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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2018 January 12 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

A. M. Cruise, *President-Elect*
in the Chair

The President-Elect. Good afternoon, and happy New Year to everyone. Those of you seated near the front will realize that I am not John Zarnecki. Our President has been at the American Astronomical Society, and he is on his way back at the present. I have been asked to chair this meeting. My name is Mike Cruise. In addition to that, I have a lot of announcements to make this evening, so I hope you will bear with me. I will go through them as quickly as I decently can, but there are some important announcements. First of all, I would like to say "Happy Birthday" to you all. Today is the 198th anniversary of the legendary dinner at the Freemason's Tavern, where a group of astronomers decided to establish a Society. Annette has been kind enough to get hold of the minutes of that meeting. An extract goes, "At a meeting held this twelfth day of January 1820, at the Freemason's Tavern, London, to take into consideration the advantages that are likely to result from the establishment of a Society for the cultivation of Astronomy, We, whose names are hereunto subscribed, being fully aware of the utility of such an institution, do hereby mutually agree to constitute ourselves a Society, to be called the Astronomical Society of London ... ." And the founding members John Herschel, Charles Babbage, and the Reverend William Pearson (who are well known to us) are in the record. It is two years until our 200th anniversary and the Society is obviously making preparations for that.

I would like also to welcome Philip Diamond, our new Executive Director. [Applause.] We are absolutely delighted to have Philip with us. He joins us from the Institute of Physics, where he was the Associate Director for Policy and Programmes. Philip studied physics at university and spent his early career as a medical physicist at the Royal Free Hospital in London before moving to the Institute of Physics in 1990. We are particularly pleased to have him as our Executive Director going forward. We have a lot of challenges and a lot of excitement and opportunities to face. I am sure that Philip will be keen to work with all of you, get to know all of you, and I am sure he will make a huge contribution to the Society.

Now, I have a number of announcements to make about the 2018 RAS Awards. I am aware that some of the people being awarded these prizes are in the room. I think it would be particularly nice if they could just stand up and we should all give them a good clap. I think we should clap anyway, because we never know who is here and who is not here. If you are here, and your name is read out, please just stand up quickly and bask in the moment. [Laughter.]

The first are the Gold Medals. I am pleased to announce that Professor James (Jim) Hough, from the University of Glasgow, is awarded the Astronomy Gold Medal, and Professor Robert White, from the University of Cambridge, the Geophysics Gold Medal. The Chapman Medal this year will go to Professor Emma Bunce from the University of Leicester. The Eddington Medal this year goes to Professor Claudia Maraston, and she is there! [Applause.] The Herschel Medal goes to Professor Tom Marsh (University of Warwick). The Price Medal is awarded to Professor [Stuart] Crampin (University of Edinburgh) and the Jackson-Gwilt Medal to Professor Wayne Holland of the UK Astronomy Technology Centre. The Patrick Moore Medal goes to Miss Jenny Lister, who is a Year-1 teacher and coordinator of science and humanities at St. George the Martyr C. E. Primary School; she is the first primary-school teacher to win the Patrick Moore Medal and I think that is great. The Annie Maunder Medal for Outreach is presented to Dr. Helen Mason from the University of Cambridge. The Fowler Award in Astronomy goes to Dr. Amelie Saintonge of UCL, and Dr. David Jess from Queen's University Belfast gets the G award. The Winton Awards go to Dr. Rebecca Bowler from the University of Oxford, for Astronomy, and to Dr. Kerri Donaldson Hanna from the University of Oxford, for Geophysics. The Group Award in Astronomy goes to the *Planck* team and in Geophysics to the *COMET* team. The Service Award in Astronomy goes to Professor Mark Cropper of the Mullard Space Science Laboratory (UCL) and in Geophysics to Dr. Matthew Taylor, who led many of the outreach aspects and the operations of the ESA *Rosetta* mission. We have awarded Honorary Fellowships in Astronomy to Professor Pascale Ehrenfreund (German Aerospace Center, DLR), and in Geophysics to Professor Jaime Urrutia-Fucugauchi (National University of Mexico). The George Darwin Lecturer is Professor Stephen J. Smartt from Queen's University Belfast. The Harold Jeffreys Lecturer is Dr. Alessandro Morbidelli from the Observatoire de la Côte d'Azur. The James Dungey Lecture will be given this year by Professor James Wild from the University of Lancaster, and the Gerald Whitrow Lecture will be given by Lord Rees of Ludlow, the Astronomer Royal. [Applause.]

So that is our list of awards and medals. It is one of the important moments in the Society's year where we recognize really high-performance activity and achievement from people at the end of their career, the middle of their career, and early in their career. Can I go back to the issue of nominating people for thesis prizes. Please do that; it gives people a huge lift in the early parts of their career if they get one of these awards.

Now I have done all the introductions (you will be very pleased to hear) and I can move on to the actual programme. I am going to ask Professor Ineke De Moortel from St. Andrews to give a talk on 'The role of MHD waves in coronal heating'.

Professor Ineke De Moortel. Ever since Grotrian & Edlen discovered that emission lines observed during a total solar eclipse were due to highly-ionized iron (and not a new element 'coronium'), the extremely high temperatures in the Sun's atmosphere have been puzzling solar physicists; the temperature of the Sun's outer atmosphere (corona) is of the order of a million Kelvin and more, orders of magnitude higher than the 6000 K surface temperature. It is now known that this phenomenon is not unique to the Sun, but that many stars have hot coronae.

It is generally accepted that the Sun's magnetic field is a crucial agent in transporting energy from below the Sun's surface into the atmosphere. A key problem, though, is the creation of sufficiently small length scales to allow dissipation of this energy to occur. Traditionally, two main heating mechanisms have been considered, namely reconnection (based on slow foot-point motions) and wave-based heating, associated with fast foot-point motions. Today, I want to focus on wave-based heating mechanisms in coronal loops.

Alfvén waves are of particular interest as they are expected to reach the corona with minimal reflection at the transition region (where the temperature and density gradients are particularly steep). Mechanisms such as resonant absorption and phase mixing have been proposed to facilitate the creation of small length scales and hence accelerate the wave dissipation.

In the last two decades, high-resolution and fast-cadence observations have confirmed that waves and oscillations are abundantly present throughout the solar atmosphere, and that these observed waves contain a substantial amount of energy. However, it is unclear if, and how, those waves contribute to coronal heating, in particular, whether heating can be 'delivered' by the observed waves in the right locations and on the right time-scales.

There are four key difficulties associated with wave-based heating mechanisms. Firstly, damping *versus* dissipation. Although many of the observed waves and oscillations are observed to damp rapidly (with the damping time generally of the order of a few periods), this damping does not directly imply dissipation. Mechanisms such as resonant absorption and mode coupling can lead to rapid damping of, for example, an observable transverse oscillation, by transferring the energy of this displacement into (hard to observe) azimuthal perturbations in the boundaries of the loop. This transfer of energy would be observed as rapid damping of the transverse-loop oscillation, but does not correspond directly to dissipation and hence heating.

Secondly, dissipation time-scales present a substantial difficulty for wave-based heating mechanisms. For 'accepted' values of the magnetic Reynolds number, the expected dissipation time is far in excess of the damping time of the oscillations, implying that no heating would occur during the (observed) lifetime of the oscillations. Current models require a magnetic Reynolds number 6–8 orders of magnitude smaller than predicted to achieve dissipation of the wave energy during the observed lifetime of the oscillations.

Next, what about self-consistency? Wave-based heating mechanisms such as phase mixing and resonant absorption rely on the presence of a gradient in the Alfvén speed, which models usually assume to be caused by a gradient in the local (transverse) density, *i.e.*, the loop is assumed to be denser than the environment. However, radiation is stronger in higher-density regions and hence the densest parts of the loop (the loop core) will cool fastest — this is where the heating is needed, not at the strongest gradient (the edges of the loops) where the wave-based heating mechanisms contribute most of their thermal energy.

Finally, I want to discuss feedback and efficiency. It has been suggested that wave heating could change the local density profile: heat is transported along the field lines to the lower (cooler) layers of the atmosphere, where it causes material to evaporate and hence alter the local density. That could create additional density gradients which might accelerate the wave-based dissipation and lead to drifting of the heating layer, and hence provide heating throughout the 3-D volume of the loop, rather than just in the boundary layer. However, using typical coronal values, this density feedback is found to be dominated by the thermal evolution of the loop and as such is unlikely to be effective.

So, what is next for wave-based coronal-heating models? The fast creation of sufficiently small length scales is the key obstacle and recent modelling has focussed on creating fine structure by processes akin to a turbulent cascade. For example, the generation of the Kelvin–Helmholtz instability at the edges of transversely-oscillating loops leads to increasingly complex vortex structures and fine-scale current sheets, which might facilitate heating distributed throughout the loop. Similarly, a complex, turbulent-like pattern of counter-propagating waves can develop from Alfvénic perturbations reflecting off internal (longitudinal) density gradients or *via* 'uniturbulence' — a recently suggested mechanism describing the *in-situ* generation of downward (co-) propagating perturbations (due to transverse gradients or structuring in the density) which also leads to the generation of thin, distributed current sheets.

To conclude then, waves are present beyond doubt in a wide range of structures in all layers of the solar atmosphere. Many of these observed oscillations are reported to contain substantial amounts of energy, of the order of the requirements of, for example, the quiet-Sun heating. However, whether these waves really contribute to heating of coronal loops remains an open question; there are substantial difficulties to be overcome by wave-based heating mechanisms proposed so far, and, certainly in active-region loops, non-wave-heating mechanisms appear less problematic based on current modelling.

The President-Elect. Thank you very much indeed, and sorry to pressure you for time. Open for one question I think. I have one! Is there a real 'killer' observation? Regardless of what instruments can now do, what would you really like to see on these two-to-three-million solar satellites that are going round our Sun at the moment?

Professor De Moortel. I do not think we know that yet. I think that is really where the models have to focus. Is there actually a signature that will allow us to say that is what the heating mechanism is? I am looking at the back row where my solar colleagues are, and I do not think we have got it yet. I think there are hints in some of the high temperatures, but I do not think we quite have a definitive observational signature yet.

The President-Elect. Thank you very much indeed for a lovely talk. [Applause.]

I would like now to invite Dr. Cosimo Inserra, who is the winner of the Winton (A) Award. He is going to talk to us about 'Exploring the brightest supernova explosions'.

Dr. C. Inserra. How do stars explode? Such a question has fired our imagination for hundreds of years. We thought we knew how to answer it, but during the last decade new types of stellar explosions, a hundred times brighter than any other type, have been found. My research on cosmic explosions, known as supernovae, tests the physics of the most luminous among them to answer that question. Supernovae are stellar explosions portraying the pinnacle of a star's life, and have a great impact upon many astrophysical areas, including chemical enrichment and stellar evolution. They can produce heavy elements, such as iron, or the raw materials for planet formation, and their extreme luminosity allows them to be seen and exploited as cosmological probes of the distant Universe.

The last decade has seen the surprising discovery of new classes of supernovae in the luminosity/time-scale parameter space. At the luminous end of the supernova distribution we find the so-called 'super-luminous' supernovae, some one-hundred times brighter than classical supernova types. They offer the potential for a new class of standard candle and occupy a previously unexplored area of the supernova parameter space. They cannot be explained by standard explosion mechanisms, such as a thermonuclear explosion or the collapse of the core of the star into itself, known as a core-collapse explosion. These events question our understanding of how stars explode. The daunting challenge over the next decade is to comprehend their observables and their underlying physical nature, which will provide several astrophysical by-products allowing the investigation of galaxy evolution and the interstellar medium up to high redshift ($z \sim 4$–6).

In 2013, my first contribution to this research area was to shed some light on the explosion mechanism. My team and I suggested that a rapidly rotating star, with a radius of about ten kilometres and a magnetic field billions of times stronger than that of the Earth, called a 'magnetar', is responsible for their extraordinary luminosity. Thanks to the analytical code we developed, we were able to reproduce the main electromagnetic observables of such astronomical transients, revealing information about the physics of the explosion in terms of energy released and amount of mass ejected into space. We also confirmed what was previously suggested by other researchers, that such super-bright explosions were indeed connected to a somewhat normal core-collapse event but with an additional contribution coming from the magnetar. Unexpectedly, this new research has also uncovered a variety of these supernova explosions.

Since we are now witnessing a variety of super-luminous supernovae, with roughly 70 objects discovered so far, we are now in a position to begin statistical studies which can better define a super-luminous supernova event. With that in mind, I led a team of researchers at the University of Southampton with the purpose of applying novel statistical and data-processing techniques from the machine-learning community. This cross-disciplinary approach has led to a more coherent methodology to define such events and to discover the existence of two well-separated subclasses of objects and, hence, possible exploding scenarios. There are still several hot research areas in super-luminous supernovae, in which interest rivals only that of gravitational-wave science. Among them, there are a few appealing to the UK community.

For example, investigating the geometry of such explosions can further probe the explosion mechanism and how the material is ejected into the Universe. This is possible through a peculiar kind of astronomical observation called spectropolarimetry, based on the physical concept of polarimetry. Hunting for them billions of light-years away is also important since they can reveal information about the evolution of the Universe, especially if used as cosmological probes. At the University of Southampton and the Institute of Cosmology and Gravitation in Portsmouth, a team of the Dark Energy Survey researchers and I have finally confirmed what astronomers hinted and hoped for years ago: super-luminous supernovae can be used as standard candles in a similar fashion to thermonuclear supernovae. A standard candle is any distinguishable class of astronomical objects of known brightness that can be identified over a wide distance range. This will open a new horizon of cosmological analysis with supernovae since predictions for the *Large Synoptic Survey Telescope* suggests that 10 000 of these objects will be found up to redshift 2·5, which will be augmented by the 200 coming from the European Space Agency *Euclid* satellite probing them up to redshift 3·5.

These numbers suggest an incredible stream of super-luminous supernovae in the next decade, which can help in revealing the physics of these objects and unleashing their true potential as cosmological probes. The most promising way to take advantage of such a wealth of data is to approach the new era of astronomy with statistical studies, deploying advanced algorithms from the machine-learning community.

The President-Elect. So, time for questions? Yes, Richard.

Professor R. S. Ellis. That was a very nice talk. You mentioned that the super-luminous events only occur in sub-luminous galaxies. Presumably that is something to do with gas-phase metallicity, but I cannot see what would differentiate those objects from the objects in the more massive galaxies.

Dr. Inserra. It has been debated now for eight years. There are people who suggest that the low metallicity (but, of course, not zero metallicity) we are talking about — roughly that of the Small Magellanic Cloud — is needed for the explosions of these events. Others have suggested that you need instead a high star-formation rate. Most likely the reply lies between those two reasons. As you said, there is no reason why you should not see them in brighter or more-metal-rich galaxies. Actually for the first time this year we got a super-luminous supernova that was in a solar-metallicity galaxy, and it was very nearby (a redshift of about 0·03); it was from the Sloan group. There are a lot of other factors involved in the evolution of these super-luminous supernovae that I did not want to include to avoid any confusion.

Professor I. Roxburgh. You present them as if they are a discrete group, different from others. Would you not expect a continuous variation, and have you not seen supernovae between your super-luminous and ordinary?

Dr. Inserra. There are some supernovae in between the super-luminous and the normal supernovae. What I believe is most likely — and if we believe the magnetar scenario — is that instead of releasing energy at a certain time and with a certain amount, it has an injection of energy that happens a little bit slower. So it would give a less luminous level than the super-luminous supernovae. But so far we have found fewer than the super-luminous supernovae, and basically we don't have any spectroscopic evolution. We always get one spectrum, a blue, hot continuum, which can basically be everything. Just a 15 000–20 000 Kelvin continuum with no lines, so we have no idea what is going on. After that, usually they all decline in seven days. So they go 'boom' and they disappear.

The President-Elect. Our next speaker is Dr. Jonathan Pritchard from Imperial College London, who will be talking about 'Mapping the Cosmic Dawn with the 21-cm line'.

Dr. J. R. Pritchard. [No summary had been received at the time of going to press.]

The President-Elect. Thank you very much indeed. Time for a couple of questions.

Professor Claudia Maraston. What hope do you think there is of distinguishing between warm dark matter, cold dark matter, and no dark matter, considering you need to decompose the initial fluctuations to start growing the signal in the matter?

Dr. Pritchard. When you start talking about the 21-cm signal there are always two directions people want to go in: to learn about the astrophysics, or to learn about the cosmology. I got involved because I thought this was going to be the next big CMB, and be really exciting for fundamental physics. As time goes by, I get a little bit more sceptical about that, because it turns out that astrophysics is really hard, complicated, and messy. Things like warm dark matter *versus* ordinary dark matter, assuming you can change the populations of low-mass halos and propagate that into the kind of heating or the ionization, then there can be large signals to look for. It is certainly not crazy. You need to come up with a way where you are confident that it is different from some other sort of feedback effect acting on the galaxies. And I think that is the sort of generic challenge for doing cosmology *versus* astrophysics: coming up with clean signatures where you are confident of what you are seeing.

The President-Elect. One more?

Mr. N. Jeffrey. I was interested by the Minkowski functionals for the topology of the bubbles. On simulations that seems fine, but if you start on data where there are literal holes from a mask or the edge of your survey, is there a simple way you would be able to fix that?

Dr. Pritchard. Simple? Probably not. Is it practical? I think that is a really interesting question. Measuring Minkowski functionals on the CMB — my understanding is that it has not been the easiest of things to do. There are some advantages here that your signal is not mean zero, and so noise and your signal are somewhat separated. Dealing with edge effects is not something that I have thought about. In general that sort of area is very undeveloped.

The President-Elect. Let's thank our speaker again. [Applause.]

People will be aware of the RAS Postdoctoral Fellowships, and we have an RAS Postdoctoral Fellow to talk to us today — Dr. David Marsh from King's College, London, talking about 'Studies on axion dark matter'.

Dr. D. Marsh. The effects of dark matter (DM) are observed across many astrophysical and cosmological systems, across a huge range of scales, from invisible substructures in the Milky Way smaller than a dwarf galaxy, to the size of the visible Universe in the Cosmic Microwave Background (CMB).

I'm a cosmologist (for the most part) and so one of my favourite pieces of evidence for DM is from the CMB. In particular, the *Planck* collaboration produced a beautiful all-sky map of the *lensing potential*. That map uses a four-point statistic of the CMB temperature to measure the deflection of photons from when they were emitted at the surface of last scattering until when we observe them today. It measures the integrated effects of DM along the line of sight. This effect is most prominent around redshift $z = 1$, but has contributions over the entire history of the Universe. From observations like this, we can infer two immediate facts about DM: (*i*) that it accounts for 84 % of the total matter content of the Universe ($0{\cdot}84 = \Omega_c/\Omega_m$), and (*ii*) that dark matter was present in large quantities at very early times when the CMB itself was formed (inferred from the relative heights of the acoustic peaks). The last observation verifies an important point about the standard cosmological model. The CMB contains small 'primordial' fluctuations. The presence of DM at early times, and the linear theory of the growth of structure, allow us to predict how those small fluctuations provide the seeds for galaxy formation later on in the history of the Universe. Thus, it is the same DM that we observe in the CMB that we also observe in local systems.

It is often said that DM is "mysterious" or that "we don't know what it is". While each statement is true to an extent, cosmologists and astrophysicists actually know quite a lot about the properties of DM, and also know a lot about what it isn't. So, what do we really know about DM? Permit me to continue the list from above: (*iii*) DM is 'cold' — if it was produced by thermal processes in the early Universe, it was non-relativistic when it decoupled from the thermal plasma (*e.g.*, CMB, galaxy clustering); (*iv*) DM is 'collisionless' — there is no observation that implies it has any interactions beyond gravity (*e.g.*, CMB, 'Bullet Cluster'); (*v*) DM was produced very early in the history of the Universe; (*vi*) it is present on many scales (*e.g.* , galaxy rotation curves, cluster lensing, CMB); (*vii*) it forms bound objects on scales as small as $10^6\ M_\odot$ (*e.g.*, tidal streams); (*viii*) DM is not composed of compact bound objects, *i.e.*, it is not made up of MACHOs or black holes (*e.g.*, microlensing); (*ix*) DM consists of just one component (plus a small amount of massive neutrinos) (*e.g.*, CMB, galaxy clustering). That is quite a list. Everything on this list is inferred from the gravitational interaction of DM only.

Furthermore, in almost all models for the fundamental properties of DM every one of those statements must break down at some level. Take, for example, the canonical 'supersymmetric weakly-interacting massive particle', the WIMP. WIMPs are produced thermally, by means of their self-annihilation. This means that they have to have some small level of self-interaction and interaction with the Standard Model particles, *i.e.*, WIMPs are not collisionless. That is how we search for WIMPs (and don't find them) at facilities like the *Large Underground Xenon* experiment in South Dakota, and the *Large Hadron Collider* at CERN. This means that WIMPs are produced with a small thermal velocity, *i.e.*, WIMPs are not completely cold. The thermal production cuts off the formation of structures by WIMPs, and the smallest bound objects composed of WIMPs are expected to be approximately Earth mass ($10^{-6}\ M_\odot$).

It is always interesting to search at the edges of our knowledge, and so I am going to explore a class of DM models that allows us to test the limits of each statement in our list of properties. The class of models is somewhat orthogonal to the standard WIMP model, but it has just as much of a vested history. This class of models goes under the umbrella term *axions*.

Axions are enjoying somewhat of a resurgence in popularity recently, thanks in part to the unsuccessful searches for WIMPs mentioned above. Axions were probably initially less popular than WIMPs because searching for them seemed extremely challenging, while the future of the WIMP was filled with much low-hanging fruit for potential tests. New ideas in direct axion detection that have appeared in the last decade have changed that story. If the proposed experiments fail to find axions in the next 15 years or so, they will probably only then be in the same situation (in terms of constraints on the most popular models) that WIMPs are in today.

Let's recall how a theoretical physicist sees the world. The world is described by quantum field theory (QFT), and to define a QFT we can use a Lagrangian density. For the Standard Model of particle physics, this Lagrangian famously fits neatly on a (very marketable) T-shirt. A term in a Lagrangian consists of two pieces: $\mathcal{L} = \text{(number)} \times \text{(operator)}$. The operator tells us what physical effect this term is describing, while the number tells us how strongly this effect should appear in an experiment, and is what we measure, and what our theories make predictions for. For the axion, the term of interest refers to the neutron electric dipole moment (nEDM).

A single term in a Lagrangian can be generated, after rearranging the equation and collecting like terms, from multiple different sources of physics. In such a case the number in our equation should really be written as:

$$\text{(number)} = \sum_{i\ \text{(Physics)}} c_i$$

where each c_i is a contribution to the measured number from different pieces of physics. In the case of the nEDM the number is the QCD vacuum angle, and there are contributions from the strong and weak nuclear forces. Furthermore, the contribution from the weak nuclear force is known to be a number of order one.

There have been experiments for decades trying to measure the nEDM. All measurements are consistent with a value of zero. The tightest bound comes from a 2015 re-analysis of data taken at the Institut Laue-Langevin between 1998 and 2002 . The value of the vacuum angle measured in radians must be less than 8×10^{-11}, suggesting that there is a cancellation between the weak nuclear force and the strong nuclear force in their contributions to the nEDM at the level of around one part in ten billion. Delicate cancellations like this make theoretical physicists uneasy. We call these cancellations "fine tunings" and we tend to seek explanations for them in terms of more fundamental principles.

The symmetry underlying the nEDM is related to charge conjugation (C) and parity (P) conservation in the strong nuclear force, and so this problem is known as the "strong-CP problem". The QCD axion solves the strong-CP problem using a dynamical mechanism and the global CP symmetry is an emergent property.

How does the axion do this? We begin with the concept of spontaneous symmetry breaking in the celebrated 'wine-bottle potential'. Spontaneous symmetry breaking happens everywhere in day-to-day life: when a pencil balanced on its end falls to one side, or when we choose to take our wine glass at the left or right hand when seated at a circular table with guests all around it. In the case at hand the symmetry is a continuous rotation: the wine bottle is a cylinder, and the breaking is caused when the physical state of the system falls off the 'punt' at the centre of the bottle, and must take a value at a single point in the 'heel' at its base, just like a piece of sediment settling if the wine rests vertically.

In physics, the angular degree of freedom, θ, describing the state of the system after symmetry breaking, corresponds to a massless particle known as a Goldstone boson. In our case the symmetry broken is known as a Peccei-Quinn symmetry, and the Goldstone boson is the axion.

Because of the rotational symmetry of the wine-bottle potential, no particular value of the field θ is favoured. The axion is said to "enjoy a continuous shift symmetry", meaning that the Lagrangian is unchanged if we make a change of variables $\theta \rightarrow \theta' = \theta \pm a$ for any real number a.

The trick is now to arrange the theory (using quarks and quantum mechanics) such that this Goldstone boson couples to the problematic operator in our Lagrangian. In such a case the sum defining the number in our Lagrangian now includes the axion:

$$\text{(number)} \xrightarrow{\text{symm. break.}} \text{(number)} + \theta.$$

Now we 'use the shift symmetry' and make a field redefinition, by which we can absorb the original value of the number into the definition of θ:

$$\text{(number)} + \theta \xrightarrow{\text{field redef.}} \theta$$

Hey presto, the multiple problematic contributions to our original number have been replaced by a single field. This in itself wouldn't solve anything: the field θ is still free to take on any value. To solve the problem, we use a quantum mechanical property of the strong nuclear force to pour our wine! The theory of the strong interactions contains a quantum quasi-particle known as an 'instanton'. The effect of instantons is that, at low temperatures (where here 'low' is anything below about 10^{12} K) they tilt the wine-bottle potential by a tiny amount (small compared to the width of the bottle). Now the sediment, the axion, slowly collects at a single point in the heel of the bottle. Thanks to the CP symmetry, the point in the heel where the sediment collects is at almost exactly $\theta = 0$, and so we have dynamically solved the strong-CP problem.

What does all this have to do with DM though? Well, it turns out that (and this was only realized some years after the original proposal of the axion) the sloshing of the sediment in the heel of the wine bottle carries energy density. The energy density contained in temporal oscillations and spatial gradients in the field θ behave exactly like cold, non-relativistic matter. The axion interacts very weakly with ordinary matter and makes a perfect DM candidate (this is because the width of the bottle, the axion 'decay constant' f_a, is very large compared to the masses of the Standard Model particles, m, and the couplings scale like m/f_a). However, because the instanton tilt of the axion potential is so small, a typical axion is about 10^{15} times lighter than a typical WIMP!

Axion DM is also very strange and different to WIMPs in another way. WIMPs are well described as particles, flying around the Galaxy and colliding with nuclei on Earth like billiard balls. The axion is better thought of as a classical field like the magnetic field, but a scalar rather than a vector. Furthermore, the energy density in axion DM is energy density held in the spatial and temporal gradients of the nEDM. This suggests a particular way to search for the axion that we will return to later.

The final part in our mini lesson in theoretical physics involves a discussion of axions in string theory. Hold on to your hats!

We are used to the concept in General Relativity that we use fields to describe the geometry of space. Simply consider the standard metric for the Friedmann–Lemaître–Robertson–Walker space–time that describes the expanding Universe in flat space using Cartesian co-ordinates:

$$ds^2 = -dt^2 + R(t)^2\, d\vec{x}^2$$

The scale factor $R(t)$ is a field that takes on a constant value throughout space, and its field equations are the Friedmann equations. We only need one scale factor to describe this flat, homogeneous, isotropic, and topologically trivial space–time.

Imagine, however, if space–time had some non-trivial topology, like a doughnut or torus. How many numbers do we need to describe the geometry on a torus? For simplicity, consider the simplest torus with a two-dimensional surface. To describe this geometry we need to specify how large is the circle through the centre, and how large is the circle around the edge. Thus we require two fields or moduli to specify the shape of the torus (in general each of these moduli could vary as we move around the torus, describing an arbitrarily bumpy doughnut, but never describing the topologically distinct football). The number of moduli we need to describe a surface of arbitrary topology in arbitrary dimension is specified by the topological invariants of the surface, numbers like the familiar Euler characteristic.

What does all this have to do with string theory and axions? Well, as you are probably well aware, string theory is a theory in ten-dimensional space–time. To make this consistent with the Universe we observe with four-dimensional space–time, we must use the old trick of Kaluza and Klein, and wrap the extra dimensions up small. Then we walk along our space–time like a tight-rope walker, oblivious to the details of the rope due to our size. The only thing about the extra dimensions that we care about is the thickness of the tightrope, or, for compact spaces with more complex topology, the values of the moduli fields.

Another property that string theory has is that it is supersymmetric. In terms of geometry, supersymmetry leads to axions 'pairing up' with moduli, so that the number of axions in the theory after Kaluza–Klein reduction is the same as the number of moduli.

As you can imagine, wrapping up six extra dimensions of space gives us a large number of different options for the topology that can be far more complicated than the humble torus. There is a very-well-studied class of string-theory models where the compact dimensions take the form of 'Calabi–Yau threefolds'. The topological invariants of these types of manifolds can be found mathematically. Using a computer program, Kreuzer and Skarke constructed a list of some 400 million Calabi–Yau threefolds, giving the relevant topological invariants of each. This list has one striking feature for our purposes: the distribution of manifolds is very strongly peaked for those containing 30 moduli. This means that a string theory 'drawn at random' from this list would be overwhelmingly likely to contain 30 axions. Nature probably doesn't draw theories at random, but this at least gives us a hint for what we might expect from string theory in the real world.

The seemingly obvious predictions of string theory, extra space–time dimensions and supersymmetry, could easily hide from us. The energy scales associated to these aspects could be huge, as large as the Planck scale and completely inaccessible to any conceivable experiment. It seems, however, that the presence of many different 'flavours' of axion is a generic, low-energy prediction of string theory.

Each different axion has different properties, mass, and couplings, determined by the values of the moduli fields. Different flavours of axions will behave differently in cosmology, and axions have been used to account for dark matter, to contribute to dark energy, to drive inflation, and even to assist with baryogenesis. They are potentially involved in solutions to all the major problems of theoretical cosmology. We can make progress in considering what such a scenario predicts for our Universe by treating the moduli as being drawn from probability-distribution functions, and relying on properties of universality stemming from the laws of large numbers.

Over the course of two years as an RAS Fellow I published a lot of work on these topics: thirteen papers as a main author, one as part of a large collaboration, two as a corresponding author, and one update of an older collaboration work. I'll give you a 'money plot only' description of five of the principal papers.

In the paper, 'Using the full power of the Cosmic Microwave Background to probe axion dark matter', I used a code I developed with collaborators, AXIONCAMB, to search for a contribution of 'ultralight axions' with 10^{-33} eV $\leq m \leq 10^{-24}$ eV to the DM density using the full *Planck* (2015) data release including temperature, polarization, and weak-lensing anisotropies of the CMB. That was the first time lensing was used to test the ultralight-axion model. We found that DM across the range of scales probed is consistent with being a single species, and the fraction of ultralight axions is limited to be less than 2% of the total DM at 95% confidence level.

I think this work is particularly cool, because the data also tell us that the CMB is consistent with all the DM being composed of ultralight axions as long as the mass is $m \geq 10^{-24}$ eV. This is the absolute lower bound on DM particle mass. It uses only linear theory, and so has very few systematic or theoretical uncertainties, and the statistics are extremely robust. I don't know of any theoretical models where the DM particle can be lighter than this, and I don't know of any statistical test as iron-clad as the CMB.

The constraint arises from two pieces of physics. The first is the scale imposed on gravitational clustering by the axion mass described above. This is related to the smallest scales on which axion dark matter clusters, and can be considered collisionless. The second comes from how the axion changes the expansion rate of the Universe at the time it was created, when the wine dregs began their descent to the bottom of the heel. So this constraint on DM particle mass is related to the constraint that DM had to be present in the Universe before CMB formation. The constraint on the ultralight-axion density is related to the constraint that DM is a single component.

Looking to the future, constraints like this will improve dramatically with the proposed *CMB-S4* mission, which could detect sub-percent ultralight-axion fractions at many sigma, and improve the lower bound on DM particle mass by up to two orders of magnitude.

A paper called 'Unbiased constraints on ultralight-axion mass from dwarf spheroidal galaxies' looks at whether the axion de Broglie wavelength can be large enough to provide cores in dwarf spheroidal galaxies. We modelled the axion-induced density cores using a parametric profile from DM simulations that include the wave-like behaviour. Analysing stellar-velocity data in a combined Jeans analysis of the eight classical dwarfs we found a preferred axion mass of $m \approx 10^{-22}$ eV, suggesting a possible resolution of the cusp-core problem in this model (as found elsewhere in the literature). Using mock data, however, we showed that Jeans analysis in such a case is biassed in the recovered axion mass due to the well-known anisotropy degeneracy. We then showed that the method of Walker & Peñarrubia, which determines the slope of the density profile using an empirical relation for the enclosed mass for two chemodynamically distinct stellar populations, does not possess such a bias. We then constructed an improved estimator to use with this method, using the averaged line-of-sight-velocity dispersion instead of the enclosed mass. We applied the improved estimator to the cases of Fornax and Sculptor, which possess the required stellar populations. We found that, if the shallow slopes of the density profiles are to be explained by the de Broglie wavelength of axion DM, rather than by a stellar feedback model, then the improved estimator requires much smaller axion masses than other methods, $m < 0{\cdot}4 \times 10^{-22}$ eV at 97·5% confidence level. This low mass is in some tension with bounds on the axion mass from the abundance of high-redshift galaxies, which typically require $m > \sim 10^{-22}$ eV. This suggests that a cosmologically consistent resolution of the cusp-core problem in the ultralight-axion model may be in trouble, as is already the case for warm DM.

In 'Searching for the QCD axion with gravitational microlensing', I explore a link between the smallest structures formed of QCD-axion DM and the microlensing constraints on the Massive Compact Halo Object (MACHO) and Primordial Black Hole (PBH) models, in which DM is composed of massive compact objects, rather than particles. In the QCD-axion model the spontaneous symmetry breaking leading to axion production can occur during the radiation-dominated epoch of the hot Big Bang (rather than before this, during inflation). If this happens then the symmetry breaking is uncorrelated on large scales, leading to large-amplitude fluctuations in the axion DM field. The horizon size at the QCD phase transition sets the minimum mass of DM halos in the QCD-axion model, $M \approx 10^{-10}$– 10^{-12} $M_\odot$, somewhat smaller than the WIMP case. The large fluctuations caused by symmetry breaking occur at exactly the scale of these smallest halos, leading to a characteristic population of extremely dense axion DM structures known as 'miniclusters'. If a large fraction of the DM resides in these bound structures, then this has profound implications for axion direct detection by dramatically reducing the rate due to the small probability of an encounter between the Earth and a minicluster. Axion DM experiments such as *MADMAX* (under construction in Germany) that target the 'classic axion window' are susceptible to this uncertainty. Simulations of axion DM do not yet give a good picture of the minicluster population, and so we set out to constrain it observationally.

We modelled mass and size distribution of miniclusters based on the Press–Schechter model of structure formation, and on numerical simulations of miniclusters in the literature. We then modified the standard microlensing-event-rate calculation to account for lensing by objects of finite size, and showed that the densest miniclusters can lead to an appreciable microlensing rate. The recently published results from the *Subaru Hyper Suprime Cam* of a high-cadence microlensing survey found no events in the range of time-scales relevant to miniclusters. We used this result to place the first observational bound on the minicluster fraction in the mass range relevant to the QCD axion. In future, if numerical simulations can make accurate predictions for the theoretical size distribution of miniclusters, our results could be used to exclude a wide range of QCD-axion parameter space. Future microlensing surveys over a longer time period (the *Subaru* survey used a single night of observations) could be used to discover evidence for miniclusters.

'Search for axion-like dark matter through nuclear-spin precession in electric and magnetic fields' is the last paper I have chosen to highlight a new direction in my work: methods of axion direct detection using particle-physics experiments on Earth. As discussed, the axion leads to a time-dependent neutron electric-dipole moment (nEDM). The coupling of this operator is g_d, and the nEDM oscillates with a frequency given by the axion mass, $f \sim (m/10^{-15}$ eV) Hz, and an amplitude set by the local axion DM density. I realized that there were no dedicated analyses of laboratory data in the literature to place direct constraints on this coupling. I computed the estimated size of the signal compared to the sensitivity of the world-leading nEDM experiment, conducted at Institut Laue-Langevin. I determined that archival data on this measurement, which goes back many years, could be used to place very strong constraints on g_d (stronger than any astrophysical constraint from stellar evolution or light-element abundances). Due to the long time over which the measurements were taken, I realized they could place constraints at very low frequency, probing ultralight axions that have not been constrained in the lab before. My theoretical colleagues and I contacted the experimentalists with this idea and asked if we could use their data to search for nEDM oscillations induced by ultralight axions. We were invited into the collaboration, and the analysis was performed by the experimentalists. Our null result placed the first laboratory constraints on g_d, covering around five orders of magnitude in particle mass, and our constraints on the coupling strength beat the astrophysical ones by up to three orders of magnitude. We were also able to use new data from the upgraded experiment at the Paul Scherrer Institute. These constraints are an important benchmark for the upcoming *CASPEr-Electric* experiment (under construction in the US), which will use the same coupling and techniques from NMR to search deeper into the parameter space with hopes of discovering the QCD axion. We also placed new bounds on the axion coupling to nucleon spins, which exceed bounds coming from direct searches for spin-dependent fifth forces and provide a benchmark for the *CASPEr-Wind Experiment* (under construction in Germany).

In the winter of 2017 I finished my time as an RAS Fellow, one year early, and left London to start a new position at the University of Göttingen. Samuel Johnson said: "When a [person] is tired of London [they] are tired of life", so why would I leave? I left to take up a long-term group-leader position, funded by the Alexander von Humboldt foundation. The position is a Sofja Kovaleskaja award (named after the first female professor in Europe) for €1·65 million, providing funding for myself, two postdocs, and two PhD students for five years. Without a doubt I would not have been awarded that position if it were not for the opportunity and academic freedom offered me by the RAS Fellowship, and the successful research I undertook during my time at King's College London. I am extremely grateful to the Royal Astronomical Society for funding my postdoctoral research. I am also grateful to my hosts at King's College London for providing a stimulating working environment and a bevy of talented collaborators without whom I could not have succeeded in completing this work.

The President-Elect. Time for one question. Claudia has got her hand up already.

Professor Maraston. I have a question, but the first is a comment. The first female professor was in Italy in sixteen-hundred and something, in the University of Bologna! You need to correct that. [Laughter.] But the talk was fantastic. I wonder why, for the cusp–core problem, you could not use massive galaxies, which have much more signal in the centre where this problem is very significant. A dwarf galaxy is very faint.

Dr. Marsh. As you mentioned, there are cores in other types of galaxies (in LSBs perhaps) and also cores in clusters. You certainly couldn't explain those cores with an axion. Those cores are much bigger. Cores are given by the ground states of the equations, so they are a one-parameter family, and the core size, as you increase the mass, gets smaller. It is like you are trying to form black holes; as you increase the mass, things get more compact, and eventually they collapse into black holes. The cores in clusters and LSBs are very massive, but also very large. If you wanted to get such cores from an axion, it would be in strong violation of the cosmological constraints. The reason we wanted to explain the cores in dwarf galaxies is because you can just about live on this knife-edge where you can explain the cores and be consistent with cosmology. You can explain the cores without recourse to baryonic feedback. So that is why we looked there, because it is the place we could try and live on the knife-edge and maybe make a prediction from observations.

The President-Elect. I think we can thank our speaker again. That was fantastic! [Applause.] Can I remind you (in case you need it), that there is a drinks reception now in the RAS Library. And finally, I give notice that the next monthly Open Meeting will be on Friday, 9th February 2018.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2018 February 9 at 16^{h} 00^{m}
in the Geological Society Lecture Theatre, Burlington House

J. C. ZARNECKI, *President*
in the Chair

The President. I have to start with some very sad news, that I am sure many Fellows will be aware of. We lost on Monday last, 5th February, Donald Lynden-Bell. Donald, of course, was an absolute stalwart of the Society. He would almost always be sitting there in the middle, a few rows back, supporting meetings, asking probing but supportive questions. It will not be the same without him. He was President of the RAS from 1985 to 1987. He was best known for his theories that galaxies contain black holes at their centres, and that such black holes are the principal source of energy in quasars. He was the first Director of the Institute of Astronomy at Cambridge. He was the first recipient of the Kavli Prize, a holder of both the Eddington and the Gold Medals awarded by the RAS, and many other awards. Some of you would have seen a full obituary in today's *Times*. Could I ask everybody to stand for a minute in his memory. [Silence.]

Some happier news to report concerning the national honours list in the New Year. The RAS is pleased to applaud space scientist Professor Michele Dougherty and geophysicist Professor Kathy Whaler, both of whom were recognized in the New Year's honours list. I do not think either of them are here, but hopefully we will be able to congratulate them in person at a future meeting.

We now move to the regular programme. It is a pleasure to introduce our first speaker, who is a fellow member of Council, Professor Brad Gibson of the University of Hull. His title is: 'Galaxy-scale catastrophes ... why we might be alone in the Universe'.

Professor B. Gibson. [No summary of this talk was available at the time of going to press.]

The President. Thank you very much, Brad, for depressing us?

Professor Gibson. It would be very easy to give a positive and uplifting talk, so I try and be a little bit different to demonstrate that there are some galactic-scale things that you are not fully aware of.

The President. We have time for a couple of questions?

Professor I. Crawford. I am not sure whether we should be depressed, because the fact is we have been around the Galaxy twenty times. The Solar System has had this history, and it has been exposed to all these risks, and yet the planet has been inhabited all that time. So doesn't that actually negate the idea that there is anything in the Galaxy that poses an existential threat, because, if there was, we wouldn't be here now?

Professor Gibson. It depends how often these things occur. If it happens every 100 million years, then yes, we have gone through 100 of these things. If it is more like a billion, then it is ten of them. Where we sit we are also in a sweet spot as well. We are at co-rotation, where we are almost moving at the same speed as the spiral arm. If we moved a little bit inwards or outwards, then the sort of effects you are talking about would become more regular. But, you are absolutely right. This is one of the positive things to take home, exactly what you just said. We are still here. There have been mass extinctions in the past.

They are probably not triggered by things like spiral-arm crossings and mid-plane crossings, but random things that have shaken up the Oort Cloud. I think that is the positive spin, we are still here.

The President. Before we move on, it was very interesting that you told us about E. A. Milne. You mentioned that Milne's daughter is here. I think it is a good opportunity to acknowledge that Meg Weston-Smith has given money to the Society and that forms the basis of the E. A. Milne Travelling Fellowships, which young Fellows of the Society are able to apply for. We are very grateful for that bequest.

Professor Gibson. We have gone from zero to twenty-seven staff and postgraduates, and we have got adverts out for another seven. A large part of that is because of support that Meg and her family have provided. [Applause.]

The President. Thank you also to Brad for your presentation.

We move now to Dr. Colin Snodgrass from the Open University, who is going to talk about 'It came from outer space..." I am not going to give the second part of the title, because it involves a Hawaiian word that I struggle with. You will tell us how to pronounce it correctly.

Dr. C. Snodgrass. 'Oumuamua was discovered on 2017 October 18 by the *Pan-STARRS* survey in Hawaii, and announced to the community on October 25 once its unusual hyperbolic orbit was confirmed. 'Oumuamua is the first macroscopic object (*i.e.*, bigger than dust grains) to be identified as passing through our Solar System rather than native to it, *i.e.*, it is a comet or asteroid from another star. It was discovered as it passed relatively close to Earth (0·16 AU), and was already fading quickly as it receded when the discovery was announced.

The discovery prompted rapid reaction from the comet/asteroid community, and discretionary time was secured at many major observatories over the following week, before 'Oumuamua faded from view. Observations included imaging with *HST*, *VLT*, and *Gemini*, and spectroscopy with the *WHT* and *VLT*, among many others. The importance of the discovery, and the urgency due to its rapid retreat and consequent fading, meant that override programmes secured data within 24 hours of the announcement, including a very rapid response from Joseph Masiero, who happened to be observing at the Palomar 200-inch *Hale Telescope* when the alert was issued. Rapid observation was followed by equally rapid publication of results, with Masiero's paper with the first spectrum appearing on arXiv by the following day, and a series of other observations, calculations, and theories appearing over the following days and weeks, and the first published result (from Karen Meech and the *Pan-STARRS* team) appearing in *Nature* by November 20.

The results were very surprising. It was expected that interstellar visitors would be comets, as most small bodies ejected from planetary systems should come from their icy outer regions, but 'Oumuamua did not display any coma or tail despite its close approach (0·25 AU) to the Sun. Its spectrum revealed a featureless red slope, similar to primitive asteroid types or cometary nuclei in our Solar System, but not as red as many Kuiper Belt objects. The largest surprise came from light-curve studies, which revealed changes in brightness over a large range on a rotation period between 7 and 8 hours, implying a very elongated body, with a ratio between its long and short axes of 10:1, vastly in excess of anything observed in our own asteroid population.

These results led to a large amount of speculation about the nature and origin of 'Oumuamua, including whether or not such a body could be formed by natural processes, or was an alien spacecraft! Radio telescopes were trained on it to search for any broadcast, just in case, but without success. The majority of researchers instead focussed on explaining the contradictory measurements *via* natural phenomena. Thermal modelling by Ben Rozitis revealed that comet-like surface properties, such as the very low thermal inertia measured by the *Rosetta* mission and others, could explain the lack of observed activity with a devolatilized crust, even if the interior of 'Oumuamua is icy. This has interesting implications for other similarly sized (about 100-m radius) 'comets' from our own Oort Cloud, suggesting that future surveys may well discover a large population of objects on Oort Cloud-comet orbits but with asteroidal appearance. Although the elongated shape implies a higher density than ice, and therefore a rocky composition, if 'Oumuamua is a strengthless 'rubble pile' like larger asteroids, it is likely that it is a single body with some material strength — and could still have an icy composition with even low (comet-like) tensile strength. Finally, the latest observational results tested whether or not the extreme light-curve was entirely due to an elongated shape, or could be due to albedo variations across the body, as seen for some larger Solar System objects. Putting together all the photometry collected over the week that 'Oumuamua was observable, Wes Fraser and colleagues found that 'Oumuamua may be slightly less elongated (but still at least a 5:1 ratio, which is still extreme by Solar System standards), is tumbling through space, and may have redder sides between more neutral coloured faces.

It remains a puzzle why 'Oumuamua should appear so unusual by the standards of the small bodies we know in our own Solar System. As the first interstellar asteroid/comet, it is natural to assume that its properties are typical of that population, which raises many questions about its formation and ejection from its home system, and what processes must be common in planetary-system formation and evolution. Alternatively, it may be that, by chance, the first object we found happens to be highly unusual. We will get a better idea with future discoveries, which are expected to become regular occurrences when the next generation of sky surveys (*i.e.*, *LSST*) come on-line in the next decade.

The President. Thank you very much, Colin, for a fascinating presentation. We have a few minutes.

Professor C. J. Lintott. If the suggestion is that it has red sides, does that make it unusual in our Solar System? Do we see small bodies with that sort of variation?

Dr. Snodgrass. It would be unusual for something that size. We don't have that much data on things of this size, but in our Solar System we know of some objects where you see changes in albedo. Pluto, for example, has got the white part one side and the dark red side on the other, but that is a much bigger object. In terms of small bodies (asteroids, comet nuclei), there isn't convincing evidence for things that have this difference of albedo across the surface. It is interesting in itself, why it should have that pattern. That is an open question.

Mr. E. Carpenter. The comet that went into Jupiter many moons ago, split up into ten or twenty bits I think. Could this be an object that consists of three, four, or five pieces?

Dr. Snodgrass. There was a talk at the Specialist Discussion Meeting earlier very much on that suggestion. It could be that this is a fragment of some larger object, and that is how you get the elongated shape. It has passed close to something, been stretched and spaghettified, smashed from a larger piece, but then escaped. There are dynamical models saying this is possible. The question, of course, with Shoemaker–Levy 9 going to Jupiter, it was spread out, but by that point it was doomed, it was going to crash into Jupiter. It had not spread out and then escaped. My understanding is that this is possible, and if Dimitri Veras is around somewhere still, he can talk more about that, because there were talks about that in the Specialist Meeting. So, it is possible, yes.

Professor S. Miller. How big did you say it was?

Dr. Snodgrass. A couple of hundred metres long, it is thought. We are waiting for the *Spitzer* data to give us an albedo and a better idea of the size. But assuming normal asteroid or comet-type albedos, it is hundreds of metres long. It is a pretty small object and that is why it was so faint and difficult to spot.

The President. Now that we have seen this strange object, is there any possibility that observing strategies or data analysis will change. Now that we know one such object exists, because of that will we find more?

Dr. Snodgrass. I think what will increase the chance of finding more is the improvement of technology of surveys. We found this thing now that *Pan-STARRS* is quite good at finding moving objects. *Pan-STARRS* has now been upgraded with a better camera, then *LSST* will come, and that will increase the rate. What would certainly be nice is discovering one of these things inbound, so we get a chance to look at it before it goes past. That would be what we would like to spot next.

The President. Thank you very much indeed, Colin. [Applause.]

Our next speaker is Dr. Christopher Chen (Queen Mary University of London). This is the Fowler Award 'G' 2017 talk, and the title is: 'Plasma turbulence in the solar wind'.

Dr. C. Chen. Plasma turbulence is a widespread phenomenon throughout the Universe. As well as being interesting and complex, it is also potentially important for understanding a range of space and astrophysical systems. For example, within our Solar System it may play a role in heating the solar corona to the high temperatures we observe and accelerating the solar wind, it controls the propagation of solar energetic particles and their space-weather impact, and it is present in planetary magnetospheres where it may contribute to particle energization. Further out, it is observed in the interstellar medium, where it controls local temperatures and cosmic-ray propagation, it is thought to enable angular-momentum transport in accretion discs, and it has been proposed as a route through which galaxy clusters can be heated.

Why is plasma turbulence so common? It is a result of scale separation: energy is injected into these systems at large (system-size) scales, but can only be dissipated at small plasma microscales (*e.g.*, scales comparable to the particle gyromotion around magnetic-field lines). Turbulence is the way nature finds to bridge that divide, forming a cascade of energy from large scales to progressively smaller scales in a scale-invariant process. Power-law spectra of fluctuations are formed, for example the famous 'Great Power Law In The Sky' of density perturbations over more than ten decades in the interstellar medium. The questions that we want to answer about this turbulence are: How do we explain the cascade process? What are the properties of a turbulent plasma? How is the energy dissipated at small scales? What are its macroscopic effects?

While there are many specific instances of plasma turbulence in nature, my research focusses on understanding the general fundamental principles involved, for which *in-situ* measurements are ideally suited. We have many spacecraft in the near-Earth plasma environment with cutting-edge, high-resolution instrumentation. For example, *Magnetospheric Multiscale*, launched in 2015, provides full 3-D ion and electron distributions at up to 150 ms and 30 ms resolution, respectively, at each of the four spacecraft, along with much higher-resolution electromagnetic-field measurements. I will talk about some of the results we have been able to extract from data sets such as this to understand plasma turbulence.

But before I get to those results, I want briefly to discuss some previous key findings. Soon after the first spacecraft reached beyond the Earth's magnetosphere into the solar wind it was realized that the fluctuations there form a power law over several decades, and that those fluctuations are polarized similarly to Alfvén waves — a fundamental plasma mode. Around the same time, theories of Alfvénic turbulence were being developed, notably the Iroshnikov–Kraichnan model of weak turbulence. Later, strong-Alfvénic-turbulence models were proposed, such as the Goldreich–Sridhar model in which the 'critical-balance' principle was introduced and the Boldyrev model in which turbulent eddies were predicted to become 3-D anisotropic or ribbon-like during the cascade. It is the predictions of those various models which we can test with the data.

To test the models, we can measure the spectrum of solar-wind fluctuations at different angles to the magnetic field. What we find is a $-5/3$ power law in the perpendicular direction but a steeper -2 power law in the parallel direction. This is exactly the prediction of the Goldreich–Sridhar critical-balance model. We can also test the critical-balance principle more directly by measuring the ratio of the Alfvén-wave time to the nonlinear-turbulence time — we find these to be equal over several decades, which is the best evidence so far for critical balance operating in space-plasma turbulence. A few years ago, we developed a technique to visualize directly the cascade by reconstructing the 3-D eddy shapes as a function of scale. What we found was that as the cascade proceeds to small scales, the eddies become increasingly elongated along the local mean magnetic-field direction, but are also anisotropic in the perpendicular plane, so end up as ribbon-like structures at the smallest scales. This small-scale shape is consistent with the predictions of the Boldyrev model. But as well as allowing such models to be tested, knowing the geometry of these structures is important for understanding how energetic particles propagate through turbulence, and the types of large-scale structures that may form in astrophysical plasmas as a result of turbulent perturbations.

For the rest of this presentation I will turn to the small-scale end of the turbulent cascade, at scales comparable to the particle gyromotion. Here, there are different possible routes for the energy — some may be dissipated to particular particle species, some may go into further cascades to even smaller scales, and some may be injected locally by plasma instabilities. Much recent work in the field has focussed on understanding the complex interaction between these processes, and we think to some extent all are taking place. In terms of further cascades, high-resolution measurements, such as those described earlier, have allowed us to observe many features consistent with a transition to a kinetic Alfvén turbulence cascade at the ion gyroscale, *e.g.*, a steeper energy spectrum and increased level of density fluctuations. In the Earth's magnetosheath we have also recently seen evidence for a transition to inertial kinetic Alfvén turbulence at sub-electron-inertial scales. In short, when we cross a special plasma scale, the properties of the cascade change.

So finally, how is the energy dissipated, *i.e.*, transferred from the turbulence to heat the plasma? Because these plasmas are highly collisionless, this is a complex problem, involving a series of plasma processes. Possibilities that have been proposed include Landau damping, cyclotron damping, stochastic heating, and specific structures such as reconnection events. Determining which of these are taking place is currently an unsolved problem, but as the quality of the data we are getting improves, we are moving towards being able to answer it. For example, we have started looking at correlations between the electromagnetic field and particle data at high resolution, seeing possible evidence for resonant energy transfer. However, this is a preliminary result and we will continue working on this over the coming months.

To finish, I'd like briefly to mention a relevant upcoming mission that will advance our understanding of plasma turbulence and the role it plays within our Solar System. Later this year, NASA will launch the *Parker Solar Probe*, a spacecraft that will travel to within 10 solar radii of the Sun with a comprehensive suite of *in-situ* and imaging instruments. For the first time, we will be able to measure directly the turbulence and heating processes in the solar corona and determine the properties and role of plasma turbulence there. This ambitious mission promises some ground-breaking new results and we are greatly looking forward to exploring this new and very different environment.

The President. Time for a few questions.

Professor Lyndsay Fletcher. As I understand it, once the energy is injected at the large scales and gets into the inertial régime, the cascade dissipation is inevitable. The plasma can only do so much to dissipate the energy, it only has a finite number of particles, or strength of field, or so on. How do the two match up? Can you get into the situation where the microphysics actually dictates how this cascade can proceed?

Dr. Chen. In a way that could be possible. What we see when we look at the inertial range cascade, the energy transfer we see happening is consistent with looking at just those large scales by themselves, and not considering the small-scale dissipation. From that, I would probably conclude that the microphysics processing is happening quickly enough that and they are not actually slowing down the cascade. If the small-scale processes were not able to dissipate quickly enough, we might get some build-up of energy, some shallowing of the spectrum, for example, but that is not what we see. So I would say that probably the plasma-physics processes on the small scale are quick enough to dissipate that energy that is coming out.

The President. Everybody seems to be satisfied. Thank you very much indeed. [Applause.]

So we come to our final contribution of the day. This is from Dr. John Veitch of the University of Glasgow. He is representing the *LIGO* Consortium, who received the Group-Achievement 'A' Award for 2017. The title is 'Listening to the stars: the dawn of gravitational-wave astronomy'.

Dr. J. Veitch. 2015 September 14 marked the fulfilment of a century-long quest to detect gravitational waves (GW), the last major prediction of Einstein's theory of General Relativity. It also marked the dawn of a new type of astronomy: for the first time we were able to listen to the minute ripples in space–time produced by the powerful engines of some of the Universe's most violent events: the collision of black holes and neutron stars. That discovery, made by the *Advanced LIGO* observatories in the United States with the aid of the worldwide *LIGO* Scientific Collaboration and the *Virgo* Collaboration (LVC), was recognized by the Royal Astronomical Society in their award of the 2017 Group-Achievement prize.

Gravitational waves were first predicted by Einstein as a consequence of his relativistic theory of gravity, General Relativity. Just as the electromagnetic field supports waves that travel at the speed of light, so too does the gravitational field, with a distinct gravitational-wave spectrum that can carry long-range information throughout the Universe. This gives them the potential to act as a medium for observational astronomy, in *addition* to all the bands of electromagnetic astronomy, from radio waves to gamma rays. Combining observations from gravitational waves, electromagnetic waves, and also neutrino and cosmic-ray observatories in 'multi-messenger astronomy' gives us the ability to study the Universe from multiple perspectives. However, gravitational-wave astronomy faces a challenge that has taken a century of advances in science and engineering to overcome: gravity is a famously weak force compared to electromagnetism. In the geometric picture of gravity as space–time curvature, it takes a comparatively large amount of energy to produce a measurable deformation of space–time. This has two implications: the strongest gravitational waves will be emitted by sources with large collections of dense matter moving rapidly, and gravitational-wave detectors must be extraordinarily sensitive to measure the tiny signals. The gravitational wave from a stellar-mass black-hole-binary coalescence produces a fractional length change of $< 10^{-21}$ by the time it reaches Earth. The nature of this strain means that a larger baseline will receive a larger absolute length change, motivating the kilometre scale of ground-based gravitational-wave detectors.

The path to the construction of the *Advanced LIGO* and *Advanced Virgo* GW detectors is the story of decades of effort by hundreds of scientists and engineers, developing the technology required to measure space–time strains of 10^{-21}. The current generation of gravitational-wave detectors operate by measuring the difference in the lengths of two optical cavities placed at right angles in the arms of the detectors using a modified Michelson interferometer placed in a high vacuum. Over the 4-km length of *LIGO*'s arms, the relative change in their length is just $\sim 10^{-19}$ m for a strong gravitational-wave source, less than the diameter of a proton. To achieve this, the laser light within the arm cavities must be stabilized in frequency, phase, and amplitude to reduce fluctuations at the output port. A high laser power in the arm cavities (100 kW) reduces the shot noise associated with the quantum nature of the light. The mirrors forming the cavity must be themselves be isolated from environmental vibrations which can easily swamp any gravitational-wave signal, which is achieved by suspension of the last stage of a quadruple pendulum. The environment of the detectors is monitored by seismometers, accelerometers, magnetometers, and other sensors so as to identify any disturbance which may produce spurious fluctuations in the output. Each of these subsystems, and the others required to control and operate the detectors for prolonged periods, has been the focus of research of the global community pursuing gravitational-wave detection. The initial *LIGO* and *Virgo* detectors, which took observational data from 2002 to 2011, marked an important milestone on this path, and gave the community the experience of operating large-scale detectors and analysing their data, producing a set of increasingly stringent limits on possible sources of gravitational waves. This was essential in the successful construction of the *Advanced LIGO* detectors, and the realization of the dream of gravitational-wave astronomy with the first detection on 2015 September 14.

The moment of the first detection passed in the blink of an eye — the gravitational wave, dubbed GW150914, lasted around 0·2 s in the detectors' most sensitive frequency band. From its short duration it was immediately clear that the origin (if real) had to be a high-mass-binary coalescence, but the natural scepticism of the collaboration scientists meant that months of frantic work had to be done to eliminate the possibility of a false alarm. Sixteen days of joint observations were taken to establish the statistical significance of the event, which was so loud that only an upper bound was placed on the false alarm probability of $< 2 \times 10^{-7}$.

Subsequent analysis confirmed that the source of GW150914 was indeed the coalescence of a pair of black holes with masses around 36 and 29 times that of the Sun, at a distance of around 400 Mpc. The existence of such coalescing massive BH binary systems had been theoretically predicted, but had never been demonstrated observationally. Since black holes do not emit light except through the effect of material in their environment, this previously unobserved world of binary black holes was an excitingly novel type of astronomical system for the first observations of gravitational-wave astronomy.

GW150914 was quickly joined by other detections: the first observing run of *Advanced LIGO* also produced GW151226, another black-hole binary with lighter components totalling 22 solar masses, and the less-significant LVT151012 event, if truly a GW signal, is of binary-black-hole origin too.

Between the end of the first observing run in 2016 January and the start of the second in November 2016, the advanced *LIGO* detectors underwent upgrades to increase their sensitivity. Three more binary-black-hole events have been reported, with analysis of the data collected still on-going. GW170104, with a total source mass $M_{\text{tot}} \sim 50\ M_{\odot}$, fell in between the first two events in terms of mass, whereas GW170608 ($M_{\text{tot}} \sim 19\ M_{\odot}$) was the lightest yet detected. GW170814 marked the first detection with the *Advanced Virgo* gravitational-wave detector, after it joined the observing run on 2017 August 1.

With those detections we are beginning to gain a fuller picture of the population of coalescing binary black holes, whose features are informing our models of how massive black holes are formed through stellar evolution. The rate of binary-black-hole coalescence is estimated to be between 12 and 213 $\text{Gpc}^{-3}\text{yr}^{-1}$, with multiple channels for the formation of such systems thought to be possible, including evolution of field binaries and dynamical interactions in dense stellar environments. The astrophysics of these different channels is uncertain, leading to variations of several orders of magnitude in the predicted rates of coalescence. Additional information on the progenitor systems can be provided by the mass distribution of the black-hole binaries, and their rate of coalescence as a function of redshift, which will be accessible as detector sensitivity improves and more detections are made at larger distances.

A particularly interesting possibility for distinguishing between formation channels is through the measurement of black-hole spins, and particularly their alignment with the orbit of the binary. Evolution of massive stellar binaries is thought likely to produce black-hole spins that are somewhat aligned to the orbit, whereas those sources formed through dynamical interactions between pre-existing black holes may not be so correlated. However, black-hole spins have a sub-dominant effect of the binary in-spiral signal compared to the masses, and so have proven more difficult to measure precisely. It may take many more detections to build up a statistical picture of the fraction of binaries formed through these different channels.

Coalescing binary systems have long been recognized as an ideal laboratory for testing theories of gravity, with radio observations of binary pulsars setting bounds on deviations of their orbits from the predictions of General Relativity. GW observations of coalescing binary black holes offer a new avenue for those tests: the orbits of compact binaries as their components merge at relativistic speeds. This has allowed completely new limits to be placed on deviations from GR in these régimes.

The second observing run, and particularly the expansion to a three-site network with *Advanced Virgo*, has also enabled a better localization of the sources on the sky. Knowledge of the source location has enabled an active programme of follow-up observations by partner observatories, with low-latency alerts set to be issued publicly in the third observing run later this year. Although black-hole mergers are not expected to produce a visible electromagnetic counterpart, the joint observing programme was to return a huge dividend on 2017 August 17 with the first observation in a new source class: binary neutron stars.

Unlike binary black holes, which were previously unobserved, binary neutron stars have been known to exist in our own Galaxy for many years, inspiring the effort to detect signals from their coalescence since before the construction of *LIGO* began. This prediction was confirmed in spectacular fashion by the observation of GW170817, the first binary-neutron-star coalescence, which was accompanied by GRB 170817A and a host of observations across the electromagnetic spectrum.

From a purely gravitational perspective this was an extraordinary event in itself, being the first in a new source class. The lower mass of neutron stars compared to black holes produces a weaker signal, but the slower orbital decay makes the duration of the signal much longer in the sensitive band of the detectors. This produces thousands of cycles of the gravitational wave instead of a few tens, carrying much more information about the rate of orbital decay. This carries much more information about the 'chirp mass' of the system, a particular combination of the component masses which most strongly determines the phase evolution. Isolating the component masses themselves requires knowledge of the mass ratio of the system, which is complicated by correlations with the spins of the individual stars. Nevertheless, the low mass of GW170817 is consistent with stars of total mass $2{\cdot}74\ M_{\odot}$, and mass ratio $>0{\cdot}4$ or $>0{\cdot}7$, depending on the assumptions made about the allowable component spins, comfortably compatible with the known masses of neutron-star binaries in our own Galaxy.

Unlike black holes, which are relatively simple objects of pure gravity, neutron stars have a material substance which responds to the strong tidal forces exerted by the stars on each other during the final stages of the coalescence. The effect that this has on the gravitational waveform can be used to infer the equation of state of neutron-star matter, which in turn determines the structure and size of the neutron stars themselves. The initial analysis of GW170817 was able to place upper limits on the tidal deformability (*i.e.*, the rigidity) of the neutron stars. These measurements are inspiring continued development of the theoretical waveform models, paving the way for more precise measurements in future.

The presence of matter in GW170817 was also responsible for the cornucopia of electromagnetic emission from the merger event, beginning with the gamma-ray burst GRB 170817A. Neutron-star mergers were hypothesised to be responsible for the energies unleashed in short gamma-ray bursts (sGRB), and so a joint detection in GWs and gamma rays was long sought after with GW observations. That the very first binary-neutron-star gravitational-wave signal should be accompanied by the closest-known sGRB was a gift from Nature. Even more fortunate was that *Advanced Virgo* had joined the run just days before, dramatically improving the localization capabilities of the GW network and enabling EM partners to identify quickly an electromagnetic counterpart near the galaxy NGC 4993. The emission from this counterpart was observed throughout the electromagnetic spectrum, yielding a wealth of observations to drive understanding of the aftermath of sGRBs and the production of 'kilonovae'.

Not long after the first gravitational-wave detection, the implications of the first multi-messenger observations are spurring excitement in many areas of astrophysics. A good example of this is the independent estimate of the Hubble constant, which is enabled by identification of a counterpart and estimation of its redshift. Gravitational-wave sources are 'standard sirens', which have a luminosity tied only to their distance and the intrinsic properties of the source, so that the luminosity distance can be measured from GWs alone. Combined with a redshift measurement, this enables a novel measurement of the Hubble parameter. Although with only one observation this is still imprecise, it shows the potential for further developments as more sources are detected in the coming years.

The huge impact of these first detections has been a long-awaited reward for the work of the thousand-strong *LIGO* Scientific Collaboration and *Virgo* Collaboration. Looking back over the first two years since the first observations of *Advanced LIGO* began, it is clear that the continuing commissioning of the detectors will lead to further improvements in sensitivity in the years to come. Along with longer future observing runs this will deliver greater numbers of detections of compact binaries, with lower noise levels, and each carrying another piece of the picture of the gravitational-wave sky. Meeting the demands of the advanced detectors as they approach design sensitivity is stimulating continual development of the analyses which identify signals, and a better understanding of their sources through theoretical and numerical modelling. It is fitting that this effort is recognized collectively through the RAS Group Achievement Award. The anticipation of the first detections has driven the work of decades in the design, commissioning, operation, and interpretation of the data from gravitational-wave detectors. Although the coalescence of compact binaries has, as predicted, been the first category of gravitation-wave signal to be observed, it is not the only one. Other types of signal are also possible, of long and short duration, and with signal morphologies that are less-well understood. Nature has shown her capacity to surprise us, and the collaboration is prepared for detections of novel and possibly unpredicted types. Alongside the continuing revelation of the population of compact binaries and the fundamental physics that drives them to coalesce, gravitational-wave astronomy and multi-messenger astronomy have a lot to offer toward our evolving understanding of the Universe.

The President. Thank you so much. That was fantastic, John.

Professor R. S. Ellis. When the first binary black hole was discovered, there was a very provocative paper which suggested that the ease with which you found the first object (so massive), meant that these black holes were a significant contribution to dark matter. And now you have so many of them, has this issue been revisited?

Dr. Veitch. It is an active thing we are actually reinvestigating. We are starting to look not just at the heavy-black-hole end, but also for lighter black holes. The thing about heavy black holes is that they can be formed by stellar evolution, so there is an explanation for their formation, without them being primordial black holes, for example. The stuff that comes from stars is not enough to infer dark matter. But, if there were primordial black holes as well, then they would expect to have a power-law mass distribution. That means that some of them would be sub-solar mass. I cannot think of any other way of producing a black hole that had a mass less than one Sun, so we are going to start looking in our data to see if anything like that is in there. Previously we started at one solar mass for our lowest-mass object. There are different camps that are either more or less positive about whether this is possible or not, even within our own community, but it is always worth looking in the data because you never know what might hit you. It is something that we are interested in for sure.

Mr. H. Regnart. Is there any possibility that the black-hole mergers you observed might be of Population III, very-massive-star remnants?

Dr. Veitch. Yes, I think so. People have been doing simulations of population-synthesis-type models, where they set up different initial conditions and try and predict the masses of the outcome. From those we know that to produce stars that produce black holes that are this massive, you need a very low metallicity, which suggests the environment they formed in was either in the early Universe or was in a particularly low-metallicity environment of one type or another.

The President. Could I ask you a technical question? You talked about sensitivity and the need for isolation. Is it such that there are no detections of terrestrial interference or are there terrestrial signals that are easy to eliminate?

Dr. Veitch. There are lots of different sources. Most of them are transient. The instruments have over one hundred thousand different monitoring channels in addition to the gravitational-wave channel (magnetometers, seismometers, and so on), so we can eliminate a lot of environmental stuff that way. But at the moment we are limited by seismic noise at the low frequency end, and more the fundamental, quantum noise at the high end. Man-made noise tends to come in short bursts, so we can try and veto it one way or another. It is a big challenge.

Dr. S. Serjeant. I have a question about your third run. I guess you are going to get to the point where you have got fifty or one hundred of these things in the bag, so what can we do to maintain the multi-messenger, multi-wavelength follow-up — the momentum — once we have got a lot of these things?

Dr. Veitch. Well, the first thing we are doing differently in the third run is the alerts, which were previously going to selected partners, are now going to be publicly available. Anyone in the world can sign up to receive them, so that will reveal the sky location of our potential sources. It just makes it easier for people to access the data that they need to do opportunistic follow-up. There will be a lot of interest in seeing if other binary-neutron-star–GRB coalescences can be detected at all. This was also the closest GRB that has ever been seen, so it is incredibly lucky, in a way, to get this event. It is not guaranteed that they will be so easy to find in the future. The orientation of the GRB jet is going to very interesting as well; there is a lot of good astrophysics going on in that process. Also, we hope to try and make it more accessible to the rest of the world.

The President. Thank you very much. I have to bring proceedings to a close. Could we thank John and indeed all four speakers. [Applause.] It just remains for me to remind you that we have our regular drinks reception over in the RAS Library, I hope to see many of you there. And finally, I give notice that the next Open Meeting of the Society will be Friday 9th of March, and I look forward to seeing many of you there.

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 261: HD 7, HD 54451, AND HD 79408

By R. F. Griffin
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Orbits are presented for the stars whose identities appear in the title of this paper. Their periods are about 14½ years, 18 years, and 5 months, respectively. The inclusion here of the orbit of HD 7 prompts a brief discussion of the radial-velocity natures of the other 12 stars whose (epoch-1900) right ascensions are given in the *Henry Draper Catalogue* as $0^h 0^m.0$.

Introduction

The first star discussed in this paper has the lowest *Henry Draper Catalogue* number of any object yet treated in this series, and seems likely to retain that record indefinitely. The first prize in that regard, however (HD 1!), has already been claimed by Griffin & McClure[1], who showed it (in this *Magazine*, but not in this series of papers) to be a single-lined binary system with a period of 2316 days. Of course, not all *Henry Draper Catalogue* stars are of late type and

TABLE I

Cambridge radial-velocity observations of HD 2, HD 4B, HD 5, and HR 2 (HD 6)

HD 2

Date (UT)	Velocity km s⁻¹
2008 Aug. 13·11	−2·8
Sept. 14·02	−2·7
Oct. 22·95	−2·7
2009 Sept. 4·05	−3·1
2010 Sept. 16·02	−2·3
2011 Sept. 14·06	−2·7
2012 Aug. 10·13	−2·0
2013 Sept. 17·03	−2·7
2014 Oct. 8·05	−2·7

HD 4B

Date (UT)	Velocity km s⁻¹
2013 Sept. 17·04	−4·3
2014 Sept. 11·09	−3·4

HD 5

Date (UT)	Velocity km s⁻¹
2008 Aug. 13·12	−14·4
Sept. 19·04	−14·4
2009 Sept. 4·06	−14·5
2010 Sept. 17·08	−14·3
2011 Sept. 15·05	−14·1
2012 Aug. 10·14	−14·5
2013 Sept. 17·05	−14·9
2014 Sept. 11·10	−14·5

HR 2 (HD 6)

Date (UT)	Velocity km s⁻¹
2008 July 24·12	+16·3
Sept. 19·05	+16·0
2010 Sept. 17·08	+15·9
2011 Sept. 14·04	+16·3
2012 Aug. 10·14	+16·1
2013 Sept. 17·05	+16·0
2014 Sept. 11·10	+16·1

therefore capable of having their radial velocities measured with spectrometers such as that used by the writer. Among the stars whose numbers are a single digit (HD 1–9), HD 3 and 4 are of types too early for observation with such instruments, while HD 9 is at a declination (–27°) inaccessible to the Cambridge telescope. The subsequent stars with *Henry Draper Catalogue* right ascensions of $0^h 0^m{\cdot}0$ (HD 10–13) are at even lower declinations. HD 8, at –5°, is marginally within declination access but has not been observed. After those disqualifications, we are left with just HD 2, 5, 6, and 7 that have single-digit *HD* numbers and are within observable ranges of declination and spectral type. Table I presents Cambridge radial-velocity measurements of the first three of those stars, all of which prove to have velocities that are constant within observational uncertainty over intervals of several years.

HD 4 is a wide (13″) visual double star (ADS 47) whose primary component is a $7^m{\cdot}7$ star of *Henry Draper Catalogue* type F0, too early for good measurement with the *Coravel*; the secondary, however, nearly two magnitudes fainter, has proved to give a measureable radial-velocity trace, although the 'dip' is broadened by an apparent projected rotational velocity of about 18 km s^{-1} that impairs the accuracy of the radial velocities. Only two measurements of the star have been made; they are included in Table I and agree with one another quite as well as could be expected from traces that show such a wide and shallow 'dip'.

HD 7

HD 7 is a ninth-magnitude star, to be found in the large but dim constellation Pisces, close to the point in the sky (RA and declination both zero) occupied by the Sun at the vernal equinox. Its declination is between 1° and 2° south, and its right ascension, now about $0^h 6^m$, was in the $0^h 0^m{\cdot}0$ strip at the epoch (1900) of the *Henry Draper Catalogue* coördinates. We are indebted to *Hipparcos* for its broad-band magnitudes, $V = 9^m{\cdot}08$, $(B - V) = 1^m{\cdot}00$, and to Miss Houk for her new classification of its spectrum (K0 in the *HD*) as G8/K0 III. The star was placed on the observing programme of the Cambridge *Coravel* in 2008. In the following year its radial velocity appeared to have changed slightly, and after another year the variation was definite, so the object was transferred to the binary programme. It has been observed 27 times, with the results listed in Table II. Two other, discordant, measurements in the table must have been of some adjacent star (not identifiable now) and have been rejected in the

TABLE II

Radial-velocity observations of HD 7

All the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity km s⁻¹*	*Phase*	*(O – C) km s⁻¹*
2008 Aug. 13·12	54691·12	–15·8	0·736	–0·4
Sept. 19·05	728·05	–15·0	·743	+0·3
2009 Sept. 4·08	55078·08	–13·5	0·809	+0·2
2010 Sept. 17·08	55456·08	–11·9	0·881	0·0
Oct. 7·02	476·02	–11·8	·884	0·0
Nov. 10·94	510·94	–11·8	·891	–0·2
2011 Sept. 14·03	55818·03	–11·4	0·949	+0·1
Nov. 17·93	882·93	–12·0	·962	+0·2

TABLE II (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O–C)* *km s⁻¹*
2012 Jan. 12·76	55938·76	−13·1	0·972	+0·3
31·74	957·74	−14·4	·976	−0·5
July 24·12	56132·12	−21·6	1·009	−0·5
Aug. 5·12	144·12	−21·3	·011	+0·3
Sept. 4·09	174·09	−22·6	·017	+0·2
13·07	183·07	−23·1	·018	+0·1
Nov. 2·98	233·98	−24·7	·028	+0·1
Dec. 8·83	269·83	−25·8	·035	−0·1
2013 Jan. 31·74*	56323·74	−23·4	1·045	+3·3
July 26·12	499·12	−27·5	·078	+0·2
Sept. 3·07*	538·07	−23·8	·086	+3·9
Oct. 6·00	571·00	−27·8	·092	−0·1
Nov. 12·92	608·92	−28·0	·099	−0·4
Dec. 27·79	653·79	−27·6	·108	−0·2
2014 Aug. 13·14	56882·14	−26·4	1·151	+0·1
Nov. 20·98	981·98	−25·7	·170	+0·4
2015 Aug. 27·14	57261·14	−24·5	1·223	+0·4
Dec. 8·78	364·78	−24·9	·242	−0·4
2016 Jan. 15·76	57402·76	−24·5	1·249	−0·1
Sept. 12·06	643·06	−23·1	·295	+0·3
2017 Jan. 19·74	57772·74	−23·3	1·320	−0·3

*Observation must be of wrong star; rejected

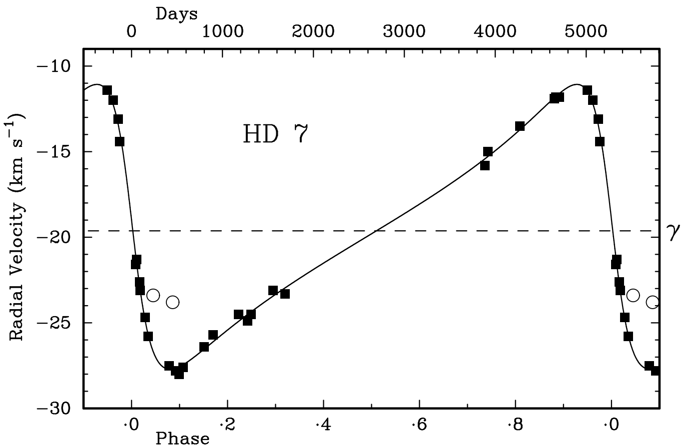

FIG. 1

The observed radial velocities of HD 7 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. In an unusual (perhaps reprehensible) deviation from normal practice, the observations of this star have not been continued for long enough to see it round a complete cycle; the earliest ones are those near phase ·7. The open circles represent observations which, though recorded as being of HD 7, must have been of some adjacent star, and have been omitted in the solution of the orbit. All the observations were made with the Cambridge *Coravel*.

calculation of the orbit, although they are plotted, with open symbols, in the diagram of the orbit that is shown here as Fig. 1. Unusually in this series of papers, the orbit has not been seen completely round even a single cycle, but its form is rather clear even though there remains an uncertainty of about 5% in the period, which is 14–15 years. The elements are listed in the informal table here:

P	$= 5279 \pm 272$ days	$(T)_1$	$=$ MJD 56086 ± 11
γ	$= -19{\cdot}63 \pm 0{\cdot}09$ km s^{-1}	$a_1 \sin i$	$= 492 \pm 27$ Gm
K	$= 8{\cdot}32 \pm 0{\cdot}10$ km s^{-1}	$f(m)$	$= 0{\cdot}170 \pm 0{\cdot}014\ M_\odot$
e	$= 0{\cdot}581 \pm 0{\cdot}020$		
ω	$= 87{\cdot}2 \pm 1{\cdot}8$ degrees	R.m.s. residual (wt. 1)	$= 0{\cdot}28$ km s^{-1}

HD 54451

Whereas HD 7 is south of the celestial equator, HD 54451 is at a high northern declination of about 73°. It is to be found about 4° south of, and 1° preceding, the $4\frac{1}{2}^{m}$ star HR 2527 (enigmatically marked '*M*' in *Uranometria 2000·0*[2]). Its *Tycho 2* magnitudes are $V = 7^{m}{\cdot}75$, $(B - V) = 0^{m}{\cdot}53$; the colour index is not out of line with its *HD* spectral type of F8. The reason that the star came to be on the writer's radial-velocity programme is that it was one of the objects that had a ΔMc_0 value that (just) exceeded $0^{m}{\cdot}5$ in the survey[3] by Griffin & Suchkov of 'over-luminous' F-type stars. The 'over-luminosity' criterion often identified previously unrecognized binary-star systems. Although it was not an infallible guide in that respect, it was successful in the case of HD 54451, which was added to the Cambridge radial-velocity observing programme in the year 2000 on the strength of its ΔMc_0 value. Only one velocity measurement was made in the first season, but in the ensuing season the velocity progressively diverged from it. By the time the survey paper[3] was written, two years later, there were 13 measurements, and the star was confidently asserted to be a spectroscopic binary. The observations available then did not by any means cover a cycle of

TABLE III

Radial-velocity observations of HD 54451

All the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2000 Feb. 20·01	51594·01	+22·7	0·081	0·0
Sept. 25·16	812·16	24·1	·115	−0·3
Nov. 14·15	862·15	24·1	·123	−0·6
Dec. 22·13	900·13	25·1	·129	+0·1
2001 Jan. 11·11	51920·11	25·5	0·132	+0·4
Feb. 14·00	954·00	25·7	·137	+0·3
15·85	955·85	25·4	·137	0·0
Apr. 28·88	52027·88	26·1	·148	+0·2
Aug. 21·16*	142·16	24·2	·166	(−2·4)
Oct. 4·18	186·18	27·0	·173	+0·1
Nov. 1·15	214·15	27·3	·177	+0·2
Dec. 12·16	255·16	+27·2	·183	−0·1

*Rejected; compromised by twilight

TABLE III (*continued*)

Date (UT)	*MJD*	*Velocity km s⁻¹*	*Phase*	*(O–C) km s⁻¹*
2002 Jan. 1·10	52275·10	+26·8	0·186	–0·6
Feb. 4·10	309·10	28·0	·192	+0·4
Mar. 1·02	334·02	28·5	·195	+0·7
Apr. 3·92	367·92	27·9	·201	0·0
May 4·89	398·89	28·0	·205	–0·1
Sept. 28·19	545·19	28·4	·228	–0·4
Oct. 18·20	565·20	28·6	·231	–0·3
Dec. 5·13	613·13	29·0	·238	–0·1
2003 Jan. 5·13	52644·13	29·7	0·243	+0·5
Feb. 15·05	685·05	29·1	·249	–0·3
Mar. 14·95	712·95	29·2	·254	–0·3
Apr. 15·87	744·87	29·4	·259	–0·2
May 7·86	766·86	29·7	·262	0·0
Sept. 18·18	900·18	30·2	·283	0·0
Oct. 18·23	930·23	29·9	·287	–0·4
Nov. 28·13	971·13	30·4	·294	0·0
Dec. 27·18	53000·18	30·6	·298	+0·1
2004 Jan. 17·12	53021·12	30·9	0·301	+0·4
Feb. 23·03	058·03	30·9	·307	+0·3
Mar. 16·97	080·97	30·9	·310	+0·2
Apr. 13·92	108·92	30·6	·315	–0·2
May 3·86	128·86	31·1	·318	+0·3
Sept. 21·19	269·19	31·2	·339	0·0
Oct. 19·23	297·23	31·5	·344	+0·3
Dec. 18·13	357·13	31·1	·353	–0·2
2005 Jan. 9·02	53379·02	31·1	0·356	–0·3
Feb. 8·97	409·97	31·1	·361	–0·3
Mar. 18·94	447·94	31·9	·367	+0·4
Apr. 18·87	478·87	31·6	·372	0·0
May 11·87	501·87	31·9	·375	+0·3
Sept. 8·17	621·17	31·3	·394	–0·5
Nov. 4·22	678·22	31·8	·402	–0·1
Dec. 15·13	719·13	32·4	·409	+0·5
2006 Jan. 26·05	53761·05	32·2	0·415	+0·2
Feb. 15·98	781·98	31·7	·418	–0·3
Mar. 22·90	816·90	32·2	·424	+0·2
Apr. 25·90	850·90	32·1	·429	0·0
Sept. 20·20	998·20	32·3	·452	+0·1
Oct. 27·22	54035·22	32·0	·457	–0·2
Nov. 19·21	058·21	31·8	·461	–0·4
Dec. 17·16	086·16	32·0	·465	–0·3
2007 Jan. 14·04	54114·04	32·4	0·470	+0·1
Feb. 14·93	145·93	31·9	·474	–0·4
Mar. 21·92	180·92	32·3	·480	0·0
Apr. 14·87	204·87	32·1	·484	–0·2
Oct. 19·18	392·18	32·7	·512	+0·3
Nov. 16·20	420·20	31·9	·517	–0·5
Dec. 11·18	445·18	32·9	·521	+0·5
2008 Jan. 25·05	54490·05	32·0	0·527	–0·4
Feb. 25·02	521·02	32·5	·532	+0·1
Mar. 30·88	555·88	33·1	·538	+0·7
Apr. 23·88	579·88	32·7	·541	+0·3
Oct. 9·21	748·21	32·3	·567	0·0
Dec. 7·17	807·17	+31·9	·576	–0·4

TABLE III (*concluded*)

Date (UT)	*MJD*	*Velocity km s⁻¹*	*Phase*	*(O – C) km s⁻¹*
2009 Jan. 6·11	54837·11	+31·5	0·581	−0·7
Feb. 4·04	866·04	32·6	·585	+0·4
Mar. 6·04	896·04	32·0	·590	−0·2
Apr. 1·92	922·92	32·1	·594	−0·1
May 3·88	954·88	32·2	·599	+0·1
Oct. 23·23	55127·23	32·1	·626	+0·1
Dec. 1·14	166·14	31·9	·632	0·0
2010 Jan. 18·04	55214·04	32·2	0·639	+0·4
Feb. 20·98	247·98	32·0	·644	+0·2
Mar. 22·94	277·94	31·8	·649	+0·1
May 6·86	322·86	31·8	·656	+0·1
Oct. 20·23	489·23	31·7	·681	+0·3
Nov. 24·18	524·18	31·2	·687	−0·1
Dec. 19·16	549·16	31·2	·691	0·0
2011 Jan. 10·11	55571·11	31·1	0·694	−0·1
Apr. 6·91	657·91	31·0	·707	0·0
Oct. 1·17	835·17	30·5	·735	+0·1
Nov. 28·17	893·17	30·7	·744	+0·5
Dec. 18·23	913·23	30·0	·747	−0·2
2012 Jan. 13·16	55939·16	30·1	0·751	0·0
Feb. 11·00	968·00	29·6	·755	−0·4
Mar. 7·92	993·92	29·9	·759	0·0
Apr. 10·88	56027·88	29·5	·764	−0·2
May 14·87	061·87	29·2	·770	−0·4
Sept. 7·17	177·17	29·3	·787	+0·2
Nov. 3·20	234·20	28·0	·796	−0·8
Dec. 2·21	263·21	28·6	·801	−0·1
2013 Jan. 3·12	56295·12	28·6	0·805	+0·1
Feb. 7·06	330·06	28·5	·811	+0·2
Mar. 5·91	356·91	28·4	·815	+0·2
Apr. 2·89	384·89	28·0	·819	0·0
May 7·88	419·88	28·2	·825	+0·4
Oct. 17·22	582·22	27·8	·850	+1·0
Nov. 9·21	605·21	26·5	·853	−0·2
Dec. 1·13	627·13	26·4	·857	−0·1
2014 Jan. 5·14	56662·14	25·7	0·862	−0·6
Feb. 2·93	690·93	25·9	·866	−0·2
Mar. 1·92	717·92	26·2	·871	+0·3
Apr. 4·88	751·88	25·5	·876	−0·1
Nov. 6·15	967·15	24·1	·909	+0·2
Dec. 6·22	997·22	23·5	·914	−0·2
2015 Jan. 11·11	57033·11	23·2	0·919	−0·2
Feb. 18·05	071·05	23·1	·925	0·0
Mar. 26·91	107·91	22·8	·931	0·0
Apr. 23·89	135·89	22·2	·935	−0·4
29·88	141·88	22·9	·936	+0·3
Nov. 28·16	354·16	21·8	·969	+0·6
2016 Jan. 1·01	57388·01	21·0	0·974	0·0
Feb. 23·92	441·92	+20·5	·982	−0·3

the orbit and little purpose would have been served by publishing them then. Instead, the star was retained on the observing programme until comparatively recently, and there are now 114 velocity measurements, all made by the writer with the Cambridge *Coravel*, from which to determine the orbit. They are set out in Table III and lead to the orbit that is plotted in Fig. 2 and has the following elements:

P	$= 6493 \pm 148$ days	$(T)_1$	$=$ MJD 51065 ± 83
γ	$= +28{\cdot}32 \pm 0{\cdot}19$ km s^{-1}	$a_1 \sin i$	$= 500 \pm 22$ Gm
K	$= 5{\cdot}90 \pm 0{\cdot}22$ km s^{-1}	$f(m)$	$= 0{\cdot}119 \pm 0{\cdot}014\ M_{\odot}$
e	$= 0{\cdot}313 \pm 0{\cdot}015$		
ω	$= 175{\cdot}9 \pm 1{\cdot}6$ degrees	R.m.s. residual (wt. 1)	$= 0{\cdot}32$ km s^{-1}

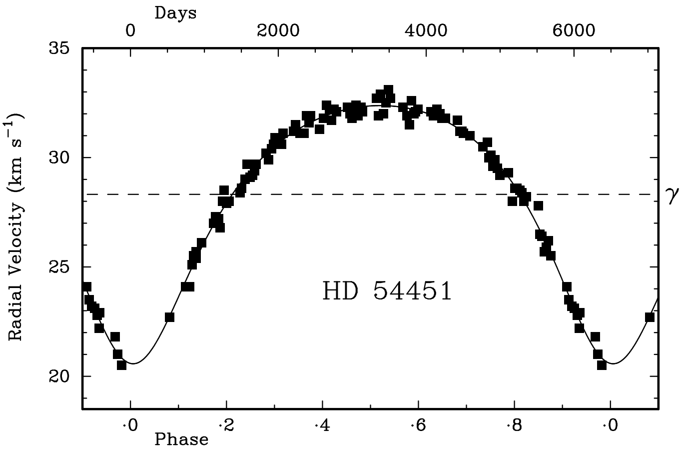

FIG. 2

The observed radial velocities of HD 54451 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations were made with the Cambridge *Coravel*.

HD 79408

This object is in the north-following corner of Lynx, some 2° north of the fifth-magnitude star 36 Lyn. *Hipparcos* has provided its apparent magnitudes as $V = 8^{m}{\cdot}36$, $(B-V) = 1^{m}{\cdot}07$, the latter quantity agreeing with the *Henry Draper Catalogue* classification of its spectrum as K0 provided that the star is a giant. It has a *Gaia* parallax of $3{\cdot}23 \pm 0{\cdot}28$ arc-milliseconds, corresponding to a distance modulus close to 12·5 magnitudes and thus to an M_V of about –4 — so it is actually approaching supergiant luminosity. The *Simbad* bibliography on the star has only two entries, which add little to what has already been said here.

The radial velocity of HD 79408 was not measured until 2012; a second observation made a little more than a year later was seriously discordant and led to reasonably attentive monitoring of the star, especially after the velocity was found to change on quite a short time-scale. There are now 34 measurements,

TABLE IV

Radial-velocity observations of HD 79408

All the observations were made with the Cambridge Coravel

Date (UT)	MJD	Velocity km s⁻¹	Phase	(O – C) km s⁻¹
2012 Mar. 10·03	55996·03	−42·1	0·096	+0·1
2013 Apr. 27·88	56409·88	−35·5	2·744	+0·2
May 2·89	414·89	−34·6	·776	0·0
13·88	425·88	−32·1	·847	−0·1
June 3·91	446·91	−31·0	·981	+0·4
Nov. 9·25	605·25	−32·6	3·994	−0·2
Dec. 20·14	646·14	−44·8	4·256	+0·1
29·12	655·12	−44·3	·313	+0·1
2014 Jan. 5·17	56662·17	−43·9	4·358	0·0
13·13	670·13	−43·3	·409	−0·1
27·06	684·06	−41·7	·498	0·0
Feb. 3·06	691·06	−40·8	·543	0·0
11·09	699·09	−40·2	·595	−0·5
20·99	708·99	−37·9	·658	+0·3
26·07	714·07	−37·7	·690	−0·4
Mar. 1·96	717·96	−36·4	·715	+0·2
19·01	735·01	−33·2	·824	−0·3
25·99	741·99	−31·2	·869	0·0
Apr. 4·99	751·99	−29·7	·933	0·0
7·97	754·97	−29·8	·952	+0·1
14·94	761·94	−32·8	·997	−0·1
16·90	763·90	−34·0	5·009	−0·1
18·92	765·92	−35·5	·022	−0·1
19·91	766·91	−36·3	·028	−0·2
May 2·95	779·95	−42·7	·112	+0·3
15·94	792·94	−45·0	·195	−0·2
30·91	807·91	−44·7	·291	−0·1
Nov. 8·26	969·26	−44·0	6·323	+0·3
24·24	985·24	−43·6	·425	−0·7
2015 Feb. 7·07	57060·07	−30·3	6·904	−0·2
Mar. 31·96	112·96	−45·0	7·242	−0·1
May 29·95	171·95	−38·4	·620	+0·7
2016 Jan. 1·16	57388·16	−33·1	9·003	+0·2
2017 Jan. 21·16	57774·16	−42·0	11·473	+0·1

listed in Table IV, all made with the Cambridge *Coravel*; they produce an orbit, illustrated in Fig.3, with the following elements:

$P = 156{\cdot}30 \pm 0{\cdot}08$ days	$(T)_5 = \text{MJD } 56762{\cdot}5 \pm 0{\cdot}5$
$\gamma = -39{\cdot}05 \pm 0{\cdot}05$ km s^{-1}	$a_1 \sin i = 15{\cdot}01 \pm 0{\cdot}17$ Gm
$K = 7{\cdot}61 \pm 0{\cdot}08$ km s^{-1}	$f(m) = 0{\cdot}00553 \pm 0{\cdot}00019\ M_{\odot}$
$e = 0{\cdot}397 \pm 0{\cdot}009$	
$\omega = 55{\cdot}3 \pm 1{\cdot}6$ degrees	R.m.s. residual (wt. 1) = 0·26 km s^{-1}

No evidence of the secondary star has been seen in the radial-velocity traces, and the smallness of the mass function does not inspire much optimism that any such evidence should appear.

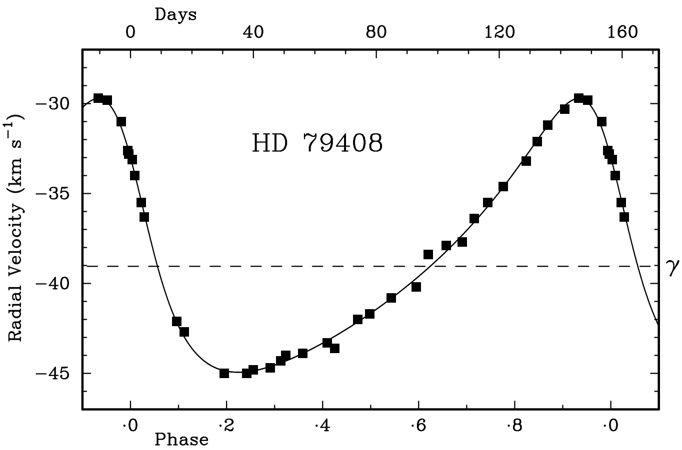

FIG. 3

The observed radial velocities of HD 79408 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations were made with the Cambridge *Coravel*.

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CORRESPONDENCE

To the Editors of 'The Observatory'

The Big Bang: Who First Suggested It?

The phrase 'Big Bang' was coined in 1949 by astronomer Fred Hoyle as a label for a cosmological model of the Universe[1], although one with which he happened to disagree. However, the theory itself had an earlier origin.

Many think that Georges Lemaître, a Belgian Roman Catholic priest, astronomer, and professor of physics at the Université Catholique de Louvain, was the first to suggest cosmic expansion. In his 1927 report, 'A homogeneous universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae'[2], he proposed that the Universe expanded from the finite static state imagined by Einstein. But only in 1931, at a meeting of the British Association on the relation between the physical Universe and spirituality [*sic*], did he propose that the Universe originated in a 'primeval atom'[3]. But this was two years after Edwin Hubble had demonstrated cosmic expansion. Many think it was mathematician Alexander Friedmann who, unknown to Lemaître, proposed a similar solution to Einstein's equations in 1922.[2]

However, what seems to be little known is the fact that both Friedmann and Lemaître were forestalled by the American writer and poet Edgar Allan Poe. Understandably this could be because the work of a poet rarely features in scientific literature. In 1848, 79 years before Lemaître and 74 years before Friedmann, Poe wrote *Eureka: A Prose Poem*, subtitled 'An Essay on the Material and Spiritual Universe'. It was his last major work and his longest non-fiction work at nearly 40 000 words. It was based on a lecture he gave on 1848 February 3 in the Society Library in New York entitled 'On The Cosmography of the Universe'. He died the following year.

Poe dedicated the work to Alexander von Humboldt, whose book *Kosmos* he must have read, at least the first two volumes published in his time. It was Humboldt who coined the word 'cosmos' (from the Greek *kosmos*) in the sense that modern cosmology uses it, to describe everything that exists in the Universe, or the Universe itself. In the volumes Poe must have read, he examined what was then known of the Milky Way, cosmic nebulae, and planets. The first volume was so popular that it sold out in two months.

Because there was no scientific literature to which he could refer (Humboldt did not speculate on the origin of the Universe), *Eureka* describes Poe's intuitive concept. His general proposition was 'Because Nothing was, therefore All Things are'. That is a bit vague, but it seems to suggest that the Universe came out of nothing. Indeed, he proposed that it had an origin: Poe contended that the Universe filled with matter after a single, high-energy particle exploded and that, since the energy of the explosion is pushing matter outward, the Universe must be expanding.

This by itself would be a startling anticipation of modern cosmology, if Poe had not also drawn striking conclusions from it, for example, that space and 'duration' (*i.e.*, 'time') are one thing, that there might be stars that emit no light, that there is a repulsive force that in some degree counteracts the force of gravity, that there could be any number of universes with different laws simultaneous with ours, that our Universe might collapse to its original state and another universe erupt from the particle it would have become, and that our present Universe may be one in a series.

Apart from suggesting a 'Big Crunch', Poe was also the first to explain Olbers' Paradox (why is the night sky dark despite the vast number of stars in the universe?). Poe claimed, as many do now, that the Universe is not old enough to fill the sky with light. The Universe may be infinite in size, he thought, but there has not been enough time since the Universe began for starlight, travelling at the speed of light, to reach us from the farthest reaches of space. A Wikipedia page on the Paradox recognizes Poe's priority in this matter.[4]

Response to *Eureka* was overwhelmingly unfavourable and the lecture on which it was based received negative reviews such as "hyperbolic nonsense", but one newspaper called it "a noble effort". Many were bored by the lecture which evidently was too long and rambling. However, Poe considered *Eureka* to be his masterpiece. He believed that the work would immortalize him because it would be proven to be true. Indeed, much of what he claimed has been verified, and some, like Arthur Eddington, praised it[5], and it is reported that Albert Einstein called it "a beautiful achievement of an unusually independent mind".

Eureka was published in a small hardcover edition in 1848 March by Wiley & Putnam priced at US75 cents. Poe persuaded George Putnam, to publish *Eureka* after claiming the work was more important than Isaac Newton's 'discovery of gravity' (Newton did not *discover* gravity, but he did *explain* it). Putnam paid Poe $14 ($300–$400 today) for the work. Poe suggested an initial printing of at least one million copies, but Putnam settled on 750, of which 500 were sold that year. The book can still be bought in various editions and it can also be read on-line.[6] Both the British Library and the National Library of Scotland have an original 1848 edition.

What Poe suggested in this inspired work, with no antecedents, except perhaps Humboldt, is astonishing in its prescience. He deserves more recognition for his insight.

Poe actually has a British connection: he was briefly at school in Irvine (Scotland) in 1815 when the Allans, his foster family, visited Britain.

For an analysis of the work, see Stuart and Susan Levine.[7]

Yours faithfully,
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REVIEWS

The Rise of Radio Astronomy in the Netherlands: The People and the Politics, by Astrid Elbers (Springer), 2017. Pp. 240, 24 × 16 cm. Price £82/$129 (hardbound; ISBN 978 3 319 49078 6).

The Rise of Radio Astronomy in the Netherlands by Astrid Elbers is a review of the development of Dutch radio astronomy from before the publication of Reber's first papers on 'Cosmic Static' in the 1940s, through to the construction of the *Westerbork Synthesis Radio Telescope* (*WSRT*) in the late 1960s. It is an important work, and fills a significant gap in the history of the field. The author takes the traditional view (popular in Leiden) that Dutch radio astronomy evolved very differently from radio astronomy in other countries. There are certainly elements of truth to this — for example, while radio astronomy in the UK was established primarily by physicists like Lovell and Ryle, the field rose to prominence in the Netherlands *via* 'real astronomers' such as Oort and van de Hulst. While it is true that the Dutch had a great deal of catching up to do in accessing the advanced radio technologies developed during WWII, it is equally true that the British, and their colleagues in Australia and the US, had very little background in fundamental astronomy — it's said that even the basic concepts such as right ascension and declination were entirely foreign to those early pioneers.

One slightly disappointing aspect of the book is the space given to van de Hulst's prediction of the 21-cm line of neutral hydrogen in 1944, and its subsequent discovery by Muller and Oort (amongst others) in 1951. On the other hand, the book's prime original contribution is to detail the interesting nature of the Dutch–Belgian collaboration in designing and constructing the *WSRT*. There is a great deal to learn here about early international post-war collaboration, and the different approaches and maturity of the national funding agencies at that time. While the Dutch astronomers were 'judge and jury' of any new funding proposals, the more mature Belgian system had many more checks and balances, placed greater value on industrial spin-off, and suffered from a good deal of bureaucratic inertia. I was surprised to learn just how large a financial contribution the Belgian government made to the *WSRT* pre-construction phase (more than 1MDfl), especially so, given their almost negligible industrial return, and their very limited involvement once the telescope became operational. The shifting focus of the *WSRT* towards shorter wavelengths, including the 21-cm line, is also fascinating, as the rise of H I science, the discovery of aperture synthesis, and the need for better resolution drove the final design.

The book contains only a few small but sometimes annoying errors (Watson-Watt is described as an Englishman, for example), and suffers a little from being largely a copy of the author's PhD thesis. Nonetheless, it represents an excellent record of the early Dutch contribution to radio astronomy, and describes the *WSRT* Dutch–Belgian collaboration for the first time in some detail. — MICHAEL A. GARRETT.

Quantum Physics, Mini Black Holes, and the Multiverse: Debunking Common Misconceptions in Theoretical Physics, by Yasunori Nomura, Bill Poirier & John Terning (Springer), 2018. Pp. 212, 28·5 × 21·5 cm. Price £16·50/$19·99 (hardbound; ISBN 978 3 319 41708 0).

At only 75p per misconception, this book is a bargain! You also get lots of equations (mostly heralded by drawings of brains), Stephen Hawking in free-fall, some Penrose diagrams, one Calvin and Hobbes cartoon, and a dead cat, next to a live one and captioned "Separated at Measurement?". The three authors address three different territories: Poitier on quantum physics, Terning on particles and space–time, and Nomura on 'the' multiverse. 'Bonus features' include pronunciation of the Greek alphabet (I disagree about Xi), prefixes from 'atto' to 'exa', but none of the feeble witticisms of the form 10^{-18} boys = one atto-boy! Never mind; there are enough feeble witticisms in italics in the margins to make up for that lack. Also marginalized are references to a large number of web sites with additional information, illustrations, animations, and all.

The technical parts, mostly in Chapter 12 with sections on Special Relativity, quantum mechanics, black holes (that is, bits of General Relativity), the *LHC*, group theory, and the Higgs, are largely unexceptional, reflecting both the expertise of the authors and oversight by Sean Carroll (the physics one, not the biologist) and others. The discussion of black-hole evaporation seems to affirm that information is lost, an issue still somewhat under debate. And cosmological redshift is called a Doppler effect. Perhaps if everyone starts calling it that again (as did Einstein), it will become so, like the 5th leg on Abraham Lincoln's horse.

My chief worry is, however, slightly different. Are there any statistics on how many children have stuck beans up their noses before and after being told not to? Similarly, how many readers will scan the advertized misconceptions and think, "That sounds about right! Never mind the rest of the section."

So, an interesting book. An almost-coffee-table-sized book, though with no big, beautiful colour photographs. And, despite the low price by current standards, perhaps not one to be given casually to interested students. The associated web site is www.mvjs.org (mvjs stands for Multiversal Journeys, the book series to which this belongs — I have not checked to see whether Hugh Everett's many-worlds sort of multiverse is there somewhere; it is not in the book). The cat, I hope, is only sleeping. — VIRGINIA TRIMBLE.

The Cosmic Zoo: Complex Life on Many Worlds, by Dirk Schulze-Makuch & William Bains (Springer), 2017. Pp. 244, 23·5 × 15·5 cm. Price £19·50/$34·99 (paperback; ISBN 978 3 319 62044 2).

This book is more about biology than astronomy. As such, it is perhaps valuable for astronomers interested in the topic who know more about the latter than about the former. Both of the authors have published on a wide range of subjects, mostly biology-related, and their astronomical publications concentrate on astrobiology. There is of course a long history of trying to estimate the number of planets which could support a technological civilization (the topic of this book — not intelligent life in general, though the probabilities of various types of life, including intelligent but non-technological life, are discussed), going back at least to the Drake equation. This book looks at the terms in that equation (which, however, is not mentioned in the book; neither is Frank Drake) in more detail, especially the biological ones.

The book opens with two chapters discussing 'The Cosmic Zoo Hypothesis', the 'Cosmic Zoo' referring to a universe in which life is common. Most of the astronomy is in the second chapter, concerned with the number of habitable planets and so on, as well as a summary of the second part of the book. The bulk of the book, the next nine of the 13 chapters, is concerned with 'Major Transitions in Earth's Life History'. The last two chapters ask the question "Are There Visitors in the Cosmic Zoo?", discussing ways to test the Cosmic Zoo hypothesis and speculations on what, if anything, the 'Great Filter' is, which might make the evolution of technological civilizations difficult.

Transitions, such as the development of multicellular life, are described by three models: the 'Critical Path Model' (each transition requires preconditions, but these are not improbable, so it is essentially only a matter of time until the transition occurs; for example, animal life had to wait for enough oxygen in the atmosphere), the 'Random Walk Model' (this is similar, but the preconditions are improbable, so the transition occurs only as a result of a lucky streak, and might not occur at all before the planet becomes uninhabitable), and the 'Many Paths Model' (here individual preconditions might be improbable, but many paths lead to the same functional result — eyes, for example — so while a particular expression of the result might be unlikely, it is likely that some path will lead to it). The authors convincingly argue that most of the transitions which led to our technological civilization follow the 'Many Paths Model', with two exceptions: the origin of life and the emergence of technology. About the former, not enough is known to decide which model best describes it. Concerning the latter, it is not clear why other species for which all preconditions apparently held did not develop technology. On the other hand, genetic evidence indicates that there was a time between 50 000 and 100 000 years ago when the human population was down to a few thousand individuals; it is easy to imagine that humanity could have become extinct at that bottleneck.

Another speculation is perhaps more interesting. It is something which I have often thought of myself, but don't recall ever reading or hearing about, namely the idea that other technological civilizations did arise. Human technology has existed for only a short time compared to the age of the Earth, and the time resolution of the geological record is easily coarse enough to have missed such a civilization. Also, the authors argue that all traces of human civilization would vanish within ten million years (less than a day if one imagines the history of the Earth as one year), except our spacecraft on the Moon and Mars. Thus, although in the end the authors discount the idea of previous technological civilizations on Earth, it does seem possible.

Several solutions to the Fermi Paradox are presented: the Great Filter could be the origin of life itself, the origin of technology, or some catastrophic event yet to come. Even if humanity survives for as long again as it has already existed, this is geologically a very short time; if other technological civilizations are similarly affected, the chance is small that another technological civilization is present in our cosmic neighbourhood. Another possibility is that extraterrestrial technological civilizations exist, but for some reason (one can think of many) are not interested in communicating with us.

I noticed no factual errors, though of course I am not an expert on this topic. Extremely annoying is the bad editing; apart from my usual complaints, there are many Germanisms (although one of the authors appears to be English and the other worked for several years in the United States) and, while there are few if any actual typos, there are several examples of questionable style and a few of simply wrong grammar. Springer's mysterious variable bottom margins are present, though not as extreme as in some other books. There is a six-page index, though I recall wanting to find something in the text but not finding it in the index. Otherwise, the book is well produced, with clear photographs and diagrams, most in colour, throughout the text. Some topics are explored in more detail in boxes. Each chapter ends with suggestions for further reading, grouped by topic, often the authors' own (usually more technical) work. A 19-page glossary is useful for those not familiar with biology (or planetary astronomy).

I enjoyed reading the book. The authors obviously know their material well and, with the exceptions mentioned above, the book is generally well written. The amount of additional effort for proof-reading and correcting the manuscript would be only a fraction of the effort which went into the writing and production of the book itself; it is a shame that many publishers, especially in recent years, cut corners there. — PHILLIP HELBIG.

Space Science and Astronomy Theatre, by Margaret Boone Rappaport & Christopher J. Corbally (Archway Publishing), 2017. Pp. 221, 23 × 15 cm. Price $16·99 (about £12) (paperback; ISBN 978 1 4808 4844 3).

This book is a charming example of a different approach to science outreach. The authors have provided teaching aids and scripts for interactive presentations of key concepts in science. This is a guide for teachers and instructors of astronomy and space science in middle school, high school, and college (ages 11–17, grades 6–12). Part 2 of the book (36 pages) explains the roles of space science and astronomy in society, with good advice on career paths for professional astronomers of the future, as well as pointing out interdisciplinary pathways in aerospace engineering, information technology, and public education. Part 3 of the book is an instruction manual on the use of script packages in the classroom. Each script is for use in a two-actor presentation package, composed of a five-minute script for two characters, one female and one male. Advice is included on how freely to adapt the scripts for production as a learning unit. Part 4 offers 12 scripts, together with background information on the historical contexts of their content. This is a splendid book for teachers who are lucky enough to work for school systems that encourage liberal approaches to educational enrichment. However, instructors who are required to teach to the tests of a rigid national curriculum will only be able to use the material in optional extracurricular situations. — SIMON MITTON.

Investigating the Origin of the Asteroids and Early Findings on Vesta, by Clifford J. Cunningham (Springer), 2017. Pp. 399, 24 × 16 cm. Price £120/$189 (hardbound; ISBN 978 3 319 58117 0).

The history of astronomy is littered with breakthrough moments. It is fun to try and draw up your own top ten. Does the discovery of the solar energy source beat the discovery of supernovae or active galaxies? And how would you rate the discovery that, what was initially thought of as the fifth element, quintessence, was nothing more than the normal chemical stuff that litters your own laboratory environment? Where would you put the 1801 breakthrough that found the asteroid Ceres wandering in the ugly gap in the Solar System between the orbits of Mars and Jupiter? Would your opinion change when astronomers discovered that Ceres was not alone, but one of what eventually has become a huge crowd of asteroids?

Most histories of astronomy give Ceres and her friends little more than a page, but Cunningham is an asteroid fan and we are treated to nearly 400. He delves into the debate with gusto. Astronomers argued as to whether asteroids were produced at the same time as the major planets and were thus as old as the whole Solar System, or whether they are a late addition, being produced by a planet blowing up. Asteroids were soon posited as being the source of meteorites and also the cause of the craters seen on the Moon. Hypotheses abounded and it is revealing just how heated astronomers got in support of their personal notions when clearly there was so little possibility of producing any observational evidence. At the time it was difficult to detect these faint moving bodies and the task of calculating their orbits and future positions was time-consuming. Cunningham investigates in detail the problems of trying to measure the individual diameters. Much is made of brightness changes and the disputed evidence of surrounding atmospheres — allegedly detected due to the poor quality of the contemporary optics.

Cunningham revels in the details. Considering the early days of asteroidal research he hardly misses a reference or an extensive quote. The book is full of hidden gems. Let me just choose three examples. The Astronomer Royal, George Biddell Airy, allegedly discovered a Royal Observatory assistant hunting for new asteroids on one of his nights off. The assistant was severely reprimanded. This task was clearly not what the Greenwich telescopes were there for! There is a mysterious horizontal metal ring on the Ramsden transit instrument at the Palermo Observatory, the instrument used to detect the first asteroid. This turns out to be a glass holder. Giuseppe Piazzi used it to hold a glass of fortifying liquor — used to warm him up on the cold winter's nights of asteroid observing. Not something you find in today's dome. And, having personally lectured on asteroids, it was also fascinating to read in full the lecture given on those minor bodies by Charles Babbage in 1815 at the Royal Institution, London.

This book is clearly a labour of love. I revelled in its details. I loved the complexity, and the illustrations, the discussions, and the letters. It is a fascinating reference source. But even so, I am not sure that it will rocket asteroids into the historic-breakthrough top ten. — DAVID W. HUGHES.

Astronomy Adventures and Vacations, by T. Treadwell (Springer), 2017. Pp. 259, 23·5 × 15·5 cm. Price £19·50/$34·99 (paperback; ISBN 978 3 319 50000 3).

With an author named Treadwell, this travel guide should have more than the average level of credibility. On the other hand, if you put Timothy Treadwell into your favourite internet search engine, you'll quickly discover that for most of his adult years, he lived among — and was eventually eaten by — North American bears. The fact that these are two entirely different Timothy Treadwells doesn't altogether banish the disquiet arising from such an unfortunate misnomer.

'Our' Timothy Treadwell is a British amateur astronomer who has made a valiant attempt to catalogue the byways of astronomy and space science not normally covered in the literature. Subtitled 'How to Get the Most Out of Astronomy in Your Leisure Time', his book adopts a refreshingly broad definition of those byways. It starts, for example, with a chapter about telescope shops and astronomy shows, picking out a few of the author's favourite haunts among those specialist outlets that have blossomed all over the world in recent years. After covering planetaria and science museums in the US, the UK, and Europe, the author goes in search of dark skies, star parties, national parks, aurorae, and so on.

The first eleven chapters of *Astronomy Adventures and Vacations* cover what its title suggests, but there is a second tranche of four chapters covering the world of space. This is fairly NASA/Roscosmos-centric, so you will look in vain for the Swedish Esrange centre at Kiruna, for example, or the new space-launch facility in New Zealand.

While the scope of the author's exploration of astro-leisure activities is breathtakingly wide (who else would have thought of writing about vacations at small private observatories, or watching tidal bores?), it would be impossible to provide a comprehensive account of all that is available. Instead, the author has given us a broad cross-section based on his own interests, augmented with a diary of his travels and experiences. That is perfectly acceptable, but this ambitious book aims not only to be entertaining, but also useful.

Does it succeed? Despite its rather haphazard contents list, and the occasional howler in the text, I think it does. It covers a vast range of activities, and provides a wealth of internet and printed resources in the appendix. The book is strongly biassed towards the northern hemisphere, but there is at least a nod to the rest of the world with a chapter on southern skies. Overall, it's a lot of fun. And it is lavishly illustrated with photos that are, for the most part, appealing, relevant, and informative.

Astronomy Adventures and Vacations is a welcome addition to Springer's *Practical Astronomy* series authorized by the late Sir Patrick Moore, and makes a significant if unusual contribution to the 'how-to' literature of amateur astronomy. I would recommend it to anyone keen to explore the ever-growing range of leisure activities available in the fields of astronomy and space. For armchair astro-travellers, it's a must. And — rest assured — the only bears you will encounter are celestial ones. — FRED WATSON.

Star Theatre: The Story of the Planetarium, by William Firebrace (Reaktion Books), 2017. Pp. 232, 21·5 × 16·5 cm. Price £25 (hardbound; ISBN 978 1 78023 835 7).

I am pleased to see this book, written by a distinguished architect and author. It deals not only with the modern planetarium, but with the ancient and early attempts to depict the appearances and movements of objects on the celestial sphere. The modern image of a planetarium is that of a large sumptuous building, forming a cultural icon in the centre of an important city — rather like a church or cathedral and donated by a rich benefactor; but there is much more. The author describes with his architect's eye almost a hundred years of change and development, bringing with it a bewildering range of styles, sometimes strange, even weird, in the design of a planetarium.

Since the sky above seemed spherical, early depictions of the sky could be represented as globes with the sky depicted. We see them everywhere even now, but here the observer is on the outside looking in. They are the 'wrong way round'! The author describes how, over centuries, there were two strands of development to show the appearance and movement of objects on the celestial sphere. Stars and constellations could be shown inside a room the right way round, ideally in a hemisphere, painted with constellation figures or with tiny holes letting in the daylight to form the stars. Of those, Gottorp and Attwood globes with fixed stars and attachments had the capacity for a small audience, and those two still survive.

The movements of individual celestial bodies relative to one another are all complex and different, so attempts here led to the invention of the orrery using wheelwork as in clocks to move model planets on a desktop. Those functions were built into the clock at Strasbourg Cathedral. Many are works of art in themselves and they are still made. Eise Eisinga built one powered like a clock which fills his house in Friesland. The last truly large example of these was built by the Carl Zeiss Company at the beginning of the 20th Century, where the audience viewed the movements of planets as little globes (light bulbs) moving in circles when the room was darkened.

The projection planetarium came into being when optical, mechanical, and mathematical problems were solved by an engineer at the Carl Zeiss Factory in Jena, Germany. He was Walther Bauersfeld, who, in the 1920s, realized that the invention of the filament electric light bulb could provide the illumination in the new projector, especially for the star images from a central projector (a star sphere) to which was attached a gear cage providing the images of Sun, Moon, and planets all aimed at what was a hemispherical cinema screen. We must thank the author here who places Bauersfeld at the initiation of the geodesic skeleton of the hemispherical screen.

The introduction of the 'Star Theatre' was a revelation, spreading quickly across Germany and the World, but not yet to Britain. It sparked creativity in literature and cinema, even starring itself on the silver screen on several occasions. The author assesses the impact on the evolution of programmes for the new medium, which was and is still very versatile, and of course we must remember that all human culture from earliest times is spread across the scaffolding of the heavens. Think of all female names that come from that of the Moon goddess, Dana, Diana, Gwen, Selena, and so on. We can ask why Shakespeare's Macbeth meets three witches, not one, two or five? It is because the three represent the Waxing, Full, and Waning Moon, the Moon goddess in triad.

The author tackles beautifully the complex running of planetaria, and the problems they find themselves in, especially the rivalry with cinemas, computer-generated images, and the intrusion of actors and voice-overs in shows. We now know from the writings here that planetaria are now popular in what might be called developing countries, and that there were some fanatics in the Third Reich who were hostile in the 1930s to the invention, just as it gained popularity, and this in its country of origin.

The planetarium can still be used seriously in teaching the science of navigation; it has been used to investigate celestial navigation in migrating birds and the northern limit of the visibility of the Southern Cross in Neolithic times. Your reviewer was a planetarium lecturer. He often found that in preparing a simple programme, low-tech sound equipment will bring to life breezes, owls, and the dawn chorus, not to mention background music, and this went down well with all age groups.

It is a delightful irony that planetarium engineers took great pains to simulate scintillation (star twinkling) under the artificial sky, one of the problems that the astronomer has to eliminate in the real sky.

Every philosopher and educator should have this book since the sky and its behaviour is so important to humanity. The author has been thorough in his research into the history and current state of play, with the future of some planetaria so uncertain. There are many excellent reference chapters and a sensible index. The book contains 82 illustrations, 43 in colour. — HARRY FORD.

Annual Review of Earth and Planetary Sciences, Volume 45, 2017, edited by R. Jeanloz & K. H. Freeman (Annual Reviews), 2017. Pp. 709, 24 × 19·5 cm. Price from $419 (print and on-line for institutions; about £318), $114 (print and on-line for individuals; about £87) (hardbound; ISBN 978 0 8243 2045 4).

A slightly slimmed down volume of *Annual Review* for 2017 contains a wide range of chapters, many on unusual subjects. Of particular interest are chapters on the dynamics of geyser eruptions, water in the Moon's interior (a subject that didn't exist in the recent past), and earthquake predictability (a subject that existed once, largely vanished, and now is apparently reborn).

Aspects of climate change are discussed in several chapters, from several viewpoints. These include climate change over geological timescales, the effect of aerosols and changes in the loess plateau of China, landscape erosion, and the role of glaciers. The sensitivity of the latter can be harnessed to reconstruct past climate. The methodological details of this are well laid out in a chapter by Mackintosh and others, beautifully illustrated with diagrams, striking historic photographs, and fascinating historical sketches.

For the astronomers amongst us, in addition to water in the Moon's interior are chapters on planetary formation by pebble accretion and the late heavy bombardment. A mathematical chapter lays out the basis for interpreting gravity data from Jupiter and Saturn returned by missions *Juno* (currently in polar orbit of Jupiter) and *Cassini* (in orbit around Saturn 2004–2017).

Palaeontology is represented by chapters on the origins of primates and the evolution of regional biota. The explosion of life at the beginning of the Cambrian is summarized in a chapter on the emergence of animals in the Ediacaran — the very last period of the Proterozoic. This latter chapter presents a succinct summary of the three distinct evolutionary assemblages recognized from the now-many localities where these rare fossils are found. It is adorned with many amazing photographs of characteristic fossils.

On the subject of the solid Earth are chapters on the lithosphere–asthenosphere system of oceanic mantle, the continental lithosphere. Earthquakes are the focus of several chapters that deal with earthquake imaging, the effect on the seismic velocity of rocks brought about by partial melting (what happens immediately before melting is new and important), and the statistics of earthquake occurrence. The problem of telling what is a precursor to a large earthquake and what is not still hampers progress.

A colleague recently accused me of always writing positive reviews of *Annual Review*. I am afraid I have to plead guilty to the charge of admiring this publication unreservedly. The subjects covered are topical, the presentations are clear, professional, beautifully and clearly illustrated, the editing is excellent, and the paper and binding top quality. I hate to be predictable, but it's a thumbs up again this year from me for Volume 45. — Gillian Foulger.

Gravity's Kiss: The Detection of Gravitational Waves, by Harry Collins (The MIT Press), 2017. Pp. 408, 23 × 14·5 cm. Price £24·95/$29·95, (hardbound; ISBN 978 0 2620 3618 4).

Someday there will be an expert, definitive, book-length history of the *LIGO* (*Laser Interferometric Gravitational-Wave Observatory*, and the *O* was a brave choice when they started) project, its back-story, and aftermath. Harry Collins' *Gravity's Kiss* is not it, but I have hopes of work in progress by Daniel Kennefick (University of Arkansas) and Dennis Lehmkuhl (Einstein Papers Project, California Institute of Technology) who are historians of science with training in physics*. Collins is a sociologist, and this is the third of his books describing gravitational-wave searches and *LIGO* from that point of view, following *Gravity's Shadow* (2004) and *Gravity's Ghost* (2011). Addressing *LIGO* in this

*A major reason for that confidence is that, early in the project, one of the authors came down to UCI to interview me about Weber, at some length. In contrast, on at least one occasion while Collins was writing *Shadow* we were catty-corner opposite each other at a luncheon table, and, though we were introduced, he showed no indication of knowing who I was or of any desire to ask questions after he could no longer ask JW.

way is not unique. There are also sociological histories of quarks and solar neutrinos (which he cites), and probably other topics.

Collins' goal in embedding himself in the project was to understand how groups of scientists come to agreement about experimental results and their meaning. He was, therefore, a bit disappointed that 'The Event' of 2015 September 14 was so very clear that its reality did not need discussing, only its 'honesty' and meaning, before its announcement at a press conference on 2016 February 11 and simultaneous posting of a long paper already accepted by *Physical Review Letters* (yes, I was there).

General Relativity has two parts: Part I says that the distribution of mass–energy in the Universe determines its space–time geometry, and the geometry determines how massive particles will move. Part II says "now do the arithmetic", which is horrendously difficult, even for simple systems, and was instrumental in the development of calculus by computer. *LIGO* thus embodied hopes that (*i*) astronomical objects would change their quadrupole moments fairly suddenly, (*ii*) information about the change would propagate outward at $v = c^\star$, (*iii*) objects on Earth would be displaced by the space–time transverse fluctuations, and (*iv*) that the displacements would be large enough to detect.

The decision to call what propagates waves rather than radiation probably came from the feeling that 'radiation' like 'nuclear' tends to frighten some folks, hence MRI for NMR at hospitals.

Bruce Allen of the Max Planck Institute of Gravitation Physics in Hannover, a member of the *LIGO* collaboration who appears anonymously on p. 210, has reviewed *Kiss* in the 2017 December issue of *Physics Today* (p. 53), where he reveals all. His strongest objections to *Kiss* are the large fraction of the text devoted to quoting from Collins' previous books and articles, and the gross under-estimation of the amount of effort, numbers of phone calls, emails, sub-group gatherings, and other interactions required for the group to come to full agreement on exactly what to write and say about The Event. Allen noted that Collins did not attend even those subgroup meetings held at his own institution in Cardiff.

On the very same page, the author writes "frequency of rotation" where he means frequency of orbital revolution. Kerr black holes have an angular momentum expressed as a dimensionless *a* (angular momentum to mass ratio), but this does not translate into a straightforward rotation rate, and the data from the first event said nothing about the *a* values of the incoming objects anyhow, though some information is available for later events. It was the orbit period, revolution, that they measured. Collins writes repeatedly that he thinks the project was too slow in releasing both its first event and the second, confirming, one. *LIGO*-leakers (my term, surely not original) from outside the project agreed with him and immediately e-blabbed whatever they had heard, first, second, or third hand. They were frequently accurate, enabling theorists to get an early start (as if theorists were often too slow in responding to new astronomical data). Clearly I disagree. Is it just chance that the two L-L's who

⋆ Collins mistakenly writes that there was no initial reason to suppose v(gravity) = v(light), though that was what Poincaré said in 1905 and Einstein soon after. In fact, getting the observed 43″/century for the excess perihelion advance of Mercury from GR fixes v(gravity) to c(light) to within about 5%, which I learned from my husband, Joseph Weber, very early in our 1972–2000 marriage.

had me on their blab-lists have also in recent years been accused of other kinds of inappropriate behaviour? Well, one is a discovery; two is a confirmation; and so watch out for the third, which will establish a well-known class of perfidious astrophysicist. On his radio programme in the early 1950s, Jack Benny said, in denigration of one of his pre-WWII motion pictures*, "Just think, there is a whole new generation that will never know." The same thing is happening with *LIGO*. In the last year or two, I have encountered several young colleagues and students who were astounded to hear that I had never been in any way a part of the project, and even more astounded to hear that Joseph Weber (1919–2000) wasn't either.

Despite or because of this, Collins devotes many words to beating the dead Weber. JW has 14 index entries (and appears on at least nine other pages), Wittgenstein seven, and Rochus Vogt and Barry Barish, the managers who brought *LIGO* through many death-defying adventures, only two each. One of Weber's favourite sayings was that the most important properties of a physicist were his power output and his signal-to-noise ratio. If the same can be said about sociologists, then Collins seems to rank rather low on both. His last paragraph, before 'The Notes and Remarks', recounts briefly how Ronald Drever was locked out of his Caltech office immediately after being fired, "many thought it was an act intended to demean, while another group thought that the locks were changed as a matter of routine maintenance. I could have found out which by exploring documents in Caltech's maintenance department, but I didn't bother; all I needed to know was that relations were such that it was possible to believe either account — exactly which one was true didn't really matter, so long as either could be believed." I suspect it mattered a great deal to Ron and his friends, among whom Joe and I were happy to count ourselves.

Conflicts of interest: this book was a review copy, not one I purchased, as was the copy of *Shadow*, which I reviewed in *Nature* (**433**, 685, 2005), but from which I also extracted several paragraphs about Drever in preparing, on very short notice, a nomination of the *LIGO* trio for a particular prize (not headquartered in Stockholm).

Anyone who is interested in counterfactual history might want to contemplate the following: for spring, 1973, Weber was offered a Sherman Mills Fairchild fellowship at Caltech. He declined it because he had already accepted a spring position at the University of California Irvine, the first of our 28 years of sharing jobs for the same period. What if he had accepted the Caltech position?
— VIRGINIA TRIMBLE.

*I think it was *The Horn Blows at Midnight*, which is not at all bad. But *To Be or Not to Be* is superb, and anyone who saw it on first release in 1939 and afterwards claimed not to know what Hitler was doing to Jews, just wasn't paying attention.

THESIS ABSTRACTS

The Evolution of Dark and Luminous Structure in Massive Early-Type Galaxies

By Lindsay J. Oldham

In this thesis, I develop and combine strong-lensing and dynamical probes of the mass of early-type galaxies (ETGs) in order to improve our understanding of their dark and luminous mass structure and evolution.

Firstly, I demonstrate that the dark-matter halo of our nearest brightest cluster galaxy (BCG), M87, is centrally cored relative to the predictions of dark-matter-only models, and suggest an interpretation of this result in terms of dynamical heating due to the infall of satellite galaxies. Conversely, I find that the haloes of a sample of 12 field ETGs are strongly cusped, consistent with adiabatic contraction models due to the initial infall of gas. I suggest an explanation for these differences in which the increased rate of merging and accretion experienced by ETGs in dense environments leads to increased amounts of halo heating and expansion, such that the signature of the halo's initial contraction is erased in BCGs but retained in more isolated systems.

Secondly, I find evidence that the stellar-mass-to-light ratio declines with increasing radius in both field and cluster ETGs. With M87, I show that the strength of this gradient cannot be explained by trends in stellar metallicity or age if the stellar initial mass function (IMF) is spatially uniform, but that an IMF which becomes increasing bottom-heavy towards the galaxy centre can fully reproduce the inference on the stellar mass.

Finally, I use the sizes, stellar masses, and luminous structures of two samples of massive ETGs at redshift $z \sim 0{\cdot}6$ to set constraints on the mechanisms of ETG growth. I find that ETGs in dense cluster environments already lie on the local size–mass relation at this redshift, contrary to their isolated counterparts, and suggest that this may be evidence for their accelerated growth at early times due to the higher incidence of merger events in clusters. I also show that massive compact ETGs at this redshift are composed of a compact, red, spheroidal core surrounded by a more extended, diffuse, bluer envelope, which may be a structural imprint of their on-going inside-out growth. Overall, the studies presented in this thesis suggest a coherent scenario for ETG evolution which is dominated by hierarchical processes. — *University of Cambridge; accepted 2017 July*.

A full copy of this thesis can be requested from: lindsay.oldham@cfa.harvard.edu

Scattered Chips in the Milky Way Halo

By Gabriel Torrealba Arancibia

In the standard model of cosmology, the structure in the Universe is driven by dark matter. In this scenario, formation is hierarchical: small structures form first, and then act as building blocks to form bigger structures. One of the key predictions of this scenario, or any scenario where formation of structure is hierarchical, is the presence of hundreds to thousands of small dark-matter halos orbiting galaxies like the Milky Way. However, due to their dark nature and small scales, these have proven difficult to find. Nevertheless, while most of the smallest of the dark halos will remain dark forever, some will be lit by small and dim galaxies, providing a window of opportunity to probe the nature of dark matter and the formation of structure at the smallest scales.

In this thesis, I present a new search for the dark halos around the Milky Way, *via* the detection of small satellite galaxies. By improving the detection algorithms and by the use of new, deep, wide surveys, I have pushed the detection limits, yielding several new discoveries. In particular, I present the discovery of 15 new compact satellites using publicly available data from different surveys: the discovery of Crater 2, a Milky Way satellite that is one of the lowest-surface-brightness systems known; the discovery of Aquarius 2, a distant satellite of the Milky Way at the detection limits of current surveys; and the discovery of Carina 2 and 3, that form a very tight pair in the sky, and are probably satellites of the Magellanic Clouds, rather than the Milky Way. — *University of Cambridge; accepted 2017 October*.

A copy of this thesis can be requested from: gtorrealba@asiaa.sinica.edu.tw

Here and There

A UNIVERSAL UNIVERSITY

14:00 — (University of Astronomy) — *RAS Meeting Notes:* 8 December 2017, p.5.

NOT EVEN TO ASTROPHYSICAL ACCURACY

A new report ... makes the bold projection that there could be as many as 1,000 interstellar visitors arriving in our solar system every year — or one every three days. — *Daily Mail*, 2017 December 13, p. 19.

A SOURCE OF WEAK LENSING?

… could … these humongous black holes have collapsed directly from the glass clouds in the early universe? — *Scientific American*, 2018 February, p. 3.

HOLISTIC THEORY NEEDED

There are also problems relating gravity to quantum physic — *Astronomy Now*, 2018 February, p. 61.