* in 2016 [**3.5**], featuring on the front cover. Tuomi had first submitted the paper in 2013 after combining data taken by the High Accuracy Radial Velocity Planet Searcher (HARPS) at the La Silla Observatory and the Ultraviolet and Visual Echelle Spectrograph at the Very Large Telescope at Paranal Observatory in Chile. However, more evidence was requested by referees to conclusively show that the 'wobble' was a planetary signal, as opposed to stellar activity. PANDORA enabled the development of further analysis techniques and Anglada-Escudé (who gained a full-time lectureship at Queen Mary University of London in September 2015) to co-ordinate the Pale Red Dot observing campaign including 30 scientists from eight countries. This enabled the team to obtain new datasets from other telescopes and ,in particular, a landmark campaign using HARPS to carry out regular observations for 60 nights. They were able to unequivocally confirm the planetary signal. An international team including Jones made further improvements to the reprocessing of the Proxima Centauri radial velocity data which further validated the signal, and the team announced a possible second planet – Proxima c – in *Science Advances* in 2020.

In 2018 an international team announced the discovery of a frozen planet orbiting Barnard's Star, the next closest star system to the Sun after the Alpha Centauri triple star system. Again, the fingerprints of the planet, named Barnard's Star b, were first identified by Tuomi using UH's radial velocity method to analyse combined data from spectrometers based around the world. Another large-scale collaboration and dedicated observing campaign coordinated by Anglada-Escudé at QMUL, this time with the newly commissioned Spanish spectrograph CARMENES, confirmed the planetary signal and the results were published in *Nature* [**3.6**].

Other key milestones included the discovery in 2017 of four Earth-sized planets orbiting Tau Ceti, 12 light years away from Earth. Two of them are located in the habitable zone [**3.7**]. These discoveries built on the methods to combine multiple datasets distinguishing periodic signals from correlated noise to reveal previously hidden planets [C, D]. Feng, Tuomi and Jones packaged the winning software into a publicly available tool called Agatha [**3.8**]. This software has now been automated and extended (Agatha 2 and PEXO), enabling a new generation of exoplanet discoveries.

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

3.1 Hough JH, Lucas PW, Bailey JA, Tamura M, Hirst E, Harrison D et al. PlanetPol: A very high sensitivity polarimeter. Publications of the Astronomical Society of the Pacific. 2006 Sep 1;118(847):1302-1318. https://doi.org/10.1086/507955
3.2 Tuomi M, Jones HRA, Barnes JR, Anglada-Escudé G, Jenkins JS. Bayesian search for low-mass planets around nearby M dwarfs. Estimates for occurrence rate based on global detectability statistics. Monthly Notices of the Royal Astronomical Society. 2014 Jun 21;441(2):1545-1569. https://doi.org/10.1093/mnras/stu358
3.3 Tuomi M, Jones HRA, Jenkins JS, Tinney CG, Butler RP, Vogt SS et al. Signals embedded in the radial velocity noise: Periodic variations in the tau Ceti velocities. Astronomy & Astrophysics. 2013 Mar;551. A79. https://doi.org/fsth
3.4 Dumusque X, Borsa F, Damasso M, Díaz RF, Gregory PC, Hara NC et al. (including Tuomi, Jones and Anglada-Escudé). Radial-velocity fitting challenge: II. First results of the analysis of the data set. Astronomy and Astrophysics. 2017 Feb 14;598. A133. https://doi.org/10.1051/0004-6361/201628671
3.5 Anglada-Escude G, Amado PJ, Barnes J, Berdinas ZM, Butler P, Coleman GAL et al. (including Jones and Tuomi). A terrestrial planet candidate in a temperate orbit around Proxima Centauri. Nature. 2016 Aug 25;536:437-440. https://doi.org/10.1038/nature19106

3.6 Ribas I, Tuomi M, Reiners A, Butler RP, Morales JC, Perger M et al. (including Feng and Jones). A candidate super-Earth planet orbiting near the snow line of Barnard's star. Nature. 2018 Nov 15;563(7731):365-368. https://doi.org/10.1038/s41586-018-0677-y
3.7 Feng F, Tuomi M, Jones HRA, Barnes J, Anglada-Escude G, Vogt SS et al. Color difference makes a difference: four planet candidates around tau Ceti. The Astronomical Journal . 2017 Sep 5;154(4). 135. https://doi.org/10.3847/1538-3881/aa83b4
3.8 Feng F, Tuomi M, Jones HRA. Agatha: disentangling periodic signals from correlated noise in a periodogram framework. Monthly Notices of the Royal Astronomical Society. 2017 Oct 1;470(4):4794-4814. https://doi.org/10.1093/mnras/stx1126

Key underpinning grants
G1 STFC: Rolling and consolidated (part-funding this work). £ 8,413,682. 2006-21. (PI's Hough, Jones, Drew, Hardcastle)
G2 STFC: Unravelling our Nearby Planetary Companions. £97,539. 2007-08. (PI Jones)
G3 EU-FP7: Rocky Planets Around Cool Stars programme. € 3,211,716. (£712,699 to UH), 2008-12. (PI Pinfield)
G4 Leverhulme: PAN-Disciplinary algORithms for data Analysis. £204,219. 2014-17. (PI Jones)

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

CAR research has made a fundamental contribution to the most high-profile exoplanetary discoveries in recent years. The identification of the exoplanet Proxima b, orbiting the closest star to the Sun, Proxima Centauri, attracted one of the highest levels of online attention out of all journal articles tracked by Altmetric, prompting comment from UK Government ministers on the UK's science leadership role. It reached a global audience in the tens of millions and a social media audience close to seven million over a four-year period. The in-depth and sustained nature of the ensuing debate over the potential for life on exoplanets more generally has increased public interest in, and understanding of, our place in the wider universe. The research findings have shaped the core objectives of high-profile interstellar space missions and inspired creative digital and artistic works designed to stimulate further public enjoyment of astrophysics.

Increasing public understanding and stimulating curiosity about our place in the universe

CAR researchers have proactively engaged with the media to maximise the impact of their discoveries and respond to strong public interest. Articles have featured explanations from CAR researchers about their data analysis techniques and what their findings mean in the context of the search for extra-terrestrial life. The *reach* of the Proxima b discovery is evidenced through Altmetric data for the 2016 *Nature* paper [**3.6**], [**5.1**]. Its 'Attention Score' of 2566 (at 31 Dec 2020) – Altmetric's high-level measure of the quality and quantity of online attention received – means the paper's public reach is ranked 1,184th out of a total 16.6 million outputs ever tracked; 17th out of 267,500 outputs of a similar age, and 5th out of 984 Nature outputs of a similar age. From the announcement of the discovery on 23 August 2016 to 31 December 2020, the paper was cited directly in 305 stories from 225 outlets around the world. It was referenced directly in 1,093 tweets from 1,049 users (77% were members of the public), reaching an audience size 'with an upper bound' of 6.9m people. According to Altmetric, **3.6** is cited on 15 Wikipedia pages, including the pages for 'Exoplanet' and 'Solar System'; *Science Magazine* named it in its top ten scientific discoveries of 2016. Many other media articles and social media coverage have discussed Proxima b without directly citing **3.6**, so the discovery's public reach is, in reality, much wider than Altmetric data can demonstrate. This allows a confident estimate that the total audience size reached over the impact period was in the many tens of millions.

The in-depth, sustained media coverage and the themes it explored serve to demonstrate the *significance* of the impact [**5.2**]. Articles reacting to the discovery discussed our place in the wider universe, the next age of space discovery and the possibility of life beyond Earth. *The Economist* devoted its front cover and leader to the Proxima b paper [**3.6**] with the headline *Brave New Worlds – Pioneers, Planets and the next Space Age*. It said: '*…a new phase in the search for life elsewhere is about to begin*' and compiled a guide '*How to find exoplanets*'. Its

leader article read: '*New discoveries, intelligent devices and irrepressible dreamers are once again making space exciting*.' Calling Proxima b '*the planet we've all been waiting for*', *New Scientist* wrote: '*getting to Proxima b might become an existential requirement*' and '*finding out more about the planet should be a high priority*'. Coverage focused on whether Proxima b could host life. The likes of *BBC News* and the *Guardian* published videos of an artist's representation of Proxima b. The BBC's Science Editor called the discovery '*a huge moment in the search for alien worlds*' and said, '*the fact that it is so close to us - in the relative terms of deep space - suddenly improves the chances of investigating if an exoplanet can be genuinely habitable*'. The *Guardian* included this independent quote: '*It will be our prime laboratory for the search for extra-terrestrial life for the decades ahead.'* The continued impact of the discovery itself on public knowledge and understanding of exoplanets is evidenced by the depth and breadth of follow-on coverage; the debate over whether Proxima b could potentially support life played out in the public sphere, via mainstream and social media, for the remaining four years of the impact period [**5.2**]. In 2017, the Financial Times reported that the Met Office had forecast the weather on Proxima b (mostly dry, with heavy rainfall in two tropical zones) and in 2020 NASA published its own climate simulations that explored a range of habitable climate scenarios [**5.2**].

The announcement in August 2017 of the discovery of four Earth-sized worlds orbiting Tau Ceti also attracted significant and sustained public attention. According to Altmetric data [**5.3**], paper **3.6** was covered in 68 news stories from 56 news outlets and reached up to 145,000 people through 71 tweets from 58 users. An article in *Scientific American* said the finding '*seems to be at least as interesting as the Alpha Centauri stars*'. Popular US online magazine *Daily Beast* in 2018 underlined the scale of the research effort, saying: '*Feng's work on the Tau Ceti system last year stretched radial velocity to its absolute limits*.' The *Nature* paper on Barnard's Star [**3.7**], published in November 2018, received an Altmetric attention score of 1,445. It was covered in 139 stories from 113 news outlets and reached an audience with an upper bound of 4.5m via 963 tweets from 852 users [**5.3**]. The debate over whether Barnard's Star b could potentially support life continued for the rest of the impact period [**5.4**]. In 2019 the Proxima b and Barnard's Star b papers were included in Nature's public-facing online collection of 43 articles on exoplanets to celebrate the 2019 Nobel Prize in Physics [**5.5**]. Nature wrote: "*Together, these discoveries have changed the way we view the Universe, and our place within it*."

Tuomi and Feng directly engaged the public in the search for exoplanets through articles for the online Pale Red Dot initiative, for which Tuomi was on the editorial team [**5.6**]. This was a public engagement campaign to inspire people in astrophysics and STEM and reveal processes behind the science. Between 2016 and 2018 the Pale Red Dot campaign was followed by 3,711 people on Facebook and 3,100 people on Twitter. A live public Q&A with members of the Pale Red Dot editorial team about the Proxima b discovery was conducted through the popular online forum Reddit, hosted by AskScience (which has 20.3m members on the platform). The thread resulted in more than 1,000 questions and comments and attracted 9,600 likes [**5.6**]. The Pale Red Dot Campaign won the Research Impact Award at the Guardian University Awards 2017 [**5.6**].

Inspiring and shaping the objectives of space missions beyond our solar system

UK Government ministers cited the Proxima b discovery as evidence of UK's global leadership role in science [**5.7**]. In the STFC media release, in which Jones and Tuomi were quoted, the Science Minister said: "*The discovery of Proxima b adds to what has already been a momentous year for UK space research, and our global leadership in science and innovation.*" The Business Secretary said the finding was "*testament to the hard work and scientific endeavour of UK institutions who are leading the charge and making discoveries that could change lives and inspire millions around the world.*" In fact, the identification of Proxima b also had a clear practical impact: it inspired or shaped the key objectives of three high-profile space missions. The discovery of Proxima b has shaped a multi-million-dollar programme to develop nano 'space probes' capable of reaching the Alpha Centauri system in just 20 years [**5.8**]. With initial funding of $100m from Russian billionaire Yuri Milner, the Breakthrough Starshot project was launched by Milner, Zuckerberg and Hawking in 2016. Proxima b has become the initiative's chief target. The project, which has received widespread media coverage, is '*aiming to demonstrate proof of*

concept for light-propelled spacecraft that could fly at 20 percent of light speed and, in just over 20 years after their launch, capture images and other measurements of the exoplanet Proxima b' [**5.8**]. The *New Scientist* quoted the head of Breakthrough Starshot's advisory board as saying: '*It (Proxima b) shows that there is a target we can go and visit*.' A presenter for The Sky at Night told the Guardian: '*I think just having a target to aim for will inspire more. Now we know it's there, surely we have to go?*' [**5.8**] The mission to Proxima b was explored in a 90-minute BBC2 documentary screened in 2017 called *The Search for a New Earth*, co-presented by Hawking [**5.8**]. In 2017, *New Scientist* reported that NASA had begun plans for an interstellar space mission in 2069 to mark the 100th anniversary of the first moon landing. Proxima b is its key target [**5.8**]. The discovery of Proxima b also inspired Project Blue, a mission to take the first image of an earth-like planet in the Alpha Centauri star system. Covered by *Science* magazine and the BBC's *Science Focus*, Project Blue aims to build and launch a compact telescope to image the habitable zones of the nearest Sun-like stars to Earth [**5.8**]. The identification of Proxima b demonstrated what might be possible. According to Project Blue: '*… we now know that there's a terrestrial-class planet orbiting one of the stars in the Alpha Centauri system. This makes us optimistic that there could be other rocky planets orbiting Alpha Cen A and B*.' [**5.8**]

Inspiring new creative digital and artistic outputs that engage the public imagination

The discovery of Proxima b resulted in the creation of artistic representations of the exoplanet, further engaging the public imagination in what a rocky, Earth-like planet four light years away might look like. A video titled *The exoplanet next door*, published by Nature on YouTube to accompany **3.6**, received 610,000 views, 3,400 likes and 861 comments [**5.9**]. There are numerous creative digital animations and HD footage depicting Proxima b on YouTube. As an example, one video published by science channel *What If* in 2020, titled *What If We Relocated Humanity to Proxima B?*, received 1.3m views, 31,000 likes and 3,900 comments [**5.9**]. In 2017 a documentary film on Proxima b – Journey to the Pale Red Dot – was broadcast on Amazon's Prime Video (it was still on the platform at the end of the impact period) [**5.9**]. In August 2020, NASA released an artist's impression of a view of the surface of the planet Proxima b orbiting the red dwarf star Proxima Centauri [**5.9**]. In December 2020, an artist partnering with the same NASA team that announced the 2069 interstellar mission announced she was developing sound artwork 'Tree of Life' to be sent to Proxima b – a deliberate reference to the Golden Record, a phonograph record sent into space on NASA's Voyager spacecraft, launched in 1977 [**5.9**].

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

5.1 Altmetric data for *A terrestrial planet candidate in a temperate orbit around Proxima Centauri*, published in Nature (2016): https://www.altmetric.com/details/10799842
5.2 Summary report of the media coverage of the discovery of Proxima b, including key articles that corroborate the fundamental research contribution of UH researchers.
5.3 Altmetric data for *Color Difference Makes a Difference: Four Planet Candidates around Tau* Ceti, published in The Astronomical Journal (2017): https://www.altmetric.com/details/23502851
5.4 Altmetric data for *A candidate super-Earth planet orbiting near the snow line of Barnard's star*, published in Nature (2018): https://nature.altmetric.com/details/51188957
5.5 Nobel Prize in Physics 2019 – A *Nature* collection inc. **3.6** and **3.7**. https://www.nature.com/collections/ebcebiijci
5.6 Summary report of articles corroborating the UH contribution to Pale Red Dot and its impact.
5.7 Comments by two UK Government Ministers on the significance of the Proxima b discovery: https://webarchive.nationalarchives.gov.uk/20200923135203/https://stfc.ukri.org/news/new-earth-like-planet-found-orbiting-nearest-star/
5.8 Collection of articles corroborating how Proxima b findings influenced three space missions.
5.9 Summary report of the digital and artistic outputs inspired by the Proxima b discovery.