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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2023 January 13 at $16^h\ 00^m$
in the Society of Antiquaries Lecture Theatre, Burlington House

Mike Edmunds, *President*
in the Chair

The President. Good afternoon everybody. This meeting is taking place *via* a webinar. I'd like to note and congratulate some Fellows and Friends of the Society as well, who have been mentioned in the New Year's Honours list. Professor Gillian Wright, who was awarded a CBE, Dr. Brian May becomes a KBE, Libby Jackson, who becomes an OBE, and Professor Terry Moore, who becomes an OBE. Congratulations from the Society to those four people.

I'm pleased to announce the following recipients of the Society's Awards in 2023. The Astronomy Gold Medal is awarded to Professor John Peacock, University of Edinburgh, and the Geophysics Gold Medal goes to Professor Timothy Palmer, University of Oxford. The Eddington Medal is awarded to Dr. Monika Moscibrodzka, Radboud University, and the Chapman Medal to Professor Nicholas Achilleos, University College London. The Herschel Medal goes to Professor Heino Falcke, Radboud University, and the Price Medal to Dr. Rhian Jones, University of Manchester. The Jackson-Gwilt Medal is awarded jointly to Professor Roberto Abraham, University of Toronto, and Professor Pieter van Dokkum, Yale University. The Fowler Award (A) goes to Dr. Christopher Berry, University of Glasgow, whilst the Fowler Award (G) is given to Dr. Oliver Allanson, University of Exeter. The Winton Award for Astronomy goes to Dr. Alexandra Amon, University of Cambridge, and the Winton Award for Geophysics is awarded to Dr. Ravindra Desai, University of Warwick. The Group Achievement Award has been given to the *MeerKAT* team. The RAS Service Award goes to Charles Barclay, University of Oxford, whilst the Agnes M. Clerke Medal for Historical Research in Astronomy or Geophysics is awarded to Professor Jim Bennett, University of Oxford/Science Museum. The RAS Primary Education Award is given to Inga Helmecke, Europa School. The RAS Secondary Education Award is awarded to Dr. David Boyce, Uppingham School, and the RAS Higher Education Award to Dr. Ravindra Desai, University of Warwick. The Annie Maunder Medal is given to Black In Astro. The following 'Named' lectures are to be delivered at a meeting of the Society: the George Darwin Lecture will be given by Dr. Dominic

Bowman, Katholieke Universiteit, Leuven, and the James Dungey Lecture by Professor Marina Galand, Imperial College London. Honorary Fellowships are awarded to Professor Erik Høg, University of Copenhagen, Dr. Premana Premadi, Institut Teknologi Bandung Department of Astronomy and Bosscha Observatory, and Dr. Rita Sambruna, NASA Astrophysics Division

Moving on to the programme for today, it is my very great pleasure to introduce a speaker following on from the group 'A' award last year. Professor Joop Schaye from the University of Leiden is going to talk about 'Cosmological simulations of galaxy formation'. Joop Schaye, after obtaining his PhD from the University of Cambridge, spent four years at the Institute of Advanced Study at Princeton as a long-time member before taking up a faculty position at Leiden University in 2005. He stayed there and since 2011 has been a full professor. Schaye works on the simulation and observation of galaxies, the intergalactic medium, and large-scale structure. He has led influential international simulation projects including OWLS (OverWhelmingly Large Simulations) and EAGLE (Evolution and Assembly of GaLaxies and their Environments). In addition he has developed analytic theories and has led observational campaigns to study the connection between galaxies and the gas around them.

Professor Joop Schaye. If we put the forces of nature into the computer, galaxies form naturally in our simulation. In this I include a hydrodynamical part including gravity as well as gas over a representative part of the Universe. These simulations are useful not just for studying formation and evolution of galaxies but also cosmology. If you want to measure the cosmological parameters by comparing them with the growth of structure then you will need something to compare to. What the baryons are doing is quite important these days as we are going to quite small scales in our observational surveys. The baryons do not trace the dark matter fully so we need to understand that. We take a cubic region of the Universe with periodic boundary conditions to avoid edge effects. If it is really a representative volume then that is fine. The box does not expand — we take out the expansion as a coordinate transformation as a solution to the Friedmann equation and that is where dark energy comes into play, for example. There is no dark energy fluid in these simulations. Then we have to discretize the simulations — we always discretize time — but then you choose whether to discretize mass or space. In the simulations being discussed today I discretized the mass, then we put in cold dark matter and ordinary baryonic matter. We have initial conditions which are fairly well known from the cosmic microwave background radiation, and also from observations of large-scale structures, but we also want to vary the initial conditions if you want to do simulations for cosmology. For galaxy formation, initial conditions are pretty well constrained for that purpose. We cannot simulate everything directly because the range of scales is large. We need some prescription for what happens below the resolution limit. To see why such sub-grid models are needed and to appreciate why they will always be needed, consider the large range of scales for these kinds of models. For the cosmological simulations ideally we want to model the entire observable Universe — several Gpc — but even if we don't want to do such a large volume, we want to study clusters of galaxies, galaxies, and maybe the star clusters in them. To do that we need to follow the formation of stars and stellar evolution. In fact we also need to care about the atomic scale because the collisions between atoms is what causes the emission of radiation. Radiation is what we see and the emission of radiation allows the gas to lose its binding energy. Actually we even need to care about nucleosynthesis inside stars as this produces chemical elements that are released and observed.

We switch from direct simulation to sub-grid models and where you draw the line depends on your interest. If you are interested in large-scale structure you invest more of your resources in going to a large volume and you need to go to sub-grid models below the galaxy scale. If you are interested in the formation of dwarf galaxies, you would invest your resources into a smaller volume but then you can go to smaller scales and probably resolve star clusters. I will discuss three examples of the sub-grid models that are needed — microscopic processes, things to do with stars, and things to do with black holes. In the first of these you need to think about how much radiation is emitted by a gas as a function of its chemical composition, density, temperature, and the radiation field that is impinging on it. Also the formation and evolution of dust grains affects how light is emitted and is important for the formation of molecular hydrogen. For stars we need to know how they form, evolve, how much mass they lose, how much energy and momentum they inject. In the case of black holes, we want to know how they grow by gas and stellar accretion, mergers with other black holes, and also what happens in terms of feedback, jets, and winds from accretion discs. Movement of black holes also needs to be done in the sub-grid models. They are supposed to be much more massive than dark-matter particles and that is why they exhibit dynamical friction. In the simulation the black-hole particles tend to be of similar mass to the particles that represent dark matter and therefore we cannot directly simulate this dynamical friction, we need some prescription for that, which is important. But the most important matter, however, is the feedback process. Years before EAGLE there was always a big problem. When people did hydrodynamical simulations, the galaxies did not look like those shown here today. They came out too bulgy, they formed their stars too early, and they were too massive. This was resolved by refining the sub-grid model for feedback to overcome what was known as numerical over-cooling. It means the gas is radiating away too much of its energy due to limited numerical resolution. When feedback happens and energy from supernovae is injected into the interstellar medium, too much mass is heated which means that the temperature does not rise much, leading to short cooling times, and the gas emits energy in the form of radiation instead of expanding through shock waves. We need to overcome that with a trick which needs to be calibrated because we do not know *a priori* what the answer is. What you need to calibrate to depends on what question you are asking. For cosmological simulations of galaxy formation, for example, it is the mass function of galaxies. Finally it was realized we needed not only stellar feedback but also AGN feedback from growing black holes, and this is really important for the most massive galaxies.

EAGLE is a team award so I must pay tribute to the other team members and the fact that the simulations have contributed to several-hundred papers led by people outside the team. I particularly want to mention Professor Richard Bower who passed away a week ago. He was one of the most important people in this collaboration.

This video shows a small part of one of the EAGLE simulations, a volume of $(25\ \mathrm{Mpc})^3$. Explosions are driven by supernovae and AGN. On this scale the galaxies occupy less than 1 pixel and are not visible. After $z=1$ not much happens. The expansion of the Universe has been scaled out — we are looking at co-moving coordinates. The hot bubbles of gas are heated by AGN but also by shock heating from gravitational in-fall. These simulations were calibrated to reproduce the galaxy mass function at $z=0$. Here is one galaxy in four different simulations at different resolutions that all reproduced the galaxy mass function but in three of the four simulations there is a dip in the galaxy sizes at 10^{10} solar masses due to numerical overcooling that could not be overcome in these simulations. We needed to calibrate to galaxy sizes to get reasonable data. After that everything followed and actually many other things agreed with observation. Richard Bower came up with the trick we needed to compensate for this numerical overcooling which was absolutely critical for the project.

There were still a lot of uncertainties in these simulations after calibration. For instance, the black-hole positions need to be adjusted by hand and moved down the potential gradient into the centre of galaxies. This can be done naturally by dynamical friction and they should stay there but we do not resolve the dynamical friction. Feedback has to be injected using calibrated sub-grid models. This doesn't just mean how much energy you should inject. Looking at the side view of a galaxy, winds which came out of galaxies tend to do so along the line of least resistance, *i.e.*, perpendicular to the disc. All these simulations inject the same amount of energy per unit of star formation. All that has changed is how the energy is distributed around the supernovae. Is the energy injected in low-density gas or higher-density gas? Mass-weighted or isotropic? If we put it in the higher-density gas then more of it is radiated away. The structure of the interstellar medium is not very well resolved so we need to make some assumptions here. You can see that these matter as much as changing the amount of energy by factors of a few. Calibration is not just about picking numbers but it is also how you implement things. These simulations and also the ones by other groups have been extremely successful in the sense that they reproduce many observables that they weren't tuned to, and that can be used to make more virtual observations to help the interpretation of real observations. There are, however, also drawbacks in addition to the uncertainties mentioned. For example, the volumes are too small to study large-scale structure even with a 100-Mpc box. A major drawback is that the interstellar medium is not allowed to cool below 10^4 K. This means that the interstellar medium will not be very clumpy and that affects the way galactic winds develop. Another issue is that because dark-matter particles in the simulation are massive — one dark-matter particle may represent one-million solar masses of dark matter — you get collisional effects that shouldn't be there and that heats up the stars in the galaxy thus changing the morphology of the gas making them too thick and too large.

The next-generation simulations that we and others are doing will deal with these problems to some extent. The two projects are FLAMINGO and COLIBRE. Both use much larger volumes thanks to the increased efficiency of algorithms and bigger computers. We added a lot of physics in COLIBRE to allow the gas to become molecular and cool down. For that we needed a molecular network, a chemical network, and we need to include shielding of the radiation fields. You need dust that forms and evolves and is coupled to the molecular hydrogen. To overcome the spurious heating by dark-matter particles, we just put in many more dark-matter particles. FLAMINGO is the next big project that we are writing papers on. This is meant for comparison with cosmological observations so it has very large volumes including the largest hydrodynamical simulation ever done, with almost one trillion particles. To put it in perspective, the EAGLE volume is 100 Mpc on the side and this picture is something that Richard Bower contributed to. FLAMINGO is much bigger than EAGLE but thanks to increased computing power we still have enough resolution to see enough detail. We track not just the gas, CDM, and stars, but also neutrinos which are also clustered, but because of free streaming they are not clustered as much as the rest of the matter. Another thing that has also been inspired by Richard Bower was to use machine learning to do the calibration. Whereas in EAGLE we did it all by hand, here we built emulators and used them to predict the effect of changing two AGN feedback parameters and two stellar feedback parameters on observables that we calibrate to.

In conclusion, cosmological simulations have come a long way. They are now sufficiently realistic to compare to observations, both to test the theories and also to test what sort of systematic effects might be present in real data. We can also use them to design campaigns for observing and instrument proposals. However, galaxy formation is not fundamental physical theory — there is a lot of uncertainty in there. These models are better for testing scenarios than for quantitative predictions. We do require calibration of sub-grid processes which is not just tuning of the parameters but also the choices you make. The next generation of simulations is coming up from us and others — compared to EAGLE it will have bigger volumes, many more resolution elements, more physics, and also machine learning. Simulations will be used to train emulators to make predictions and to investigate interactions between cosmological parameter changes and physics changes.

The President. Thank you very much, very interesting. Thank you, too, for informing us about Richard Bower, which I hadn't personally been aware of, and was really sorry to hear of his passing. Can I open the floor for questions? Please give your name for recording purposes.

Reverend Garth Barber. Do you see with the FLAMINGO simulations any problems with reconciling them with the ultra-high-*z JWST* observations?

Professor Schaye. The resolution of those simulations is a little bit too low to make good predictions for objects at high redshift. We can see if we look at the history of the galaxies that we can do the low-redshift part but for high redshift we would really like higher resolution. We can do the volume but we'd still like better resolution.

Professor Michael Rowan-Robinson. Could you say a little more about the distinction between what you called calibration and the tuning of free parameters? It did look rather as if something didn't fit very well so you tweaked something to bring it into line.

Professor Schaye. You have to choose an observable that you use to calibrate the uncertain feedback processes. Which observable depends on what you want to do. If you want to do reionization simulations then you would tune the escape fraction because you can't simulate that. In our case we are interested in the galaxies so we calibrated to the galaxy mass function and galaxy sizes. Hopefully, you don't need even more. What you need limits the kind of questions you can ask of the simulations. The point I made is that the calibration is not only changing the parameter values, sometimes it is a free function or just a choice of implementation.

Dr. Robert Massey. We have a question from Ofer Lahav. "What is the status of incorporating neutrinos in your simulation?"

Professor Schaye. The status is good. For a long time people did it mostly by changing the initial conditions because neutrino particles introduce a lot of Poisson noise, but there are now new techniques developed to suppress Poisson noise. One of them, which we are using here, is called the delta-f method. In FLAMINGO we can include the noise suppression at little extra cost.

Dr. Paul Wheat. I'm just wondering what assumptions you make about angular momentum — whether it is randomly distributed throughout the Universe, or whether there is a net zero overall.

Professor Schaye. Net zero on the scale of the entire Universe you mean?

I would certainly assume that is the case. Whether or not that is true is not something we can answer with these kinds of simulations because we assume global isotropy of the entire Universe.

Professor Richard Ellis. It has been suggested that cosmic rays should be incorporated in many of these simulations. What is the status on that?

Professor Schaye. Yes, there are pieces of physics that are not in EAGLE and will not be in our next generation of simulations that might well be important and one of them is cosmic-ray pressure. The problem with cosmic rays is that it is still very unclear whether it is very important or not important at all. It depends on the microphysics. There is very important and useful work being done to test this at the moment but our feeling was that if we made one big investment of computational time it is too uncertain to pick one of those scenarios, but I would not be surprised if it indeed turns out to be important.

Mr. John Salmon. If you run the simulations forward what do you get?

Professor Schaye. Beyond the present time? We've actually done that with EAGLE. There are papers by Jaime Salcido and Luke Barnes who did that. We did this because we were interested in the anthropic principle. What we found was that the cosmic star-formation rate per unit volume is now going down. If you wait long enough it will go back up according to these models unless you get very strong AGN feedback, and that is because in clusters of galaxies where the cooling time is long, at some point the age of the Universe is similar to that cooling time and you start cooling down that gas again. If you have very efficient AGN you can prevent it.

The President. Any further questions? Can I ask what is rather a naive question? Looking at all these wonderful simulations do you have a feel yet about the primary processes in galaxy formation? In other words, these are the very important things you need to put in — all these other things are peripheral; there are five or six major processes that do it all and you can forget the rest. Have you reached that state yet or not?

Professor Schaye. Not fully. It really depends on the question you are asking. To give an example, if you are just interested in how many stars are forming you don't have to care about the star-formation law. If you are interested, however, in how much gas there is in the galaxies, then the star-formation laws are really important. There is, I think, disagreement about which physics is important but everyone agrees that you need more than one channel of feedback. You need something that dominates at low mass and something else that dominates at high mass in galaxies, for instance, black holes and supernovae. It's not unique.

The President. Thank you very much and congratulations for getting FLAMINGO as an acronym [laughter]. My next one is going to be DODO! [Applause.]

For our next talk, the George Darwin Lecture, I'm absolutely delighted to introduce Alan Fitzsimmons from Queen's University Belfast, who is going to talk about 'Small-body impacts across the Galaxy'. Alan is Professor of Astronomy at the Astrophysics Research Centre at QUB. He performs observational studies of comets and asteroids, mostly in our own Solar System, and he is the author of more than 160 scientific papers. Highlights of his career include studies of the collision of Comet Shoemaker–Levy 9 with Jupiter, which I'm sure many of you remember, and also 2008 TC3, identified as the first asteroid predicted to impact Earth. I asked him about this rather worriedly and yes, it had hit Earth somewhere in the Sudan, but it was only three to four metres in diameter, so fortunately it didn't do a great deal of damage. He has also been involved in the discoveries of the first interstellar objects. Currently he is an active member of the *Asteroid Terrestrial-impact Last Alert System* (*ATLAS*) and the NASA/*DART* (*Double Asteroid Redirection Test*) Consortia, and ESA/*Hera* Planetary Defence mission, obviously of particular recent interest. He asked me to point out that neither asteroid 4985 Fitzsimmons nor Comet C/2018 X2 Fitzsimmons are expected to hit the Earth in the next few millennia. With that good news I hand over to Alan.

Professor Alan Fitzsimmons. [It is expected that a summary will appear in a future issue of *Astronomy & Astrophysics*. Although we have now started hitting comets and asteroids ourselves, most small-body collisions are of the natural kind. We have now observed many asteroid or comet impacts in our Solar System. Not only do these studies fuel our planetary defence programmes, they give us insight into the collisional and accretion processes that go into shaping planetary systems. Further afield, small-body collisions give rise to debris discs around young stars and polluted white-dwarf photospheres. Finally, the discovery of the first interstellar objects has brought alive the possibility of cross-contamination between planetary systems in the Milky Way. This talk briefly covered some of these advances in the past few decades, and highlighted the ubiquitous effects of collisions in planetary systems.]

The President. Thank you very much Alan, for banging the rocks for us. Can I invite questions both in the hall and also on-line please?

Reverend Barber. The diagram of the lunar impacts is quite worrying, in terms of the energy involved and the frequency. The Earth must have a similar situation because it's part of the Solar System.

Professor Fitzsimmons. The important thing about the lunar impact history is, of course, when we look at the lunar surface today that's really a record of the early-bombardment history.

Reverend Barber. That's going right back?

Professor Fitzsimmons. Yes. When you look at the Moon through a telescope or binoculars you see the craters and large impact basins; most of these were formed over 3·9 billion years ago when the Solar System was still being pretty much cleared out of stuff that was left over from planetary formation. Now there clearly have been some changes in the impact rates in the inner Solar System since then. There is an interesting study, published about a year ago, that implies there is a sudden jump back up, perhaps by a factor three or four, in the impact rate on the lunar surface, and therefore by proxy, on Earth's surface, about 600-million years ago for reasons that aren't very clear. Perhaps there had been a major impact in the main asteroid belt before then that fed the resonances that drive that material towards the inner Solar System. The nice thing is that the lunar surface is much older than us in all senses of the word, but importantly it gives us that insight into what was happening back then.

Dr. Wheat. When you whack an asteroid to try to move its orbit, obviously it isn't an elastic collision, the thing doesn't just stick in it, and you have debris coming off. Do you know how much momentum is transferred to the more solid block and how much of it goes into the debris? What difference does that make to the orbit?

Professor Fitzsimmons. That was one of the main goals of the *DART* mission. I can't give the exact numbers because the paper has not yet been published. We know the momentum of *DART* when it came in — 570 kg of spacecraft moving at 6·1 km sec^{-1}. That momentum went into moving the asteroid but then we have the angular momentum given by the ejecta and that is what *DART* wanted to measure. Even if just the momentum of the spacecraft had moved the asteroid, the period of the asteroid around the parent Didymos would have been changed by 7 minutes. In fact the orbital period was changed by 33 minutes so one can see that we have about four times as much momentum transfer as we would have had from the spacecraft alone. Actually working out what happened in that impact is going to take quite a while — how did that momentum and kinetic energy get spread out among the ejecta, what can we find out about the ejecta that was dug out of the surface of Dimorphos? Those data will be worked on certainly for the next year or two, but then in almost exactly four years' time the ESA *Hera* mission will rendezvous with the asteroid system and then measurements will tell us probably what happened.

Dr. Wheat. Of course that depends on the cohesiveness of the material that you are hitting. The positive side is that you are trying to deflect it to prevent a possible collision with Earth; of course you have smaller fragments hitting as well if you are doing the right thing.

Professor Fitzsimmons. The kinetic energy of the mission was much smaller than the binding energy of the asteroid by about an order of magnitude, but what it could certainly do is to tell us what happened in that collision.

Professor Ellis. You talk about the risk of collisions with the Earth; what about the risk of collisions with the mirror of the $10 billion *JWST*?

Professor Fitzsimmons. All I can say is try to get your *JWST* time in the early cycles [laughter]. The micrometeorite environment in the near-Earth system is not something I work with. They did not expect such a large impact so early in the mission.

Professor Ellis. Where on your plot would it be — is it a big extrapolation?

Professor Fitzsimmons. Oh yes, absolutely. Going to the plot and looking at impacts from near-Earth asteroids you are still looking at objects a few cm across and I assume that the object that hit the *JWST* mirror was probably a few microns in size. I don't know, to be honest.

Professor Rowan-Robinson. I want to get some insight into collisions between asteroid families in the infra-red zodiacal band. The thing about trans-Neptunian objects is that there should be a component somewhere that is due to that.

Professor Fitzsimmons. The interesting thing is that if you look at the simulations they imply that the dust content of the Solar System is completely dominated by the dust generated in the trans-Neptunian region — 99% of the Solar System dust should be out there beyond Neptune, but it is so cold and faint and the sky brightness is so low that it has never been detected.

Dr. Paul Daniels. To what extent do you think that the detection of the hazardous near-Earth objects will be hampered by the proliferation of low-Earth orbit satellites?

Professor Fitzsimmons. That is a good question. This is something that is not just a worry for the asteroidal sky surveys but for all astronomy. I think, from experience in *Pan-STARRS* (*Panoramic Survey Telescope And Rapid Response System*) and *ATLAS*, that for the next few years things will be okay, and there have been many studies about this. There is no problem in mistaking a low-Earth orbiting satellite from an NEO because they are travelling much faster than the asteroids. If you have an asteroid travelling fast then you are in trouble because you missed it and it's too late. The real problem is how much of your real image that you are using every night to survey is contaminated by those satellite tracks which can be very bright so that saturation can easily bleed into surrounding areas on the chip. I think it is going to be a small problem, because in the NEO game you always take at least four exposures, because you want to see that point of light moving in a consistent manner. Experience has taught us that having three exposures is not good enough but you can go back and check. I think it is going to hurt the transient-astrophysics community a lot more. If you are looking for fast transients and you miss one because there is a satellite track over it and you don't get back there for three or four nights, I think that can be more serious than for the near-Earth asteroid surveys.

The President. The problem with low-Earth-orbit satellites is something the RAS takes very seriously. Robert Massey is doing a lot of work with international bodies to frame our response to such problems and hopefully we can keep you updated and keep them in check.

Ms. Gail Campbell. I wanted to say thank you very much for your talk. I want you to say a few words about the *Sentry* system.

Professor Fitzsimmons. I'll just briefly explain how the *Sentry* system works. Let me re-assure you that it is completely international and completely open in that when a new object or a known object is observed and measured, it is sent to a central clearing house at the Minor Planet Center at Harvard. If it is new and unknown, it is immediately placed on an open-access pocket website so that any astronomer can follow that object up and go and get more observations. Within ten minutes the potential risk from that object has been published on the NASA/JPL Scout website and it's pretty good. It really does tell us, if we have a limited amount of telescope time, what objects to follow and track to determine the orbit. Once we know the orbit then that moves to what is called the *Sentry* system where a future impact-risk assessment is made using independent algorithms in both Europe and the US. Those risk pages are also completely open so I am afraid to say that if we are in significant danger the astronomers will know just as quickly as you or the politicians will know.

Professor Cruise. Is there any significant difference in the impact of a given mass on the Earth's atmosphere whether it is solid form or a rubble pile? Can you cheer us up at all? [Laughter.]

Professor Fitzsimmons. Probably not, not to first order. Remember these objects have a typical impact velocity of 17 km sec^{-1} or so, which means you only have five or ten seconds for that object to pass from the top of the atmosphere to ground level and that is really not enough time to disrupt any further that rubble-pile object. That question was asked by the Shoemaker–Levy 9 impact, because we suspected comet nuclei were relatively low-density rubble-pile structures. There was a famous paper published a week beforehand saying these things are low density and they may be big so you won't see anything.

The President. The one fascinating thing you left hanging was this date of 3rd May 2029.

Professor Fitzsimmons. No. Friday, April 13th.

The President. I've got the date wrong! I've already invited people [laughter]!

Professor Fitzsimmons. This is the close approach of a famous NEA called Apophis. Why worry, we've just called it after the god of death. This was a relatively threatening object when it was first discovered — there was a significant possibility that it could hit us sometime in the next decade. We now know that this is not going to happen through continued observation, particularly radar studies; it's not going to hang around.

The President. You said it would be a 3rd magnitude object?

Professor Fitzsimmons. Yes. It will pass the Earth closer to us than the geostationary satellites and that night it might reach 3rd magnitude when it passes over northern Europe

The President. Has there been any previous recorded event in history in which a passing asteroid has been seen with the naked-eye?

Professor Fitzsimmons. Not in recorded history. It is something to look out for. It will probably be raining [laughter].

The President. The next monthly A and G meeting of this Society will be on Friday, 10th February. I remind you that there will be a drinks reception in the RAS Council Room straight after the meeting and can we thank Alan again for a fascinating talk [applause].

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2023 February 10 at $16^{h}\ 00^{m}$
in the Geological Society Lecture Theatre, Burlington House

Mike Edmunds, *President*
in the Chair

The President. Fellows, visitors, good afternoon. It is good to see a fair number here today, better than we have had recently for an Open Meeting. This is a hybrid meeting. Questions may be asked *via* the chat facility and they will be read out by Dr. Sue Bowler. The first speaker we were meant to have was Dr. Beatriz Sánchez-Cano, who was the recipient of the Fowler 'A' award. I am very sorry to say that she was taken ill this morning . I gather that she is out of hospital and back at home. That talk will be given another time and I assume that it is your will that I should convey your best wishes for a speedy recovery.

The first talk is by Professor Eleri Pryse from the University of Aberystwyth. Eleri Pryse graduated in physics from the University of Wales and went on to obtain her PhD in ionospheric physics for the investigation of small-scale irregularities in the ionosphere using radio signals from satellites. She was appointed a physics lecturer at Aberystwyth in 1989 and is a very valued colleague across Wales. I invite her to give her talk entitled 'Extending astronomy outreach through Eisteddfodau in Wales'.

Professor Eleri Pryse. We know the importance of science outreach. A tremendous amount of excellent outreach has been made through educational activities. But there is a tendency for such activity to reach those with an underlying interest in science. The main aim of the project was to extend astronomy and geophysics beyond conventional outreach, by introducing the science to new audiences using the arts. When Dr. Mandy Bailey visited Aberystwyth over eight years ago for an RAS200 Town Hall meeting, interest was shown by several institutions including the two national Eisteddfodau. An inclusive combination of institutions offered a novel way to reach a general audience. Central to this project have been collaborations between many contributors with complementary skills.

These were the two national Eisteddfodau. Both are major annual cultural festivals in Wales. The contributions of the public to these is enormous and shows the affinity the people of Wales to the festivals. Whilst each Eisteddfod is about a week long, the activities leading to each festival occur over some two years prior to the event, with involvement from the local community. They have a combined attendance of approximately 250 000 per year.

The Urdd Eisteddfod culminates with its national festival during the summer half-term. It has local and county rounds prior to this and focusses on children and youth. Competitions include singing, dancing, crafts, and poetry.

The National Eisteddfod is in early August. The festival is a celebration of Wales's culture and language. It includes many competitions of high standards for all ages, including many prestigious poetry competitions and large-scale cultural events.

The Eisteddfodau by nature are inclusive. They provide for competitors and participants of different backgrounds, interests, age, fluency in Welsh, learning needs, and geographic areas. Both are touring festivals. Both alternate between the south and north of Wales, such that when the Urdd is in north Wales the National Eisteddfod is in south Wales and *vice versa*.

Other main project contributors were Telesgop, a multi-media company. Its role became crucial during the Covid lockdown; the Coleg Cymraeg Cenedlaethol, the national institution that supports universities with their Welsh-medium teaching; and Ysgol Glan Clwyd, a Welsh-medium school where the physics teacher specializes in astronomy. All three institutions have expertise in communicating with different audiences. For science support there were fellows and scientists from universities — Aberystwyth, Bristol, UCL/MSSL, Swansea, and Cardiff — each of us with our own research speciality.

Many activities on A&G themes were held and displayed at Eisteddfodau. These included art and crafts, modern and traditional clog dancing, story-telling and composing, each led by specialists in the fields and with science support. When Eisteddfodau were in Cardiff displays and performances were in the foyers of the Wales Millennium Centre and the Senedd and in the Pierhead. There were also competitions, composed songs, and poetry on astronomical themes. Photos of activities are on the Coleg Cymraeg Cendlaethol virtual resource centre. Additional science support came from other scientists, teachers, and amateur astronomers. There was also support by AstroCymru, the Brecon Beacons National Park's Educational Department, the Royal Observatory Greenwich, *A&G* journal, and British Antarctic Survey, and valuable inputs given by the RAS and Jenesys Associates.

Lloergan was the collaborative opening musical production of the Ceredigion National Eisteddfod in 2022, with the Eisteddfod securing additional sponsorship. It was set in a space-exploration context, and presented important questions on ambition, challenges of raising family, and balancing work, travelling, and home life. It was held at the Main Pavilion (capacity of about 1800), televised on S4C essentially live and subsequently available on iPlayer. This large-scale production had professional actors, musical director, and band, and a volunteer choir of more than 100 people.

During the project the exhibits were mainly displayed in venues other than the science pavilions, to extend reach. However, in the final year substantial effort was made by the 2022 Ceredigion Eisteddfod to bring the general audience into the science venue using approaches similar to the project. The Eisteddfod appointed a science coordinator with a background in art and experience of STEM outreach. The venue was a Science and Technology Village, with the *Sfferen* where talks were held (*Seren*/Star and *Sffer*/Sphere), and the *Lloeren* (Satellite) with activities for children and smaller stalls. The main stalls were in huts outside, set in a semi-circle, giving an open venue. The project had two large stalls, with the main inputs from Aberystwyth University, MSSL, and Cardiff University. We were delighted that the RAS President and Senior Secretary visited the village and the Eisteddfod.

There was a series of RAS talks in Welsh throughout the week, at a set prime time. Some were with the artists, others by early-career scientists, and others by established scientists. Early images from the *James Webb Space Telescope* were shown, which were only available a matter of days before. The national media picked up on the opportunity for an early-career female astronomer, with an article by Non Tudur in the magazine *golwg*.

There are photos and memories of the activities, but legacy is more than this.

Hopefully we've shown how the project has enhanced collaborations and networking across disciplines, and revealed the complementary roles of professional communicators and scientists. The project also contributed significantly to evolving the presenting of science to a wider audience.

A popular activity for the family at the Science Village was *Ceffyl y Sêr*. This wasn't directly part of the project, but it was set on the pattern of project activities. It had a professional story-teller, musicians from the Aberystwyth Philomusica orchestra, animation, and was written by a prominent bard and composer.

A glimpse at the past shows the evolution of science at the Eisteddfodau. The first exhibition was in a small tent at the Bangor National Eisteddfod in 1971 whilst the science provision at the Urdd had its first *GwyddonLe* at their Eisteddfod in Ceredigion in 2010. Science pavilions and a larger *GwyddonLe* followed. We hope that the recent development of the Science and Technology Village at Ceredigion will leave a legacy of an additional step towards a welcoming venue to draw in a more general audience.

The President. Thank you very much — questions?

Professor Steve Eales. I was struck by the number of multi-disciplinary things which seemed to come naturally. Is that part of the Eisteddfod tradition or is so much of it multi-disciplinary because the Eisteddfod started as an arts festival and gradually expanded into science or is it part of the Welsh-speaking tradition?

Ms. Elen Elis. We have 25 stages; we also have a literature village, and a science village which we have recently developed with help from this project. We have a children's village, a folk village, and dance. We have all the art forms and we also cater for diversity, accessibility, inclusivity, equality, the environment, and well-being at the heart of all our programming. We exist to promote the Welsh language and the culture in Wales and we are evolving as the world around us evolves, so we are there to celebrate our culture, national and international — we are developing collaborations across the world. It is an eight-day festival with 170 000 attending. You don't have to speak Welsh to enjoy it — we encourage you all to come along to be immersed in Welsh culture.

Professor Eales. It was very appealing to see how the different disciplines naturally connect. You do get art and science together elsewhere but it seems to be added-on instead of being allowed to grow naturally.

Ms. Elis. We've proved in a way that the arts do help us to promote science and that is the beauty of this project, supported as it is by the RAS. In the science village we celebrate all the subjects but in this particular project we celebrated geophysics and astronomy.

Professor Steve Miller. This is just for the record, Eleri. I have your proposal in front of me and it says "envisaged highlights are musical items from the musician's medal competition at the National Eisteddfod and the commissioned music at the Urdd Eisteddfod", so I think that you have delivered big time on that.

Professor Pryse. Thank you.

Dr. Sue Bowler. This is from Geraint Day. "Have any Eisteddfodau sessions ever mentioned the idea of alternative constellation names, taken from characters and creatures in Welsh mediaeval folk tales?"

Professor Pryse. We haven't had any meetings on that but we have had some nice ideas coming in. If anyone has any ideas for this please send them to me.

The President. I know a little Welsh but the Welsh days of the week are all planetary, whilst the English ones have some intruders. Thank you very much [applause].

For the next talk we have Andy Newsam — 'Access to the Universe for all. The National Schools' Observatory'. It sounds like a pretty tall order [laughter].

Professor Andy Newsam. It is a real honour and pleasure to be doing this today. Earlier on there was a talk about sustainability in astronomical projects. I have been involved in one for 20 years and it is still going strong. Today I want to give a status report, partly because I am proud of it and partly to show what can be achieved.

The background is astronomy and education. As many of us know, both anecdotally and from hard evidence, astronomy is a science which maintains interest regardless of gender, ethnic, or social background right through the school years. That is not true for all branches of science. A report by Osbourne and Collins in 2000 stated that this was the only science that kept that interest growing. We need to use that fascination to help enthuse school children all around the world about other areas of science such as computing, engineering, and even the art that leads into our subject.

The telescope we use for this is based in La Palma — it is an astonishing place aesthetically and it is an astonishing place to see the sky. The *Liverpool Telescope* (*LT*) was built by Liverpool John Moores University (LJMU). It has a 2-metre mirror and is special because it is fully robotic. The instruments include an optical camera, a fast camera for doing rapid measurements, a spectrograph, a polarimeter, and sky cameras. Changing between instruments occupies less than a minute so science projects can bring together different aspects of the kinds of measurements we want to make. It slews rapidly across the sky so that it can react quickly to events. It is fully automated. So, for example, if a satellite detects a gamma-ray burst it will tell the telescope which will start observing it. In addition to LJMU staff, UK astronomers can apply for time *via* PATT, astronomers in Spain also get a lot of time, and amateur astronomers around the world can also get time allocations.

The facility for schools is not an add-on — it was intended from the very start. The original idea from Mike Bode was for a telescope to study novae but he also felt that access should be very wide. This has led to the National Schools' Observatory. It is free to anyone, with special access for UK and Irish schools. We aim for ages 6 to 18. We have 20 000 regular and active observers including teachers, students, and educators and so far more than 200 000 observations have been taken. Much of our effort goes into the supporting resources — the website gets about three-million hits per year.

In order to allow the greatest number of people to make use of the *LT* we have a range of different ways in which the telescope can be used. There is the very simple observing request — you can click on a picture of the Moon, for example, or choose a nice galaxy from a list. More complex requests lead to multi-school projects often with research involvement. We have done projects with organizations such as Rotary International and the Royal Institution, including a six-month project monitoring novae in other galaxies. We also have non-observing projects involving the use of large archives, for instance.

I have learned a lot from this project. My background is not originally in observational astronomy — I drifted into it as a way of not dropping other physics subjects. I began to think of the brighter objects, particularly the Moon, as a nuisance but then started taking images for schools and the changing aspect of the Moon's surface excited me.

The fundamental drive behind all of this is raising people's curiosity and awareness of science as a means of answering questions and just not a big block of facts. So we have to find out if that is working. We needed to work out what we want to achieve and how to achieve it, which leads us to our 'Learning Outcomes', and an 'Evaluation Framework' used to find out whether we are achieving them. It is important to note that the learning outcomes are not just about knowledge and skills but also about feelings, behaviour, and values and how we are changing those. Web analytics allow us to explore the range of users and what they are looking at. We have user groups, particularly teachers, who give us feedback. Every three or four years we commission an independent external evaluation — they do case studies, monitor lessons, and carry out interviews with pupils and teachers and undertake larger surveys. The evaluations targeted schools of particular types and pupil demographics and find that we were very popular and that there is a sizeable impact on student learning outcomes, with one of the independent evaluations concluding that "The NSO is one of the most important initiatives in the STEM field linked to a University". The NSO project is run by an average of just 3·2 people, so this shows you can have a substantial impact by gradually developing and consolidating.

Our next project is a new telescope. It's going to be bigger (4-metre aperture) and faster — we hope to get it across the sky in under 30 seconds. It will be located near to the *LT* on La Palma. As well as enhanced research there will be a potential for further education as we will have different ways of using these telescopes. As we look to the future we have the possibility of expanding what we are doing now and we are hoping to turn this into an international programme. We have already made it possible for anyone in the world to register and now we want to make it worthwhile. We have been looking at pilot projects in countries which are culturally different to the UK. So far we have pilot projects in Thailand and Kenya. Thailand is developing a high-tech economy but it is short of high-tech workers coming out of school. The Thai government has decided that astronomy is a way to supply those workers. A version of the NSO is now operating in Thailand. Kenya is very different. There we are working with a wonderful organization called the Travelling Telescope who work in rural areas. About a decade ago there was a great increase in the number of tablets in Kenya but internet access is still rare and slow. We have developed a simple app based on the Moon which mostly does not need internet access.

So to summarize all that, the NSO has supported schools education in astronomy for more than 15 years. It is based around unique access to the *LT*. There is extensive educational material for all of STEM. We are building a new telescope and designing new software so we've got the potential for significant expansion.

The President. Thank you very much, Andy. Twenty-thousand users? Amazing. Questions please.

Ms. Marguerita Laporte. I introduced astronomy in schools in the seventies. I found a very interested Chief Executive of education and we pursued this — it was very successful. One of the programmes we did was to build a polystrene box on a telescope and treated it as a spectrohelioscope. It caused a sensation. Recently in January I was invited to go to the school and talk about astronomy and I was most impressed with what the teacher had done. The children had filled the ceilings with models and rocket ships and they had sheets asking many questions. I wish you great luck with this wonderful project.

Professor Newsam. Thank you very much, that does sound like a great project. There is nothing like going into a primary-school classroom and just letting them loose with the questions. You will get questions you don't know the answer to. My favourite question was "What happens to the dark when you turn the light on?" and I had no answer to that.

Dr. Olivia Keenan. I represent the South-East Physics Network. Thank you for the talk — such an inspiring project. I note that you have a REF case study for this. What were the challenges of demonstrating a change element, and I'm also asking very cheekily if you have any idea what score you might have got for it?

Professor Newsam. We could not have done it without getting external evaluators in — they provided us with independent evidence. Our biggest challenge was not showing the change — that we were able to demonstrate — our biggest challenge was tying in to particular research papers which was a nightmare. Overall we don't know the ratings for individual Case Studies, but overall we were highly rated for the impact so we are fairly certain this was a four-star.

Dr. Bowler. This is a question from an anonymous attendee: "How do you prioritize access and observing time limits?"

Professor Newsam. That is a very good question. We tend to do it algorithmically. Generally speaking we are close to the limits of the telescope time that we have got. So if, for example, 50 primary-school children ask for an observation of Jupiter we'll take it and give it to 50 of them. If two minutes later, someone asks for a new one, they will get a new one. The way we deal with competing challenges is two-fold. Firstly, things that are harder to observe we tend to prioritize, so the Moon and planets can be done in twilight every night. If you want to get deep observations we'll push them up the order a little bit so the telescope finds it a little bit easier to schedule. But the most important thing we do for each individual user, whether it be a teacher or a student, is that their first few requests go in at very high priority, then it drops down over the course of a term. The next term it resets. The exception to that is if we think it is a programme connected to coursework which nearly always goes in as a higher priority and dropping down slightly as they make more and more requests. Generally speaking we also tend to divide observing requests into those we can realistically hope to do and those we can't. We offer the option of observing Mercury but we say we can almost never do that — so anyone who requests Mercury is most likely not going to get it. If we exclude all the ones that are very unlikely, about 90% of them are done and the remaining 10% is nearly always because of bad weather.

Professor Sara Russell. I wondered if there were any groups that you find a little challenging getting to — particular cultural groups, for instance, such as teenagers.

Professor Newsam. Yes, absolutely. The biggest challenge tends to be based on socio-economics. When we look at our distribution of schools, it roughly follows the demographics of schools in the UK, but we should probably be doing more to reach the ones that will benefit more. In our new strategy, we continue in our international programmes but also have a focus on our local area — the local city region where we can much more easily try something that is risky — we don't know if it is going to work. We can go to a school and ask to be given access to a class and we'll go in and try it. That allows us to target areas which have significant social problems — for example, one of the local authorities near us does not offer 'A' levels. They have very specific and very particular problems and if we can help them to address those then we can roll this out for the whole country. Schools with no physics teachers are also really hard to reach so that is another target for us.

Mr. Steven Grey. I'm working with community groups myself. I wondered whether there is any access for groups outside schools.

Professor Newsam. After twenty years I'm regretting the name NSO. It sounds great, but it is international, not really an observatory, and not just for schools. As far as we are concerned if you are working with school-age people in some way then that is education. If there is not enough access, then drop us an e-mail and we'll see what we can do. When you register as a teacher you need to fill out a little box to say why you want to do it.

Dr. Quentin Stanley. Do you have any thoughts on the *Starlink* constellations considering that they also give internet access to Kenya?

Professor Newsam. We have not done that yet — the project we did with the Travelling Telescope was done out of a specific fund that was time limited. We haven't started looking at the *Starlink* side of things, though if there is an observation affected by a *Starlink* object we flag it up. In terms of what *Starlink* provides we haven't yet done a lot with that, but we will.

Reverend Garth Barber. Thanks for a very fascinating and enthusiastic presentation on the subject. Are you the only university observatory doing this or are there groups around the world in the international collaboration to share out these telescope requests?

Professor Newsam. There are other similar projects in the UK such as the *Faulkes Telescope*. There are other robotic telescopes around the world — some offering dedicated time and some doing it for schools. We all talk to each other but we don't tend to share out the observations in that way — the logistics would be difficult. Also we tell the school children the story of how our telescope was built and who runs it. If it's too widespread and too disparate you can't do that anymore and you lose the sense of realness of these observations. There is no competition between these projects. It is a good thought and we have had the discussions but we can't see the benefits of doing it that widely.

The President. For our final talk we move on to a fascinating title: 'The fall, recovery, and analysis of the Winchcombe meteorite'. It sounds just like a Sherlock Holmes story. It will be given by Ashley King who is a UK Future Leader Fellow at the National History Museum where he investigates the origin of the Solar System and formation of the planets through lab analysis of meteorites and samples returned by space missions. Ashley is also the current head of the UK Fireball Alliance (UKFAll), a collaboration between meteor-camera networks that aims to recover freshly fallen meteorites in the UK.

Dr. Ashley King. I would like to start off by saying thank you to the RAS for presenting the Group Award for Geophysics to the UK Fireball Alliance (UKFAll) for the recovery of the Winchcombe meteorite, and for the opportunity to come and tell you all the story of this amazing space rock!

UKFAll has several core members but this really has been a team effort over the last two years, with more than 150 scientists, citizen-scientists, and members of the local community working together to recover and study the Winchcombe meteorite.

For those not aware of us, UKFAll is a collaboration between the UK's meteor and fireball camera networks that aims to recover freshly fallen meteorites in the UK. One of the main roles of UKFAll is to share data efficiently between the different camera networks. A fireball recorded by multiple cameras in different locations can be used to calculate the object's pre-atmospheric orbit and trajectory, and determine if meteorites made it to the ground.

UKFAll also coordinates media activities, raising awareness of potential meteorite falls and providing a consistent message about what happened, and then organizes searches when we think a meteorite has landed somewhere in the UK.

Since the fall of the Winchcombe meteorite, the networks have expanded rapidly and there are now over 200 cameras. We have good coverage across most of the UK, but we can never have enough cameras, and there are still gaps in Northern England, Scotland, and Ireland.

So, let's go back to Sunday 28th February 2021. Just before 10 pm, as I was getting ready for bed, a bright fireball was widely seen across the UK and parts of Northern Europe. Social media lit-up, with over 1000 eyewitness reports to the International Meteor Organisation (IMO) and UK Meteor Observation Network (UKMON) and numerous videos posted from doorbell and dashboard cameras.

The fireball was also recorded by 16 dedicated meteor cameras, enabling UKFAll to estimate quickly that meteorites had probably landed in the Cotswolds. However, as this was during a period of lockdown in the UK, we couldn't just jump in our cars and travel over to the predicted strewn field. UKFAll therefore put out a press release early on Monday morning asking people in the area to look out for black, shiny rocks that had suddenly appeared in gardens or on driveways.

And fortunately for us, that is exactly what had happened! The Wilcock family woke-up in Winchcombe to discover a pile of dark rocks on their driveway and small fragments scattered over the lawn. Hannah Wilcock heard the bang the night before, describing it like a picture frame falling out of a window, but obviously did not think a meteorite had crash landed. Rob Wilcock saw the news reports and donned a pair of marigolds, collecting the material into sealed bags only 12 hours after it had landed.

He contacted UKMON, who sent photos of 'the splat' to me on the Monday evening. I'll admit that when I first saw them, I wasn't convinced it was a meteorite — it was just too perfect — but after sharing with colleagues my excitement grew, and on Wednesday 3rd March Richard Greenwood from the Open University visited the Wilcock family. I received a very excited phone call from Richard and was immediately on a train from London to meet the Wilcock family later that evening.

We knew that we had meteorites on the ground, but as it was a period of lockdown special permissions were required from institutions to allow us to travel and work in groups. However, a small team of planetary scientists from across the UK was put together and started searching the local area from Thursday morning. Hunting for meteorites is an ideal social-distancing activity; teams of four or five people form a line about two metres apart from each other and walk across the terrain looking for unusual rocks.

On Saturday 6th March the largest individual piece of the Winchcombe meteorite was found by Mira Ihasz and a team from the University of Glasgow. The stone, which weighs about 150 g and is similar to a good-sized piece of chocolate cake, was slightly embedded below the surface in a sheep field and split into two pieces during recovery. The interior is a black-grey colour and relatively featureless, consistent with a group of meteorites known as the carbonaceous chondrites.

Carbonaceous chondrites are the building blocks of the Solar System. They contain minerals and inclusions that formed about 4·6-billion years ago and many are rich in water and organic matter. Carbonaceous chondrites are thought to be fragments of dark asteroids that probably played an important role in delivering water and prebiotic molecules to the early Earth. However, we still don't know exactly where in the Solar System carbonaceous chondrites come from, and what the pristine composition of their volatile components is. The Winchcombe meteorite can help us answer some of those questions.

There are about 70 000 meteorites in the worldwide collections, but we only have pre-atmospheric orbits for around 40 of those, of which only five are carbonaceous chondrites. However, because of the UK's meteor-camera networks, the Winchcombe meteorite is the most accurately recorded carbonaceous-chondrite fall to date.

The pre-atmospheric orbit for Winchcombe is similar to the Sutter's Mill and Maribo carbonaceous chondrites and suggests that those rocks were delivered to Earth from bodies in the outer region of the main asteroid belt. We cannot say which specific asteroids, but we know that meteorites like Winchcombe started their journey somewhere near Jupiter.

The mineralogy and composition of the Winchcombe meteorite has been studied by many groups using a wide range of analytical techniques. Electron microscopes and isotope ratios reveal that Winchcombe is a CM carbonaceous chondrite containing refractory inclusions that date back to the start of the Solar System. However, these inclusions have been extensively altered by water on the asteroid and most of the meteorite is made from phyllosilicate and clay minerals, similar to a mudstone on the Earth. It also contains carbonate minerals that precipitated directly from the fluid within the first few million years of the Solar System. Like other CM chondrites, Winchcombe is a breccia with several different lithologies that were mixed together on the asteroid to form the final rock.

As Winchcombe was collected rapidly, we were able to measure the abundance and composition of water less than one week after fall, minimizing the effects of terrestrial contamination. We found that the Winchcombe meteorite contains about 12% by weight of water locked-up in its minerals.

We think the Earth accreted dry, so one of the biggest questions in planetary science is: where did our oceans come from? To answer this we look for reservoirs in the Solar System that contain significant amounts of water with a similar composition to the water on Earth. Comets are good candidates because they contain lots of water, but the few that we have visited have hydrogen isotopic compositions that are not a good match to Earth's water.

Water-rich carbonaceous chondrites are a closer match, although their compositions are variable, in part due to the influence of terrestrial contamination. However, we found that the hydrogen composition of the Winchcombe meteorite and a few other recent carbonaceous chondrite falls is comparable to that of Earth's water. This suggests that those bodies made an important contribution to the volatile budget of the Earth.

The Winchcombe meteorite also contains about 2% by weight carbon in the form of pre-solar grains, which formed around ancient stars over 4·6-billion years ago, carbonate minerals, and soluble and insoluble organic matter. The soluble organics include abundant extraterrestrial amino acids. Meteorites like Winchcombe therefore not only provide a mechanism for bringing water to Earth, but also the ingredients needed to kick-start life.

To summarize, Winchcombe was the first meteorite to be recovered in the UK for 30 years, and the first ever carbonaceous chondrite recovered in the

UK. It comes from a primitive asteroid that has remained largely unchanged for 4·6-billion years. The Winchcombe meteorite records water-rock reactions in the early Solar System and contains hydrated minerals, about 12% by weight water, and extraterrestrial amino acids. Its rapid recovery allows us to study these volatile components with minimal terrestrial contamination and better understand the sources of Earth's water and organic matter.

Finally, I also wanted to mention that in addition to studying the Winchcombe meteorite, the story of how it was recovered has been a fantastic opportunity for us to get people enthused and engaged with planetary science research in the UK. Over the last two years we have visited many schools, societies, and festivals, culminating in a stall at last summer's Royal Society Summer Science Exhibition. And with the expansion of meteor- and fireball-camera networks, I am confident that we won't have to wait another 30 years for the UK's next meteorite.

Professor Miller. The chemical composition is clearly incredibly interesting. Do you have a list of the amino acids that you have found and have you found any sugars in the organic materials?

Dr. King. I can give you a list. There are two papers which have come out.

Ms. Laporte. Knowing the value of these pieces of rock — anything from hundreds of thousands up to a million pounds and trading does go on behind the scenes. Is there a law as in archaeology requiring you to give it to the authorities?

Dr. King. There is nothing. We work it out with the landowner but there are no clear laws in the UK although it varies from country to country. Caroline might want to comment further.

Professor Caroline Smith. I'm head of collections at the Natural History Museum. There is no current law that covers meteorites in the UK. Other countries and territories do have laws covering meteorites or important scientific or cultural objects. As Ashley said, we were able to get hold of this wonderful, large 100-gram piece that is on public display. The Secretary of Culture, Media and Sport, Nadine Dorries' first visit in the job was to the Museum and we showed her the Winchcombe meteorite. We raised with her the issue of the lack of laws to protect meteorites and other scientific objects of interest, so DCMS is now interested and there is some traction in government.

The President. I hope it is not for taxation purposes [laughter].

Professor Smith. I should add there is one way in which we should be able to persuade politely: we set a precedent in that we were able to use something called the Cultural Gift Scheme which is a way for people who have objects of importance to be rewarded by the UK for donating it to the museum.

Professor Miller. We gave them an honorary RAS Fellowship.

Dr. King. The Wilcocks have been a dream to work with and there have been other donors as well.

Dr. Bowler. A question from Paul Wheat about what to do when you find a meteorite. "It's okay to log position when you make a find but could you give some guidance on picking up specimens? What sort of plastic bag is needed? Do you record which side is up and do you avoid breathing on it?"

Dr. King. Our general guidance is to take a photo and write down everything about where you found it. To pick it up use gloves — if not, a clean plastic bag or aluminium foil. We don't expect people to have lab-grade equipment, for instance. What is really important for Winchcombe is that we have all the materials that it was collected in. Every container and even the toothbrush used to sweep up material is at the museum so we can monitor contamination.

The President. This is from Kate Earl. "Why do you think it formed further out than Jupiter?"

Dr. King. We can say where it came from because we have the orbit and it has water in it so it must have been formed beyond the snow-line in the Solar System and there must have been ice there accreting into that asteroid. Exactly where the snow-line was in the Solar System is not known — it may be beyond Jupiter — we just can't say.

Professor Phil Charles. We are almost a decade on from the biggest asteroid impact in our lifetime which was the Chelyabinsk event. One of the reasons that we knew that we were able to get its orbit so precisely was the intense levels of corruption in Russian society and insurance claims. Everybody who was a driver had a dashcam. This led to the spectacular event that we are familiar with. I was very impressed with the camera network you had in place for this but we all know the problems of getting this information in a climate like ours. Would it be worth emphasizing to anyone who is interested that having a dashcam would be a potentially great enhancement of your meteorite network?

Dr. King. Yes. The dashcams are wonderful and I hadn't thought about this but when Winchcombe came down there are doorbell cameras which many people have. If you get a bright fireball — and there are several per year — then people put the doorbell footage on social media. They are pretty low resolution but you can see what is going on. What I would say is that we just didn't need them for the Winchcombe event but if they were the only things we had then we would use them. Of all the five carbonaceous chondrite falls, Winchcombe is by far the best recorded. We have 16 videos which we used to get the orbit. The more footage the better and if we only had a doorbell or dashcam camera then that is what we will use. We have so many cameras in the UK now that the chances are that one of them is going to get it.

Dr. Colin Snodgrass. Here's a related question — you showed that there are areas where there is no coverage from these cameras. Has anyone done the analysis of where to place these cameras? Could we find schools and colleges which might host them?

Dr. King. I helped set up a camera in a school about five years ago. The challenge is people — equipment can be installed but rather than put cameras in a school, put them where they can be looked after.

Mr. Christopher Taylor. I have seen four great fireballs over the years going back to the Northern Ireland fall of April 1969 and I saw that from East Anglia. Is there any possibility of fitting a spectroscopic capability to those camera networks?

Dr. King. Some of the camera operators do have spectrographs on their cameras and we do have some of these data for Winchcombe. It is not being used widely at the moment but it's a good idea. What we really want is access to the Met. Office radar so if there is a bright fireball we can track the object down if it is big enough. We got lucky with Winchcombe — it was 35 km up when it extinguished, then the rocks fell out of the sky in what is known as the dark track which we can't follow. The effect of winds can blow them off course but in Winchcombe the atmosphere was calm and it just fell in a straight line.

The President. What is stopping you fitting the radar?

Dr. King. The Met. Office.

The President. And they won't let you?

Dr. King. It's just not their priority. If we have radar then we have a much better chance of tracking them right down.

The President. Is Robert Massey here? [Laughter.] Is there something we can do about it?

Dr. Robert Massey. That's not a question I was expecting!

The President. I think that's it for the questions. I'll try and draw things to a close. What an interesting two days. I've been amazed at some of the personal stories about how astronomy can influence individual lives. The impact on STEM, obviously, the breadth of our outreach programmes, and the incredible breadth of novel ideas. Fantastic, totally enjoyable. I give notice that next month the Open Meeting of the Society will be on Friday, March 10th and I remind you now that there will be a drinks reception in the RAS Council Room straight after this meeting. Thank you very much to all our speakers and to all of you.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2023 March 10 at $16^{h}\ 00^{m}$
in the Geological Society Lecture Theatre, Burlington House

Mike Edmunds, *President*
in the Chair

The President. Good afternoon everybody — in the room and elsewhere. This is a hybrid meeting. Questions can be asked on-line *via* Dr. Pamela Rowell. I announce the winners of the GCSE poster competition sponsored by Winton: the second prize, with a poster entitled 'Can we throw satellites into space,' goes to Abbott Bai (Marlborough College, Wiltshire) who receives a book token for 50 pounds, whilst first prize is awarded to Maya Charman (Parkstone Grammar School, Poole) for a poster entitled 'How to find exoplanets — the search for hidden worlds', and who receives a book token for 100 pounds. I give notice that the 203rd Annual General Meeting of the Society will take place at 4 pm on May 12th, 2023. That will also be a hybrid meeting.

We now move on to today's programme. I'd like to introduce Professor Yuan-sen Ting, Associate Professor at the Australian National University, who is going to talk to us about 'Reconstructing galaxy-merger history with graph-neural methods'. He is jointly affiliated with the astrophysics and computer-science departments. His research endeavours revolve around the utilization of machines in advanced statistical inference — specifically utilizing the vast astronomical survey data. Hailing from Malaysia he was awarded a PhD in astronomy and astrophysics from Harvard University in 2017 and was subsequently awarded a four-way fellowship from Princeton, the Carnegie Institute of Sciences, NASA *Hubble*, and IAS Princeton. In recognition of his pioneering work in AI science he was recognized as a future leader in research in astronomy by the Associated Universities for Research in Astronomy (AURA) as well as being honoured with a NASA Fellowship. He recently received the ARC DECRA fellowship following his induction into ANU and in a very distinguished career it is unusual to note that at one time he was a top Night Elf player in Warcraft 3 in Malaysia. I am delighted to introduce him and I look forward to his talk.

Professor Yuan-Sen Ting. In contemporary astronomy, astronomers are grappling with one of the fundamental inquiries regarding the origin and evolution of galaxies. To unlock the mysteries of galaxy evolution, astronomers have been relying on cutting-edge hydrodynamical simulations that enable the study of how galaxies interact and merge within the vast expanse of the Universe. Moreover, we also deploy advanced telescopes, like the recently launched *James Webb Space Telescope*, which allows the observation of some of the oldest galaxies, providing crucial insights into how these ancient galaxies eventually formed the present-day galaxies such as the Milky Way.

Despite the enormous advances made through simulations, the complexity of galaxy evolution and merging history poses a formidable challenge for astronomers. Although we can simulate these processes, we still lack the mathematical language to describe these complex phenomena in a robust and comprehensive manner. Consequently, the lack of statistical rigour hinders the study of these systems.

Over the last few decades, astronomers have developed various models based on human heuristics to analyse the history of galaxy mergers and gain insights into their properties. However, these traditional methods tend to oversimplify the problem, reducing complex phenomena to a few critical characteristics of galaxies based on human intuition. While this approach has led to significant intuition about galaxy evolution, it may have overlooked essential information in the simulations and observed data.

Thankfully, recent advance in machine learning, particularly in the context of deep generative models, have opened up new avenues of exploration. The line of study called simulation-based inferences now enables researchers to summarize directly all the knowledge in a simulation, guide intuitions, and make inferences based on observed data without relying on human heuristics. A simple analogy is to think of ChatGPT, a generative model that can produce all possible text based on human prompts. A similar approach can be applied to simulated data, allowing researchers to learn the knowledge from simulations and probabilistically recover all possible routes leading to a galaxy such as the Milky Way.

While generative models on text and images have shown tremendous progress, understanding galaxy evolution requires more intricate forms of generative models — an AI model that can generate 'graphs'. A graph is a visual representation of the connections between objects with nodes and edges, making it a natural tool for analysing the precursor systems that lead to the formation of galaxies. Recently, the AI community has made significant progress in developing generative graph models, which my research harnesses to understand galaxy evolution better.

In conclusion, I have demonstrated how generative graph neural networks can learn from the simulations, and I have highlighted how this innovative approach also holds the potential to identify anomalies in galaxy formation and uncover subtle correlations between progenitor features. Moreover, this technique enables us to relate probabilistically high-redshift precursor systems, such as those observed by the *James Webb Space Telescope*, to present-day observations with the utmost rigour. Through these developments, I aspire to come one step closer to comprehending the rich history and evolution of galaxies.

The President. Thank you very much. I'll invite some questions.

Professor Steve Eales. We already know that simulations often fail to predict observations. Can your method actually test the simulations at the same time as testing the observations?

Professor Ting. The strength of simulation-based inference lies in its ability to perform statistical calculations that integrate the likelihood, ultimately producing what is referred to as the evidence. This evidence enables the evaluation of which hypothesis in the simulations more accurately represents the observed Universe. Although this is a powerful technique to assess pre-existing hypotheses embedded in the simulations, it does not generate new hypotheses.

Professor Eales. So you would take two different simulations?

Professor Ting. Absolutely — simulation-based inference allows us to compare and determine which of the two simulations is more accurate in representing the observed data.

Professor Ofer Lahav. I think that the view, also expressed in talks earlier today, is that probably one can no longer do cosmology without machine learning. But how far to go and how revolutionary would that be in cosmology, compared to, say, protein folding? If we give all the astronomical data accrued to date to an algorithm, could it re-discover General Relativity?

Professor Ting. The best way that I can put it is that astronomy is too simple, and biology is too hard. In comparison to protein folding, the application of machine learning to astronomy remains somewhat constrained due to the relative simplicity of the questions being addressed. For instance, in cosmology, our existing human heuristic models can often sufficiently explain the observations. The potential impact of machine learning is closely tied to the complexity of the problems it tackles. Since protein folding is a more challenging question, it offers greater opportunities for improvement through machine learning. However, as demonstrated, machine learning can still enhance cosmological inference by 10–20%, and in certain cases like reionization, even achieve a several-fold improvement. While these advancements may not be as dramatic as those observed in protein folding, they can still lead to significant new discoveries that would otherwise be unattainable.

The President. Astronomy is too simple? I remember that Fred Hoyle was once reported to have said that "viewed at 10 parsecs a star is a pretty simple system" and somebody said "viewed at 10 parsecs you'd be pretty simple yourself, Fred".

Dr. Belinda Wilkes. Following on from Steve's question, we know that the simulations are not perfect, so in doing these comparisons can you find the bits that are wrong? Do you understand how they are biassing your results?

Professor Ting. It is possible to extract valuable insights from machine learning. As I'm constrained by time in this talk, I've opted to concentrate on how machine learning can enhance inference by maximizing the information extracted from data. Additionally, machine learning can be applied to investigate the 'synthetic gap', which refers to the differences between the two domains. However, this is a complex subject that I won't delve into further at this time.

Dr. Quentin Stanley. Will we get to a position with this where we can actually look at previous data sets we've got and process those to extract more information and possibly determine where the data have been misinterpreted?

Professor Ting. Absolutely, that's an excellent point. Astronomy has a rich history of discovering innovative approaches to examine older data, which has led to significant successes. With the integration of machine learning, it has become evident that there's still a wealth of information hidden within existing data that awaits exploration and analysis.

Dr. Stanley. On the flip side, would the too-wrong processing of data bias the models in any way?

Professor Ting. Yes, data bias can indeed impact the inferences drawn from it. This is one of the limitations of machine learning. As it extracts information in a somewhat intricate manner, it may be challenging to identify specific aspects, such as the contributing frequency or scale. Generally speaking, in data modelling and machine learning, there is always a trade-off between learning and interpretability. As we focus more on the learning aspect, we may lose some of the analytic interpretability and control over the information we retain or discard. However, I would argue that contemporary machine learning provides us with a wide range of techniques, enabling us to choose between greater control over the inference process or pushing the limits of inference capabilities. Instead of being restrictive, I find this flexibility empowering.

Dr. Pamela Rowell. I have a question on-line. Mutthiah Ravichandran asks "How can the error rate of a simulation be decreased?"

Professor Ting. This is somewhat connected to the previous question we discussed. While no simulation is perfect, machine learning enables us to determine which simulation is probably closer to the truth. Another approach we haven't touched on is closing the synthetic gap through domain adaptation. This method involves using machine learning to find the optimal way to transform one domain into another, thereby auto-correcting for any imperfections in the simulation. It is important to note, while domain-adaptation techniques are mathematically sound, it may not necessarily lead to a deeper understanding of the physical aspects that might be missing in the simulations.

Dr. Rowell. The next question is also from Mutthiah Ravichandran. "Could the simulations have predicted the presence of dust without the *BICEP2* experiment which changed inflation cosmology?"

Professor Ting. It could be challenging. As we discussed, simulation-based inference excels at evaluating existing hypotheses but might struggle to generate new ones. However, if something seems amiss in the data, it should result in a lower likelihood value, which could signal the need to develop a new hypothesis. In this way, simulation-based inference can indirectly prompt the exploration of alternative explanations or ideas.

Dr. Simon Mitton. I've got a simple-minded question because I like to look for analogies and crossovers. Is there any overlap in terms of philosophy and simulations between the work you are describing and, for instance, simulating global climate change, or the weather, or a national economy?

Professor Ting. That's an excellent question, leading us to contemplate the deeper philosophical aspects of what constitutes understanding. This challenge is particularly pronounced in astrophysics, given its vast range of topics. Some areas of astrophysics resemble biophysics, where even in the absence of a simple, ground-up, analytic theory, we can still make proper inferences. Conversely, other parts of astrophysics are more akin to particle physics, where the goal is to develop a better foundational theory rather than simply making the best inference. As we discussed today, machine learning continues to push the boundaries of what we consider learning and inference. Determining where the line lies between these concepts is indeed a profound philosophical question that warrants further exploration.

The President. I believe that the Presidential Lecture this year might touch upon what we mean by understanding in astronomy.

Dr. Rowell. This question comes from an 'anonymous attendee'. "Can a set of responses from one or several AIs be used to train another AI, or would it simply be a case of 'garbage in — garbage out'?"

Professor Ting. Indeed, we can generate a large sample by having the machine approximate the underlying data distribution. However, this may not fundamentally resolve the issue. The inclusion of human input, particularly domain expertise, is essential for refining the model of the underlying distribution. This idea aligns with modern research in machine learning, such as the development of ChatGPT, where human expertise plays a vital role in enhancing the capabilities and performance of the model.

Dr. Rowell. Ranjan Ballichamaran asks "How do simulator machines recognize higher dimensions?"

Professor Ting. You've raised an important point, which leads us to the key question of how machine learning can overcome the curse of dimensionality — namely, how it can perform tasks like regression in millions of dimensions with only finite data. The solution lies in what's called inductive bias. In essence, machine learning makes fundamental assumptions about the symmetry of the data. For example, consider a 3D sphere. One might assume that a large number of data points are needed to fill the sphere, but if we know it's indeed a sphere, *i.e.*, it has some symmetry, the problem simplifies significantly. In this case, we only need to describe the radial profile. The same principle applies even at higher dimensions. There's no magic involved; machine learning consistently assumes some sort of data symmetry, which enables it to tackle high-dimensionality problems more effectively.

The President. Can we thank the speaker very much indeed [applause]. Our next talk is by Nicholeen Viall, research associate at NASA Goddard Space Flight Centre (GSFC) and the title of her talk is 'The Grand Challenge — questions of solar-wind physics'. Dr. Viall is a research astrophysicist at GSFC with expertise in solar coronal and solar-wind physics. She is a winner of the NASA Early Career Achievement Medal and 2018 winner of the Karen Harvey Prize of the Solar Physics Division of the American Astronomical Society (SPD/AAS). She currently serves as the SPD/AAS vice-chair and is the mission scientist for NASA's *Polarimetry Mission to UNify the Corona and Heliosphere* (*PUNCH*). It gives me great pleasure to ask her to give her talk.

Dr. Nicholeen Viall. The two overarching questions we address in this talk are: how does the solar atmosphere create the solar wind and how do the resulting structures drive geospace? The solar wind is often comprised of periodic density structures on scales of 0·2 mHz (about 90 minutes) up to 5 mHz (about a few minutes). Periodic density structures are periodic dynamic pressure structures, and thus directly drive oscillations in Earth's magnetosphere as a forced-breathing, wherein each density structure engulfs the magnetosphere, squeezing it as it passes. A solar cycle of measurements of the solar-wind density upstream of the magnetosphere, as well as the magnetic field in the magnetosphere, show that periodic density structures occur at discrete, repeatable frequencies, and that they directly drive the magnetosphere to oscillate at the same frequencies. This occurs about 50% of the time that the solar wind has periodic density structures in it. This leads to the question: what causes the solar wind to have periodic density structures at repeatable discrete frequencies? The Grand Challenge questions of solar-wind physics encompasses these and other questions.

Current models of solar-wind formation can only predict the long time evolution of global solar-wind structures. They do not predict solar-wind structures on mesoscales, such as the periodic density structures. Yet high-resolution, deep-field *Solar TErrestrial RElations Observatory* (*STEREO*) *COR2* imaging data show that the solar-wind density is comprised of periodic density structures at its formation.

The first three Grand Challenge questions (Q1–3) are regarding solar-wind formation, divided by the time history of the plasma, with the first question (Q1) being where the solar wind originates from and the energization low in the corona, or the coronal heating problem. The second one (Q2) is how the plasma is released, and the third one is how the solar wind is accelerated (Q3) through the upper corona.

Coronal holes, quiet Sun, and active regions are heated differently, thus will result in different types of solar wind. Individual coronal heating events (nanoflares) are below instrument resolution and sensitivity — there will be many along a given line of sight, and they are not directly observable with current instrumentation. Most observations are of thermal emission in the corona that occurs long after the energy release.

However, there are ways to take advantage of the fact that the heating phase is relatively invisible in a nanoflare event, and the slow cooling after the nanoflare dominates the emission. Cross correlation of light-curves as the plasma cools is a way to measure systematically the cooling time of the plasma, and the time between nanoflares on a given magnetic flux tube. Applying light-curve analysis with differential emission-measure analysis to *Solar Dynamics Observatory Atmospheric Imaging Assembly* data show that active regions exhibit post-nanoflare cooling, with a typical reheat time-scale per flux tube of about 1000 seconds.

Q2, how the solar wind is released, asks whether the plasma is already on open magnetic fields, or does it require magnetic-reconnection events to be released. This reconnection might not be energetically important. *STEREO COR2* and *Heliospheric Imager* data show a roughly 90-minute periodic reconnection releasing (Q2) plasma from the tips of quiet-Sun (Q1) helmet streamers (the heliospheric current sheet). Acceleration (Q3) is observed long after plasma release, so this magnetic reconnection does not seem to be energetically important.

Elemental composition, which is frozen into the plasma in the corona, shows that these largest periodic density structures survive to L1 and drive magnetospheric oscillations. The higher-frequency periodic solar-wind structures, though larger than the Earth's magnetosphere, are at or below resolution of current coronagraph and heliospheric imaging capabilities.

The *Wide-Field Imager for Parker Solar PRobe* (*WISPR*) has been able to observe periodic density structures with higher frequencies in the newly-formed solar wind. The *PUNCH* mission, a NASA mission in development, will be able to answer how many periodic density structures survive to 1 AU, and if they evolve *en route*. *PUNCH* will have a large field of view, with sufficiently high cadence, spatial resolution, and sensitivity to track periodic density structures and other mesoscale solar-wind structures through the inner heliosphere.

We show another event of periodic density structures that directly drives globally coherent, discrete waves in the magnetosphere. The magnetospheric oscillations are observed in ground magnetometers around the world. We identify the source of these periodic density structures at the Sun as a large, decayed, unipolar part of an active-region periphery. The periodic solar-wind density structures cease when the Sun rotates and a younger, multipolar active region is the source of Earth-impacting solar wind, suggesting that details of the active-region magnetic field and heating may determine whether periodic density structures are created, or at least whether they survive to about 1 AU. Periodic density structures also drive dynamics in Earth's radiation belts, with particles as high as 1·728 MeV exhibiting pulsations and corresponding particle precipitation into Earth's atmosphere at the same discrete periodicities.

Two solar cycles of measurements of the alpha-to-proton abundances during periodic density structures at 1 AU exhibit a similar occurrence distribution between about 1–4 mHz as the transverse magnetic-field oscillations observed low in the solar corona. Thus we speculate that a possible driver of the periodic density structures between about 1–4 mHz is driven periodic magnetic reconnection between open and closed coronal magnetic fields, periodically releasing plasma into the solar wind. We also speculate that spacecraft making *in-situ* measurements of the magnetically-closed-field corona are required to solve several of the Grand Challenge questions and suggest a mission concept '*Huygens* Probes at the Sun' that could accomplish this goal.

In conclusion, the details of coronal heating, solar-wind release, and acceleration result in different types of solar-wind structures that drive dynamics in the Earth's magnetosphere about four days later. Mesoscale solar-wind structures such as periodic density structures are the ground state of space weather: they produce a dynamic connection between the Sun and Geospace that occurs even during so-called 'quiet' times.

The President. Thank you very much indeed for the Eddington Lecture. Do you really have no idea about what is happening at the bottom of these flux tubes? Something is heating them. You must have an idea.

Dr. Viall. I do. It's the magnetic field — that is ultimately where the energy comes from. Those magnetic fields are rooted down through the atmosphere into the photosphere. They are tangled and they are being wiggled all the time. Probably in the closed-field corona it has to be magnetic re-connection to explain the amount of energy we see. Maybe in the coronal holes where the magnetic field is open, waves can be doing some of the energization.

The President. It's on such a scale that you cannot get any observations there.

Dr. Viall. No, we cannot see the direct energization.

The President. Even if you send in one of the *Huygens*-like probes?

Dr. Viall. If we had such a probe we could.

Professor Eric Priest. There are observations of magnetic fields on the solar surface coming together with opposite polarity and cancelling. We used to think that these were just few and far between but the latest observations show that they are extremely common. Those are likely good candidates for generating the coronal heating.

Dr. Rowell. I have a question from AC and it's "Do the dynamics of the solar wind effectively change to specific typical structures in resonance to the sunspot cycle or is it uncoupled from the 11-year cycle?"

Dr. Viall. That is why I showed the plot separated into 11 years. There does seem to be a correlation. The frequencies seem to evolve with the solar cycle and we are not exactly sure why. A big speculation is that this is because the coronal loops change as a function of solar cycle — whether or not there are active regions, which have shorter loops, *versus* the long quiet-Sun loop. Loops of different length will be in resonance with different parts of the spectra that are being pulled in, and that is maybe why you get particular discrete frequencies which seem to change with the solar cycle, but we don't know.

Dr. Rowell. This is a question from Mutthiah Ravichandran and it is "What is the earliest point in the solar wind's lifetime and can we identify whether it re-connects or not?"

Dr. Viall. Low down we see this evidence of reconnection and sometimes you can tell that the plasma makes it into the solar-wind. A lot of the time you will see something happen low in the corona in the ultraviolet and then the signal falls off with height and you have no idea whether the plasma made it out or not, so there is speculation that maybe that was a reconnection event that maybe created the solar wind. We don't know, it's hard.

Reverend Garth Barber. Thank you very much for a fascinating talk. Is there any difference between the activity in the solar equatorial plane and the poles?

Dr. Viall. That's a very good question. Firstly, the picture I showed wherein the poles were very different to the equator was taken during solar minimum. At maximum the situation gets turned around and the poles also have complex structures. Considering the case of solar minimum, one of our projects is to look at *Ulysses* data as it goes over the pole to see if there is any difference in the types of structures that are being created. When *Solar Orbiter* moves up out of the ecliptic plane then we can start looking at those data as well. *PUNCH*, which will be able to image over the poles, will also give us some information about that, but right now we only have white-light images taken in the ecliptic, so we can't see.

Professor John Zarnecki. Thank you very much for the talk, which I'm sure everyone enjoyed. However, I feel as one of the original *Huygens*-probe experimenters I do have to record an objection. I think we have a copyright on the name.

Dr. Rowell. This question is from Mutthiah Ravichandran. It states "Are there significant gravitational interaction-like waves caused by the high-speed solar wind? What would be the magnitude expected from these?"

Dr. Viall. Gravity waves from high-speed streams. I don't think so.

Professor Steven Schwartz. I have a question about the van-Allen-belt observations that you made. Are you suggesting that there is more than just compression as you go back and forth across the gradient and does the energization go in or out of phase with the external driver?

Dr. Viall. That is Leena Vazhayil Kurien's thesis project. It's actually quite complex. Sometimes you see energization and sometimes you see the radiation belts get depleted, and why one *versus* the other we don't know yet. It probably has to do with steps along the way — the ULF waves that lead to chorus or hiss waves, which are a different type of wave, then those do the scattering; and so Leena has to figure all this out.

Professor Schwartz. Is it more than adiabatic compression?

Dr. Viall. It's not just adiabatic compression — there is particle scattering in this event. If you just see the pulses in the radiation belt only, then it could just be that, but because we see particle precipitation we know there is more going on. Also sometimes you can get magnetopause shadowing because of the original squeezing of the magnetosphere, and the particles on the outer drift shells are lost that way. There are quite a few different things that can happen to the particles.

The President. If there are no more questions then thank you very much indeed [applause]. I give notice that the next Open A and G meeting of the Society will be on Friday, April 14th. There will be a drinks reception in the RAS Council Room directly after this meeting, to which you are all warmly invited.

SIMPLE APPROXIMATIONS TO THE POSITIONS OF THE LAGRANGIAN POINTS

By John Southworth

Astrophysics Group, Keele University

The Roche potential is the sum of the gravitational and rotational potentials experienced by a massless body rotating alongside two massive bodies in a circular orbit. The Lagrangian points are five stationary points in the Roche potential. The positions of two of the Lagrangian points (L4 and L5) are fixed. The other three (L1, L2, and L3) are along the line joining the two masses: their positions depend on the mass ratio, q, and can be calculated numerically by finding the roots of a quintic polynomial. Analytical approximations to their positions are useful in several situations, but existing ones are designed for small mass ratios. We present new approximations valid for all mass ratios from zero to unity:

$$x_{\rm L1} = 1 - \frac{q^{0.33071}}{0.51233\, q^{0.49128} + 1.487864}$$

$$x_{\rm L2} = 1 + \frac{q^{0.8383} + 2.891\, q^{0.3358}}{1.525\, q^{0.848} + 4.046596}$$

$$x_{\rm L3} = -1 + \frac{q^{1.007}}{1.653\, q^{0.9375} + 1.66308}$$

in a rotating frame of reference where the more massive body is at $x = 0$ and the less massive body at $x = 1$. The three approximations are precise to 6×10^{-5} for all mass ratios.

The Roche potential

The motion of two point masses in orbit around each other is a well-known and well-understood[1–4] solved problem in celestial mechanics. Its extension to three bodies was a major goal of 19th-Century astrophysics, until Henri Poincaré demonstrated in 1887 that it was insoluble.

There is one situation where analytically tractable results can be obtained, known as the *restricted three-body problem*. In this case, termed the *Roche model*, two point masses are on a circular orbit and the third body is massless. The Roche potential is the sum of the gravitational and rotational potentials and can be used to describe the shapes of stars in close binary systems. The more massive star is defined to be at the origin of a Cartesian co-ordinate system ($x = y = z = 0$) and the less massive star is at $(x, y, z) = (1, 0, 0)$. The co-ordinate system therefore rotates with the binary system.

The Roche potential experienced by a massless particle at point (x,y,z) is

$$\varphi = -\frac{GM_1}{r_2} - \frac{GM_2}{r_2} - \frac{G(M_1 + M_2)}{2}\left[\left(x - \frac{M_2}{M_1 + M_2}\right)^2 + y^2\right], \qquad (1)$$

where G is the Newtonian gravitational constant, M_1 is the mass of the more massive star, M_2 is the mass of the less massive star, r_1 is the distance from the point to mass M_1, and r_2 is the distance from the point to mass M_2. Simple trigonometry gives

$$r_1 = \sqrt{x^2 + y^2 + z^2} \tag{2}$$

and

$$r_2 = \sqrt{(1 - x)^2 + y^2 + z^2}\,. \tag{3}$$

It is convenient to work with the normalized Roche potential

$$\varphi_n = \frac{-2}{G(M_1 + M_2)}\,\varphi \tag{4}$$

which yields

$$\varphi_n = \frac{2}{r_1}\,\frac{1}{1+q} + \frac{2}{r_2}\,\frac{q}{1+q} + \left(x - \frac{q}{1+q}\right)^2 + y^2, \tag{5}$$

where $q = M_2/M_1$ is the mass ratio. Thus the Roche potential has been simplified into a function which depends only on the position of the massless body, the mass ratio, and the scale of the system which is set by the semi-major axis of the relative orbit of the two massive bodies.

The Lagrangian points

There are five stationary points in the Roche potential where no net force is exerted on a particle, *i.e.*, the gravitational and rotational forces balance. These are called the Lagrangian points and will be denoted L1, L2, L3, L4, and L5 below. The first three were discovered by Leonhard Euler and the last two by Joseph-Louis Lagrange. All five Lagrangian points are in the x–y plane so have $z = 0$. Fig. 1 shows their positions in the case that $q = 0{\cdot}5$.

The positions of the L4 and L5 points each form an equilateral triangle with the two masses at the other vertices. Their positions are thus fixed at

$$x_{L4} = \frac{1}{2} \qquad y_{L4} = \frac{\sqrt{3}}{2} \tag{6}$$

$$x_{L5} = \frac{1}{2} \qquad y_{L5} = \frac{-\sqrt{3}}{2} \tag{7}$$

and need not be discussed further. Orbits at the L4 and L5 points are stable for mass ratios $q < 0{\cdot}04004$ (Prša[5]).

The L1 (inner Lagrangian), L2 (outer Lagrangian), and L3 points are all along the x-axis (so $y = z = 0$) but their positions depend on mass ratio and are less straightforward to determine. By setting the derivative of Eq. 5 to zero we find

$$0 = -\frac{1}{x^2} + \frac{q}{(1-x)^2} + (1+q)x - q, \tag{8}$$

where $r_1 \rightarrow x$ and $r_2 \rightarrow 1 - x$. Further algebra leads to the equation

$$0 = -1 + 2x - x^2 + (1 + 3q)x^3 - (2 + 3q)x^4 + (1 + q)x^5, \quad (9)$$

which is quintic so does not have a general solution. Eq. 9 can be solved using numerical methods, *e.g.*, bisection, Newton-Raphson, or grid search (see Leahy & Leahy[6]). The positions of the L1, L2, and L3 points are shown as a function of mass ratio in Fig. 2.

Existing approximations to the positions of the L1, L2, and L3 points

There are times when a precise solution of Eq. 9 is not necessary, and a quick and simple approximation is adequate. These cases include when making a plot, trying to put together the first version of a piece of code, or as a starting estimate for iterative refinement. Approximations are available*†, but in general are only valid for small mass ratios.

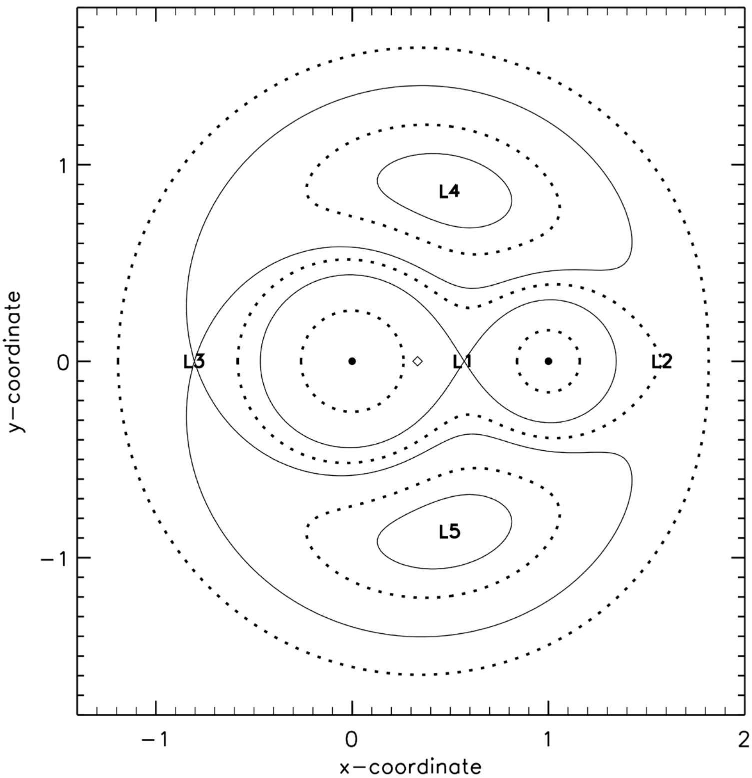

FIG. 1

Visualisation of the Roche potential for a system with $q = 0{\cdot}5$. Lines of constant potential are shown with solid or dotted lines. The positions of the two masses are shown with filled circles. The position of the centre of mass is shown with an open diamond. The Lagrangian points are labelled.

* https://en.wikipedia.org/wiki/Lagrange_point

† https://map.gsfc.nasa.gov/ContentMedia/lagrange.pdf

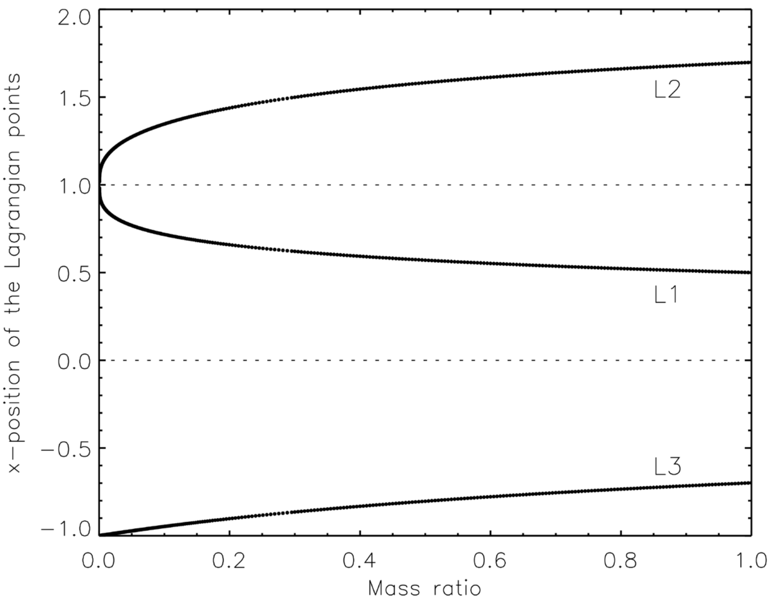

FIG. 2
x-positions of the L1, L2, and L3 points as a function of mass ratio.

At small mass ratios the distances of the L1 and L2 points from the second mass become approximately equal to the size of its Hill sphere (*e.g.*, ref. 7):

$$x_{L1} = 1 - \left(\frac{q}{3}\right)^{1/3} \quad x_{L2} = 1 + \left(\frac{q}{3}\right)^{1/3}. \tag{10}$$

Another set of approximations was reported in the textbook by Prša[5], and come from a perturbation analysis presented in the textbook by Battin[8]. In the geometry adopted in the current work these are:

$$x_{L1} = 1 - \zeta + \frac{1}{3}\zeta^2 + \frac{1}{9}\zeta^3 - \frac{58}{81}\zeta^4, \tag{11}$$

$$x_{L2} = 1 + \zeta + \frac{1}{3}\zeta^2 - \frac{1}{9}\zeta^3 + \frac{58}{81}\zeta^4, \tag{12}$$

$$x_{L3} = -1 + \frac{7}{12}\mu + \frac{1127}{20736}\mu^3 + \frac{7889}{248832}\mu^4, \tag{13}$$

where $\mu = q/(1+q)$ and $\zeta = (\mu/3)^{1/3}$. These are designed for small mass ratios so are imprecise for larger values. The deviations for the positions of L1, L2, and L3 are less than 10^{-5} for $q < 0{\cdot}01$, 0·03, and 0·26, respectively. The largest deviations are 0·035 at $q = 1$, 0·0014 at $q = 0{\cdot}41$, and 0·0012 at $q = 1$, respectively. The largest deviations can be decreased by optimizing the numerical coefficients in Eqs. 11 to 13 at the expense of lowering the quality of the approximations for small mass ratio.

Similar approximations to those in Eqs. 11 to 13 were given in Murray & Dermott[9] (pp. 78–80). They work well for small mass ratios, but deviate at higher mass ratios by much more than do Eqs. 11 to 13, so will not be considered further. Other approximations suitable for small mass ratios are available and will not be summarized here.

New approximations to the positions of the L1, L2, and L3 points

We were motivated to obtain analytic approximations to the positions of the L1, L2, and L3 points with a higher precision than existing approximations. This required a grid of positions as a function of mass ratio and a fit to this grid of various analytical functions.

After some experimentation we set up a grid of positions as a function of mass ratio containing two components. The first component consisted of 448 points which were spaced equally in log q in the interval $q = [10^{-5}, 0{\cdot}295]$. The second component consisted of 141 points spaced equally in q in the interval $q = [0{\cdot}3, 1{\cdot}0]$. The final point at $q = 1$ was given ten times the weight of the other points, as this was found to decrease the amount of 'flailing' at this extremum. The positions of the Lagrangian points at each q were obtained to high precision using grid-search methods. We then experimented with a range of possible analytical formulae including numerical coefficients which were optimised using the MPFIT package from Craig Markwardt[10].

After some experimentation, we found that a good approximation for the position of L1 is

$$x_{\rm L1} = 1 - \frac{q^{a_1}}{a_2 q^{a_3} + a_4}, \qquad (14)$$

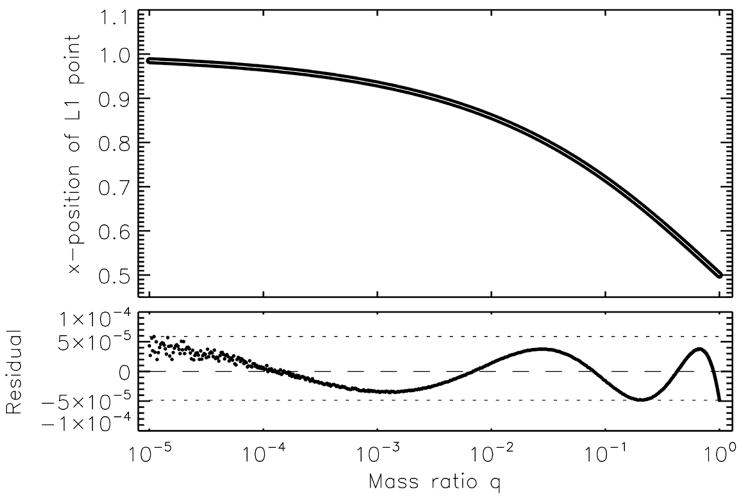

FIG. 3

Top: x-position of the L1 point (black filled circles) compared to the approximation in Eq. 14 (white line) on a logarithmic scale. Bottom: residuals of the approximation to the true values, with the values of the largest positive and negative residuals indicated with dotted lines.

where a_i are the numerical coefficients to optimize. The values of the coefficients are $a_1 = 0{\cdot}33071$, $a_2 = 0{\cdot}51233$, $a_3 = 0{\cdot}49128$, and $a_4 = 1{\cdot}487864$, and the largest deviation from the true position is $5{\cdot}9 \times 10^{-5}$. For convenience, we have attempted to limit the number of significant figures required for these coefficients. Our choice of this function was inspired by that for the Roche lobe radius by Eggleton[11]. The fit and residuals are shown in Fig. 3.

Approximating the position of L2 required a more complex formula. We found

$$x_{L2} = 1 + \frac{q^{b_1} + b_2 q^{b_3}}{b_4 q^{b_5} + b_6}, \tag{15}$$

where the coefficients are $b_1 = 0{\cdot}8383$, $b_2 = 2{\cdot}891$, $b_3 = 0{\cdot}3358$, $b_4 = 1{\cdot}525$, $b_5 = 0{\cdot}848$, and $b_6 = 4{\cdot}046596$. The largest deviation in this case is $5{\cdot}6 \times 10^{-5}$ (Fig. 4). We have again limited the number of decimal places required for all coefficients except b_6; a slightly more precise result (maximum deviation $5{\cdot}5 \times 10^{-5}$) could be obtained without this restriction.

For L3 we found the formula

$$x_{L3} = -1 + \frac{q^{c_1}}{c_2 q^{c_3} + c_4} \tag{16}$$

to be adequate, where $c_1 = 1{\cdot}007$, $c_2 = 1{\cdot}653$, $c_3 = 0{\cdot}9375$, and $c_4 = 1{\cdot}66308$. The largest deviation is $3{\cdot}3 \times 10^{-5}$ (see Fig. 5) but this could be lowered to $3{\cdot}2 \times 10^{-5}$ if the number of decimal places is not restricted for c_1, c_2, and c_3.

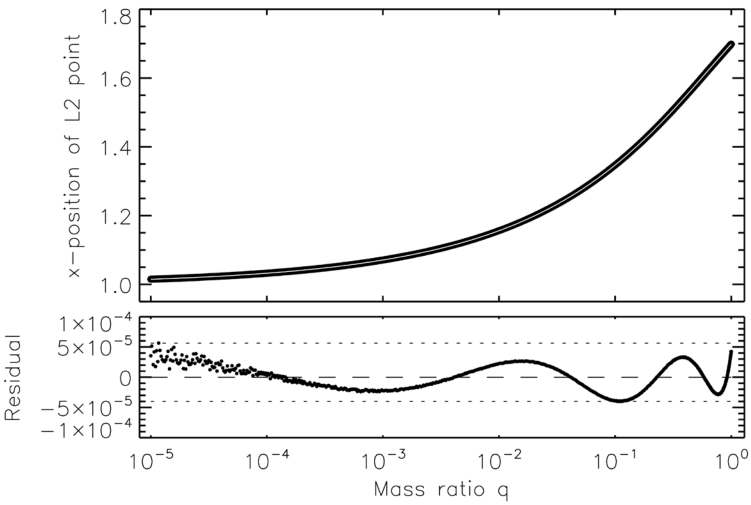

FIG. 4
As for Fig. 3 but for the L2 approximation in Eq. 15.

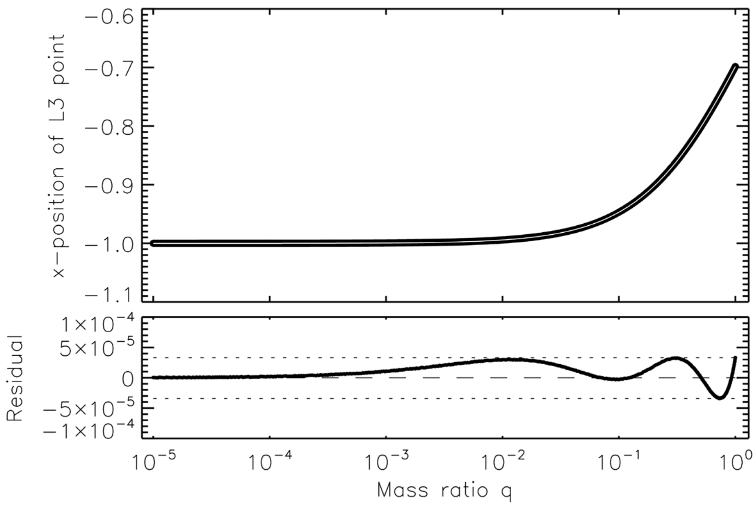

FIG. 5
As for Fig. 3 but for the L3 approximation in Eq. 16.

Final comments

The positions of the five Lagrangian points are of interest in many areas of celestial mechanics, in particular the positions of space missions such as *Gaia* and *JWST*. The L1, L2, and L3 points can be found by solving a fifth-order polynomial, which has no analytic solution so must be performed numerically. There are times when an approximate answer is adequate, but existing analytical approximations are designed for small mass ratios.

We have therefore derived new approximations for the positions of the L1, L2, and L3 points, which can be used for convenience when an exact answer is not needed. They are accurate to within 6×10^{-5} (absolute deviations) for all mass ratios from 10^{-5} to unity. Although we have taken care to limit the required precision of the numerical coefficients to four decimal places where possible, some must be specified to six decimal places to achieve the quoted precision

Our new approximations for the L1 and L2 positions perform less well at the smallest mass ratios. For mass ratios less than 10^{-5} we recommend that the Hill-sphere approximations are used instead.

Acknowledgements

We are grateful to Dr. Andrej Prša for useful discussions, and to the referees for their comments and help. The NASA Astrophysics Data System was used in the course of this work.

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REVIEWS

Foundations of Physics and Cosmology, by Li Ti-Pei (Science Press, Beijing, China), 2021. Pp. 249, 24 × 16 cm. Price $148·00 (about £119) (hardbound; ISBN 978 7 03 070821 2).

Author Li Ti-Pei is part of the Department of Astronomy of Tsinghua University and the Institute of High Energy Physics of the Chinese Academy of Sciences, both in Beijing. He is a member of the International Astronomical Union (Division D, High Energy Astrophysics) and the author of a couple of 2011 papers that appeared in *MNRAS* and *ApJ Letters*. His more recent publications can be found on arXiv, and in journals published in China.

Li is one of a fairly small cluster of astronomers who have concluded that there have been major errors in the analysis of *WMAP* data (involving pointing, timing, and side-lobes) such that the actual, physical quadrupole moment of the CMB is very nearly zero rather than the hump in plots of power spectrum *versus* angle that we are used to seeing. For him this is strong evidence for a theory of gravity and cosmology very different from the ones we call General Relativity and the standard models.

His universe is absolutely flat, with no curvature even associated with the propagation of gravitational waves. The constituents are equal amounts of gravitationally attractive matter and repulsive cosmological constant, both of which thin out as the Universe expands.

The equations of gravity in this universe are closely analogous to Maxwell's for electromagnetism. Other differences from conventional cosmology and astrophysics include (*i*) the Dirac large numbers (some attributed to Weyl in 1918) become calculable, (*ii*) the energy to power supernova explosions comes largely from the formation of a hard core of dark energy at the centre of a black hole or neutron star, the latter aligning pulsar spin axes and velocities in the observed fashion, and (*iii*) the 'electric type' gravitational-field intensity is available to power jets from black holes. In addition, "Hawking's black hole information paradox does not exist." And because the gravitational and electromagnetic equations are already of the same form, they constitute a 'theory of everything', though the weak interaction seems to be left hanging. There are, however, a few uncomplimentary words about electroweak and grand unification because they also imply curved space time.

The author emphasizes that there are really three scales around us: the microscopic (realm of quantum mechanics), the macroscopic (realm of Newtonian gravitation and electromagnetism), and cosmoscopic (realm of his theory). He also concludes that there is as much wisdom to be found in the writings of Laozi as in those of Thales, and with this I would not like to disagree.

Conflict of interest: My copy of *Foundations* was a gift from the author. — VIRGINIA TRIMBLE.

A Course in Cosmology. From Theory to Practice, by Dragan Huterer (Cambridge University Press), 2023. Pp. 422, 26 × 21 cm. Price £49·99 (hardbound; ISBN 978 1 316 51359 0).

With many cosmology textbooks available these days, this new one enters a fairly crowded market, but it really does deserve to do well. It is a very well-judged book that makes many excellent decisions about what to cover and at what level, focussing on the key concepts and covering them in enough detail to understand them. To avoid going into too much technical detail it does not always go right back to fundamentals, but this allows the book to cover in a well-balanced way essentially all of the important topics in present-day cosmology. It is very well paced, and the structure lends itself to being an excellent course textbook for starting postgraduates or advanced undergraduates. The clarity of the writing is exceptional, and the text will inform and inspire students in equal measure. By covering statistical and data-analysis techniques in addition to the underlying theory, it is also able to provide a wealth of problems, many of which are computational, which will prepare students well for research in cosmology. It makes for a very well-rounded textbook and is highly recommended. — ALAN HEAVENS.

The Irresistible Attraction of Gravity: A Journey to Discover Black Holes, by Luciano Rezzolla (Cambridge University Press), 2023. Pp. 293, 22 × 14 cm. Price £20·00/$24·95 (hardbound; ISBN 978 1 009 19877 6).

Luciano Rezzolla is professor of astrophysics at the University of Frankfurt (he is also a Senior Fellow at the nearby Frankfurt Institute for Advanced Studies and Andrews Professor of Astronomy at Trinity College Dublin). His main area of research is numerical relativity, particularly, especially recently, in connection with simulations of the appearance of phenomena associated with black holes; such simulations allow one to learn about the physical properties of such objects by comparing them with observations such as those by the Event Horizon Telescope Collaboration, of which Rezzolla is a member. The book is thus especially timely, and one of the long chapters is on the images of the supermassive black holes in the Milky Way and M 87. Other long chapters cover neutron stars, black holes, and gravitational waves.

Books on relativity can be classified *via* several criteria: maths first or physics first, breadth of topics, and level of detail. This book is somewhat unusual in that it is a popular-science book, but taking a maths-first approach (though the maths is kept to a minimum). The first four — short — chapters give a brief introduction to gravity, the history of its study, and its description in terms of space-time. The introductory chapters are brief, but give enough information to understand the astrophysics discussed in the longer chapters. In his own translation of the Italian original (there is also a German edition, translated by Enrico Heinemann), Rezzolla presents the reader with a good overview of some current topics in relativistic astrophysics. The language is better than some books written by native speakers, and the story is told well in a casual style without sacrificing correctness, though experts might quibble at a couple of somewhat imprecise explanations.

There are several black-and-white figures scattered throughout the book.

Those which benefit from colour are repeated as colour plates (as usual, all together, here a bit more than half-way through). That is useful as it allows one to refer to the figure while reading about it in the main text, but with the option to study it in more detail in colour. In such cases, the caption says that in some formats (obviously print, presumably in contrast to an e-book) the figure will be black and white but also that there is a colour version in the plates section — much better than books which refer to colours in the captions of black-and-white figures. There are no footnotes; ten-and-one-half pages of endnotes follow the main text, consisting of both footnote-style additional text and references. The book ends with an eight-page small-print index.

Due to the length of the main chapters, the reader gets more details than from a similar article in a popular-science magazine, and also an interesting behind-the-scenes look at big, international projects. As such, those wanting to delve a bit deeper into such popular topics without too much mathematical detail, but also without oversimplification, should enjoy this survey of extreme objects in the Universe and how we observe and aim to understand them. — Phillip Helbig.

Pulsar Astronomy, 5th Edition, by Andrew Lyne, Francis Graham-Smith & Benjamin Stappers (Cambridge University Press), 2022. Pp. 407, 25 × 17·5 cm. Price £120/$155 (hardbound; ISBN 978 1 108 49522 6).

The book *Pulsar Astronomy* by Andrew Lyne, Francis Graham-Smith and Ben Stappers is the fifth addition of this textbook on pulsars which was first published in 1990, at that time with Lyne and Graham-Smith as authors. Stappers joined only in this last edition, and this is not the only change compared to the previous edition(s). The book is now structured into four different parts, containing separate chapters. The four parts cover 'Discovery and Techniques', 'Observed Physical Characteristics', 'Neutron Star Physics', and 'Environments and the Interstellar Medium'.

Obviously, the book has much evolved since its first edition. Since then, the number of pulsars has increased by an order of magnitude, the number of the known millisecond pulsars even more massively so. Obviously also, pulsars are studied now in abundance at other parts of the electromagnetic spectrum, in particular at gamma-rays thanks to the *FERMI* space telescope. The book nevertheless focusses still mostly on radio pulsars, which seems fair, as this is still (by far) the dominant way of studying pulsars. Non-radio pulsar properties are discussed where appropriate and the abundant references allow the reader to follow further leads. Hard-core *FERMI* colleagues may be a bit disappointed that there is not more about gamma-ray properties, but as an introduction to pulsars, the presentation seems right.

Indeed, the book tries to provide an overview of the subject of pulsar astronomy as such, even though this is a challenge as the field is still continuously developing with rapid speed. This explains why this book is updated with new editions so regularly. But, actually, I like this fifth edition much more than the previous third or fourth editions. There is a clear change. Rather than simply adding new material based on new results (which I think somehow happened in the last editions), this time there have been real efforts to restructure the book and to update the different chapters. Perhaps not all figures are as up to date as they could be, but clearly the authors have made great efforts to have a nice balance between old (or established) results and those that are more recent. This is important since I think students should learn how a phenomenon was discovered and studied over the years, rather than simply being referred to some recent paper that has been published on a given subject. Therefore, I think the book remains the best textbook if people want to learn about pulsars and pulsar astronomy as a subject, whether they simply want to learn more about the subject or even want to become involved in its research. The book cover says that the authors provide an "introduction into historical and physical terms" and that is exactly what the book does.

The vast experience of the authors, who are world-leading experts in this field, clearly shows. It is therefore no surprise that almost all figures in the book are taken from relevant publications in peer-reviewed journals. This really provides an easy way for the reader to follow-up on certain topics. For interested students and colleagues that is indeed necessary, since the book can only provide a snapshot of the field. Having said that, I cannot find a glaring gap in the book in terms of relevant new insight that the reader should know about. For instance, Rotating Radio Transients (RRATs) are introduced, as are Fast Radio Bursts (FRBs), even though it is understandable that the FRB section can only cover the basics as this particular sub-field is evolving with amazing speed.

I know many students and colleagues who, like me, own an earlier edition of *Pulsar Astronomy*. Would they benefit from a new edition? I think so, since the improved structure, combined with updates and the much-more-than-just-cosmetic changes to various chapters make the book worth buying, even if one has an old edition. It feels simply easier to read and handle, while still providing a good balance between breadth and depth. Surely, if one wants to become a pulsar astronomer, one has to dig deeper, but for all others, who have not yet read a book about pulsars, this is the 'go-to' introduction to the field. — Michael Kramer.

Annual Review of Earth and Planetary Sciences, Volume 50, 2022, edited by R. Jeanloz & K. H. Freeman (Annual Reviews), 2022. Pp. 661, 24 × 19·5 cm. Price from $496 (print and on-line for institutions; about £440), $118 (print and on-line for individuals; about £105) (hardbound; ISBN 978 0 8243 2050 8).

This year's Volume of *Annual Review* finds me in Palo Alto, having managed to get back on the conference circuit without yet succumbing to Covid-19, an on-going nuisance at scientific meetings. At least reviewing *Annual Review* Vol. 50 should be safe. An introductory chapter instructs geoscientists to work across discipline boundaries to solve the world's problems. It is followed immediately by a chapter on hydrocarbons. The next chapter also focusses on carbon but brings ambivalent news — the land and sea are doing a surprisingly good job of removing carbon from the atmosphere. However, global warming may hinder this and reductions in industrial emissions may thus be accompanied by increases in natural carbon release as ecosystems degrade. It's too early to celebrate, evidently. Moving on to more cheerful subjects, Vol. 50 also offers a diverse smorgasbord of subjects that include other aspects of the environment — ocean temperatures, biomarkers for change, evolution of Earth-life systems, and geologically recent changes in landform, environment, and their relation to human evolution. Yet other papers focus on aspects of the Solar System, Earth's surface, and tectonics. Perhaps the strongest theme of this year's volume is volcanism. Some half-a-dozen papers deliver updates on issues that include how melts form below, how they travel up to the surface, and how eruptions affect the atmosphere and environment. These complementary aspects of how heat and melting redistribute rocks in Earth are nicely bridged by a chapter that provides us with respite in our comfort zone — a review of one of the greatest volcanic shows on Earth — the Deccan Traps flood basalt. Lest we relax too much, of particular remark is a technical review of Earth's inner core. It is not that long ago (at least it seems to me!) that the first observational data were reported demonstrating that it even existed. The inner core is a very small target, a long way away from our seismometers. Even today we know less about it than we know about many aspects of other planets in the Solar System. Now we are aware of the existence of an 'innermost inner core' and wave-speed anisotropy. Why these features exist is not addressed, presaging perhaps even more fascinating discoveries in future. — Gillian Foulger.

The Sounds of the Cosmos. Gravitational Waves and the Birth of Multi-Messenger Astronomy, by Mario Díaz, Gabriela González & Jorge Pullin (MIT Press), 2023. Pp. 209, 23·5 × 15·5 cm. Price $40 (about £33) (hardbound; ISBN 978 0 262 54494 8).

The purpose of this book, say the authors, "is to bring the subject of gravitational waves to the general public and to tell the story of how it was possible to discover and understand these waves." Twelve short chapters take the reader from the ancient Greeks to hopes for seeing primordial gravitational waves (with a glance over the shoulder at the 2014 confusion of radiation by dust with the desired primordial signal, by the *BICEP* collaboration).

The authors (members of the winning *LIGO* collaboration) provide us with introductions to Newtonian gravity, Special and General Relativity, stellar structure and evolution (especially for white dwarfs, neutron stars, and black holes), binary stars, and numerical relativity before setting out in Chapter 8 to explain the history of terrestrial gravitational-wave detectors. The last four chapters describe the technology of the *Laser Interferometer Gravitational-wave Observatory* (*LIGO*); the early detections; the first 'multi-messenger' event (a pair of merging neutron stars that was also a source of gamma rays and other forms of electromagnetic radiation), and hopes for the future.

The statutory photograph of Joseph Weber bent over one of the two-ton aluminium bars in 1969 appears as Figure 8.2, but you will not find him in the very sparse index. Indeed the only individual human beings there are Copernicus, Pierre-Simon Laplace, and Mileva Marić. Other folks you expect, like Einstein and Newton, appear only as part of eponyms. It must be said, however, that the authors do make clear their opinion that the field of gravitational-wave or radiation astronomy would have started much later, if at all, without Weber's pioneering efforts.

I have one major objection to the book and a whole flock of minor ones. The minor ones are factual errors, like saying that novae (well, they write novas) are the product of stellar collision; glitches like Royal Astronomer for Astronomer Royal; missing persons (as when that 1919 eclipse expedition is credited entirely to Eddington, and credit to Bethe without von Weizsäcker for nuclear fusion in stars); calling the *Lunar Surface Gravimeter* a sort of seismometer; ignoring early detections of gravitational redshift in white-dwarf spectra and the evolution of the orbit of DQ Her due to emission of gravitational radiation; the description of spiral nebulae as "dots" of light; a misleading description of what Einstein wrote to Karl Schwarzschild in 1916*; and so forth.

*The one of these items that perhaps needs further explanation is what Einstein wrote to Schwarzschild. Schwarzschild had written to Einstein asking about waves in General Relativity. Einstein responded that there was nothing like the waves in Maxwell's equations or words to that effect. This is perfectly true: EM waves have dipole radiation as the dominant term; for gravitation it is quadrupole radiation.

The major objection is to the use of the word "sound" in the title and in the text, which is not unique to these authors, another one having written that hearing was replacing sight in astronomy. Yes, any signal with frequencies in the range 20 to 16 999 Hz can drive a sound generator. The word for this is probably 'sonification'. But sound *per se* does not propagate through intergalactic space. Very many school children already know this, and surely a book that seems to tell them we are listening to the cosmos is likely to cause unnecessary confusion.

I finished reading the book sitting on the porch where, on many a sunny spring Sunday afternoon between 1991 (when we moved from Tustin to Irvine) and 2000, I would be sprawled when Joe came in from his standard five-mile jog, leaned down to kiss me, and proclaimed, "I wish to announce my safe return!" The first *LIGO* event arrived safely on Rosh Hashona in 2015, which was Joseph Weber's 15th Jahrzeit. This probably constitutes a conflict of interest. — VIRGINIA TRIMBLE.

What's Gotten Into You. The Story of Your Body's Atoms, from the Big Bang Through Last Night's Dinner, by Dan Levitt (HarperCollins), 2023. Pp. 385, 23·5 × 16 cm. Price £25/$32 (hardbound; ISBN 978 0 06 325118 2).

All astronomers know that we (and indeed all life) are made of stardust, and that it all started with the Big Bang. We also know that the secret of how life formed from this stardust has not yet been revealed, and perhaps we are happy just to leave it at that and get on with our lives. But Dan Levitt, a professional documentary maker, wanted to go much more deeply into what happens along the way, and has produced this remarkable book, which was inspired by wanting to know what we are made of.

To begin at the beginning*: the Big Bang produced atoms out of energy and led to the expansion of the Universe, so the book starts with Abbé Georges Lemaître's 1931 talk at the British Association for the Advancement of Science, where he argued that the Universe started with a 'primeval atom'. Levitt then relates the discovery of cosmic rays by Hess and X-rays by Röntgen, which led to C. T. R. Wilson building his cloud chamber, which in turn initiated the discovery of a whole zoo of new particles. These first few chapters set a pattern, where new discoveries are described as part of a story about the discoverer, so the book is not only describing the science but also telling the reader about the relevant scientists. This makes for compelling reading, and emphasizes how many new discoveries take a long time to gain acceptance by the 'established' community because of a range of biasses (he lists six in his Introduction).

Payne-Gaposchkin's insistence that stars are mostly made of hydrogen led to Hoyle's insight into nuclear fusion as the power source. Safronov in the Soviet Union single-handedly developed a theory of planetary formation and Levitt then discusses the evolution of the Earth from its molten beginnings and how it obtained its water. He describes the famous Urey–Miller experiment and the question of whether life came from space or first appeared in hot geysers in deep-sea vents (or both). At this point cells, membranes, and DNA make their appearance, and much of the rest of the book is devoted to a deeper and deeper study of what is going on inside us and in particular inside the cells that make us up. In addition, photosynthesis plays a vital role in providing the oxygen which we need to maintain life — the mechanism turns out to be extraordinarily complicated.

* Dylan Thomas, *Under Milk Wood*.

What about the Earth itself? How was it transformed from a barren rock into the green space and oceans we see today? Evidence of ancient glaciations suggests that it went through several phases in deep freeze — Snowball Earth — in which the whole Earth was covered in ice. Photosynthesis caused this by producing oxygen that converted the major greenhouse gas, methane, into carbon dioxide and water, allowing the Earth to cool and freeze in a feedback process. The only way out is volcanism, which provides local heating and a warming blanket of cloud. Amazingly, simple life (in the form of cyanobacteria) seems to have survived the most ancient of these events and then started to multiply dramatically. A key player in understanding what happened next was Lynn Margulis, who realized that symbiosis played a vital role in producing more complex structures.

Many more fascinating tales keep the reader involved, wondering what happened next, as in a good detective novel. One amazing fact is that lichen (a symbiosis of algae and fungi) grows on rock because fungi can actually eat rock, or more precisely extract mineral nutrients from the rock. Life started as plants which developed all the nutrients that animals need, and keep us alive. The cells of which we are made are extraordinarily complex; we all know the story of DNA and the double helix (well told here) but did you know that every cell in our body is essentially a factory? It contains within its protecting membranes tiny molecular motors, powered by a current of protons, and sodium–potassium pumps that trigger waves of electric charge that carry messages along nerves. Levitt concludes by pointing out that our cells are continually dying and being replaced — 98% of our atoms are replaced every year. Two per cent are not, which is why we are mortal, because they are in our brain and heart. However, all the atoms of which we are made are immortal and may some day become part of another life.

Levitt has provided us with a comprehensive account of what we are and where we came from. It is also beautifully written and a compelling read. I strongly recommend it — Robert Connon Smith.

Ghost Particle. In search of the Elusive and Mysterious Neutrino, by Alan Chodos & James Riordon, foreword by Don Lincoln (MIT Press), 2023. Pp. 304, 23·5 × 16·5 cm. Price £25·00 (hardbound; ISBN 978 0 262 04787 6).

Neutrinos are, as the name implies, neutral fundamental particles. The suffix ‘ino’ acknowledges that they have a surprisingly small mass. What sets them apart even more from other fundamental particles is that neutrinos hardly interact with matter; hence the nickname *ghost particle*. Understanding them is a hot topic in particle physics as we know that they exist, but we still know far too little about their properties. As well as being intriguing fundamental particles, neutrinos are very interesting messengers, showing us parts of the Universe that are hard to study with other means. For example, they come directly from the core of the Sun or can show us a supernova explosion in our Galaxy before we can see the light produced.

This book takes you through our encounters with this fascinating particle: from the initial postulation of the existence of the neutrino to what we currently know about it, what we still don’t know, and what we are looking for in current and future experiments. It is a result of a collaboration of two Americans: the physicist Alan Chodos and science journalist James Riordon. The journalistic influence is clear as it is accessible to non-scientists and written in a captivating manner. The foreword is given by Don Lincoln, who is a science communicator and scientist at Fermilab in Chicago in the USA. This is the laboratory currently constructing a multi-billion-dollar neutrino experiment. The USA stamp on the book is very noticeable. There is a strong emphasis on that country's (significant) contributions to understanding neutrinos. However, the many interesting activities in Europe and Asia are not presented on an equal footing. This left me with the distinct impression that the intended readership is the people paying for the flagship USA experiment that is currently being built at Fermilab.

Overall, *Ghost Particle* is highly entertaining and is filled with interesting facts. I will certainly recommend this to my non-physics friends who want to know about what I do and why. — SIMON PEETERS.

Worlds Without End. Exoplanets, Habitability, and the Future of Humanity, by Chris Impey (MIT Press), 2023. Pp. 368, 23·5 × 16 cm. Price \$29·95 (about £25) (hardbound; ISBN 978 0 262 04766 1).

Most of the stars visible in the night sky are accompanied by planets. That becomes slightly less surprising with the information that there are more planets than stars in the Milky Way galaxy. More intriguing is that about 60% of planets around Sun-like stars are similar to the Earth and in principle habitable — according to statistical extrapolations from satellite and ground-based telescope surveys of the last few years. At least four of those planets are within 30 light years of Earth.

Unless actively involved at the cutting edge of exoplanet research, I would imagine that many readers of this *Magazine* would be informed and delighted by the insights from this well-written book. Impey has a brilliant, enviable style of writing in which he explains clearly and concisely while never seeming to talk down — rather he takes you along with him for the voyage, and seems just as excited by the discoveries as for the person to whom this is all new territory. He deals with data gathered in the last few years, so much of this material will be new for most readers. Even specialists may not be up to date on the latest thinking on possible human futures. Not only is the writing style accessible but the particular format of sections and chapters also makes for enjoyable reading. Each short chapter of ten or so pages deals with a particular topic, but also includes chatty asides, such as the details of the personal lives of the scientists involved and also Shakespearean quotes and references to non-western cultures.

It was, of course, the last of those subtitle headings on the future of humanity that caught my eye. Just over 60 years ago under a bright sunny afternoon sky, I was standing on a school playground in South Norfolk looking up to watch a pure white V-bomber heading East with a nuclear stand-off bomb clearly visible, slung beneath its fuselage. At that time the future of humanity seemed to be measured in minutes. Chris Impey's latest book has arrived in equally troubled times; war has been raging in Europe for over a year and just as 60 years ago the aggressor has nuclear weapons; run-away climate change looks set to make life for humans very difficult very soon, and advances in computing and adaptive artificial intelligence seem likely to exacerbate the inequality of distribution of the world's resources. Impey takes an upbeat, forward-looking, but nuanced view in his exploration of a potential future for humanity. He begins with a little history: with the ancient starwatchers who first postulated the existence of other worlds, a couple of millennia earlier than my school-boy experience; and in passing even the epic of Gilgamesh gets a mention.

The book, which may seem to be squarely aimed at the non-specialist or interested layperson, expands on the subtitle in four main sections. Thus

Section 1 deals with searches for and the discovery of exoplanets: planets outside of our Solar System. This section of seven chapters is a beautifully written description of the variety of techniques used to identify such planets. It takes us through radial-velocity and photometry changes detectable in the light from the host star, though direct imaging by adaptive optics and occulting discs, to gravitational lensing, microlensing, and high-precision transit telescopes. In Section 2, six chapters describe the variety of exoplanets discovered so far and their potential for habitability by humans. We are introduced to Gas Giants, Ice Giants with an introduction to the many forms of ice, the horrific atmospheres of Hot Jupiters, full of micro silicates and molten metal storms, mini Neptunes, Water Worlds, Earth Clones, Exomoons, and the vast number of Rogue Planets. In this section Impey also discusses some features of planetary resonances and orbit dynamics, and the potential for rogue planets to be transport systems for life across the Galaxy. Section 3 deals with the possibility and search for other life forms beyond Earth. What sort of signal may be identified as a biosignature in an exoplanet? Searches for departures from equilibrium are possible — for example, oxygen co-existing with methane, or seasonal surface-feature changes. A clear unambiguous artificial signal detected, for example, by SETI would obviously be interesting — but raises the question of what could we say to the putative alien, given that we cannot even currently communicate with great apes with whom we share 99% of our DNA. The search could also be closer to home, with the potential for detecting micro-organisms using interplanetary probes sent to investigate Solar System moons. The six chapters of Section 4 cover the means by which humanity may travel to other worlds — 'The Promise of Space Exploration'. As Impey notes, space exploration by humans is currently rather dangerous; the odds of not surviving a space mission, including the training period, are about 1 in 20, and he explores space-elevator systems as a means of avoiding rockets. Finally, an epilogue is a speculative look at imagined futures of humankind. An extensive index and 54 pages of notes makes this a compelling, thorough, but accessible work of scholarship.

There was a time in which the belief in the prospect of finding complex life on other planets divided along subject lines — the physicists said, given the numbers of galaxies, stars, and planets, of course there is intelligent life out there somewhere; the biologists said do you realise how unlikely complex life is? On a planet demonstrably suitable for the emergence of life and indeed complex life, the particular cell and molecular arrangement that allows for such complexity has emerged only once in the 4·5 billion years of Earth's existence — although as Impey notes, the Earth has been biologically active for less than half of this time. He reflects this in a footnote on rogue planets, in which he says "Evolution from a simple cell with no nucleus to multicellular organisms and higher order creatures is extremely uncertain, and may not be inevitable". But then of course there is the potential of huge numbers of planets, albeit with vanishingly small probabilities of life, which when multiplied out still leaves some, maybe very small, positive probability. All of which is formalized in the Drake equation. Frank Drake himself said of his fundamental contribution to the debate, that it isn't an equation with a solution but more a container for ignorance. If the Drake equation is reformulated to ask how unlikely is it that we are the only technological species ever to have arisen in the Universe, the outcome is that it is rather unlikely — Impey quotes 1 in 10^{22}. But when this number is adjusted to assess our chances of being contemporaneous with intelligent life on another world, and Impey guessed 10 000 years as the average lifetime of a technological civilization, then the probability drops to almost zero.

Given these uncertainties and the likelihood of complex life existing, if at all, either very far away in the Universe or at another time, what possible reason, other than curiosity, is there for the continued search using SETI, METI (Messaging Extra Terrestrial Intelligence), or other means. One reason is to answer Fermi's question, which in summary says, in a Universe full of habitable planets, with plenty of time to evolve, life should be ubiquitous: Where is everybody? An answer to that question was postulated by an economist, Robin Hanson, who proposed the idea of the 'Great Filter'. An evolutionary hurdle which for some unidentified reason acts as a very stringent barrier to the development of complex and technologically savvy organisms. Life forms need to pass the filter otherwise they do not evolve. We do not know what this filter is — perhaps it is early in the development of cells capable of evolving complex life, perhaps it comes later as some feature of advanced civilizations, such as an instability due to technology (my V-bomber moment). Each time we investigate another world and find no life increases the possibility that the filter was early in evolution and that humanity has been fortunate enough to pass this test already. However, if we find life, of any form, then the possibility that the filter is still waiting for us in the future increases. There are other solutions to Fermi's question — for example, as some have suggested, by looking in detail at the Drake equation. Using realistic distributions of uncertainty in the chain of extremely uncertain factors that make up the equation, there is no reason at all to be confident about the existence of other civilizations in the Galaxy or even the Universe. The Fermi question just vanishes.

In summary this is a thoroughly enjoyable and informative book, ranging from detailed but concise descriptions of the methods and results of the search for exoplanets, to well-reasoned discussions on the habitability of these other worlds, by humans or native life forms. Highly recommended. — Barry Kent.

With Stars in their Eyes: The Extraordinary Lives and Enduring Genius of Aden and Marjorie Meinel, by James R. Breckinridge & Alec M. Pridgeon, with an invited chapter by Donald E. Osborn (Oxford University Press), 2022. Pp. 518, 23 × 15 cm. Price £29·99 (hardbound; ISBN 978 0 19 091567 4).

The authors are, respectively, an AAS member retired from the Jet Propulsion Laboratory (where he was the Meinels' boss near the end of their careers), a professional writer, and an expert on solar energy. The subtitle tells you what the authors think of their subjects. Their opinion is bolstered, back to front, with a complete list of the scientific publications by Aden and/or Marjorie and lists of selected publications of Edison Pettit (father of Marjorie), Hannah Steele Pettit (her mother), and Helen Pettit Knaflich (her sister), plus sixteen pages of references. There are, of course, also 457 pages of main text, including lots of footnotes and many illustrations, with six pages of colour, and the rest in glorious black and white, though colour might have been more informative, for instance, in the photograph of the 354-megawatt solar-power couples in San Bernardino County (California).

Some of the items mentioned are extremely enlightening, for instance, the significance of radar proximity fuzes (yes, with a 'z') during WWII and the extreme unpreparedness of the US to take over designing and manufacturing its own optical glass for range finders, binoculars, bomb sights, cameras, and small telescopes at the outset of the war. Yes, the US had been buying these crucial things from Germany, just as it had been prior to the onset of World War I.

Aden's role in diagnosing the problem with the *Hubble Space Telescope* mirror as launched is also part of the story, because he was, first and foremost, a dreamer, designer, sometimes developer, and rather rarely constructor of astronomical optics. As such, he is part of the history of Kitt Peak National Observatory, the *Multi-Mirror Telescope*, and the optical sciences lab at University of Arizona (plus a number of other affiliations). Marjorie was a some-time collaborator on these tasks as well as their ventures into solar energy and things that could be done best from space, while also raising the couple's seven children, five of whom were still living at the time the book was written.

Why then my muted tones? Several reasons, first the style makes it very difficult to figure out who/what/when (Chapter 1 goes back to Robert the Bruce, King of Scots). A timeline would have helped a lot. Second, while there is much information that was new to me (the V-1 had wings!!), items needing correction are very frequent (*e.g.*, that astronomical observing at Mt. Wilson stopped permanently in 1958. And Chapter 2 begins by crediting the foundation of Mission San Gabriel Archangel to the wrong year and the wrong people.). Third, that the extended presentations of historical background context are perhaps the most interesting part, but they make it difficult to discern just what part Aden and Majorie played in them. The optimal reader for the volume has to be someone who already knows a great deal about Aden Meinel and optical astronomy observing. If my copy weren't so marked up, I would send it on to Helmut Abt. — Virginia Trimble.

Reversing the Arrow of Time, by Bryan W. Roberts (Cambridge University Press), 2022. Pp. 263, 25 × 17·5 cm. Price £29·99/$39·99 (hardbound; ISBN 978 1 009 12332 7).

The arrow of time is one of the most famous concepts not just in physics but in a wider sense as well, and is a good example of a meme in the sense used by Dawkins[1] (as opposed to the modern but related concept of an internet meme).* In particular, its relation to the second law of thermodynamics and thus to the future 'heat death' of the Universe and the (not necessarily correct) conclusion that the second law rules out an infinitely old Universe has played a large role in the history and philosophy of physics but also in religion and culture[3]. In an astronomical context, the cosmological arrow of time is one of the several arrows of time, and a distinctive feature of Big Bang (as opposed to steady-state) cosmology.

In this book, Roberts, a philosopher of physics and associate professor at the London School of Economics and Political Science (where he is director of the Centre for Philosophy of Natural and Social Sciences), explores not only the statistical-mechanics and cosmological arrows of time, but also others (radiation, quantum collapse, and causal structure), concluding that all of those 'misfire' in the sense that they are not true arrows of time at a fundamental physical level. Possible reasons are resorting to heuristics, relying on boundary conditions, and describing a situation with missing information. It is not that those bogus of arrows of time are unimportant; indeed, they can provide a good explanation for our asymmetric experiences. Most important for cosmology is the 'past hypothesis'[4] that the Universe started in a low-entropy state. (Of course, in some sense such a hypothesis does not solve the problem of the apparent existence of a cosmological arrow of time, but replaces it with an earlier mystery.[5])

*Its present ubiquity might lead one to believe that the arrow of time is something which is a given, perhaps even in the sense of Kant's concept of an *a priori* concept. However, for much of history, as opposed to time's arrow, time's cycle was the more important idea.[2]

But that discussion doesn't occur until the fifth (of eight) chapters. The first four provide a brief introduction to, and a very detailed discussion of, the problem from both mathematical and philosophical points of view. In addition to physics, there is a huge amount of detail here, probably unfamiliar to many readers. (More diagrams than one might expect in such a book contribute to its clarity, as do the author-year-style citations and footnotes rather than endnotes.) By contrast, there is little exposition of the various arrows of time themselves, but most readers probably need nothing more than a definition and brief description. The approach is thus very different from many other books about arrows of time, in particular those by physicists as opposed to philosophers (*e.g.*, ref. 6). Chapter 6 is a discussion of the (absence of an) arrow of time in equilibrium thermodynamics. Chapter 7 discusses what Roberts believes to be the only true physical arrow of time, time-reversal symmetry in electroweak interactions. An entire section is devoted to refuting arguments due to Price[7,8] that that is not a true arrow of time. Experiments indicate that the standard model of particle physics does not admit a representation of any of the discrete symmetries C (charge conjugation), P (parity), or T (time reversal) nor the combination of any two, leaving only the combination of all three, CPT, which is discussed in the final chapter. The CPT theorem is based on assumptions which (so far) cannot be proved, but are widely regarded as being true. Nevertheless, some physical theories predict CPT violation, so it is important to look for it, remembering that lesser symmetries were once held to be absolutely true only a few decades ago.

As the many references for this short (for me) review indicate, this is a field in which much development is based on a canon with which readers are assumed to be familiar, in contrast to the (astro)physical literature, much of it in books rather than articles. I regard myself as only an interested bystander in the field of history and philosophy of physics, yet more than a dozen of the cited authors were familiar to me from similar discussions elsewhere. Reflecting the importance of the literature, the bibliography consists of 28 pages set in smaller type, including the titles not only of monographs but also edited volumes and even articles. (A three-page index in even smaller print concludes the book.)

The title of the book is perhaps something of a misnomer; 'finding the arrow of time' might be more appropriate. Perhaps Roberts means that all of the bogus arrows of time actually describe interactions which are reversible at a fundamental level. Because he (usually relatively quickly) dismisses them, there is not much discussion of those bogus arrows of time nor of other aspects of time, such as the (old or new) idea of cyclic universes in cosmology. But such discussions can be found elsewhere. As a result, the book is complementary to many discussions about (real or imagined) arrows of time in physics, and is clearly written despite the philosophical and mathematical details. The potential readership is probably limited but, as mentioned above, much of the technical literature in this field is a Great Conversation in the sense of Hutchins[9]; this book will probably become an important part of that conversation and is thus essential reading for those interested, whether or not they completely agree with Roberts. — PHILLIP HELBIG.

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Great Mysteries in Astrophysics. A guide to what we don't know, by Nicole M. Lloyd-Ronning (IoP Publishing), 2022, Pp. 165, 26 × 18·5 cm. Price £30/$50 (hardbound; ISBN 978 0 7503 4049 6).

If you are going to deliver an 'Astronomy 101' course, there's a myriad of introductory astronomy textbooks available aimed at the non-specialist with little or no physics or mathematics background. These make good use of astronomy's awe-inspiring images and general 'wow' factor to provide the novice with a sense of the excitement and current state of the subject. Nicole Lloyd-Ronning's book takes a different approach: rather than show the reader where astronomy knowledge is now, she asks where are the gaps in our knowledge, and how do we go about filling them? The book conveys the general sense that the pursuit of knowledge never ends: we can never draw a line and say this is the final answer. Lloyd-Ronning frequently states that deep mysteries may point to new physics, or to something as mundane as calibration issues, or the way we conduct our observations. But it is *exciting* when measurements show up shortcomings in our understanding.

Great Mysteries in Astrophysics is based on a course that Lloyd-Ronning gave for the University of New Mexico's Community Education Program. The course was open to everyone irrespective of background knowledge, and course participants included those with no background in physics whatsoever, to those with physics PhDs. Lloyd-Ronning's experience of taking her science to the uninitiated shines through, as does her enthusiasm for, and love of, the subject.

The 'Mysteries' presented are generally in high-energy astrophysics, where Lloyd-Ronning's expertise lies (she admits that the examples given reflect her "own bias towards what [she finds] most fascinating"), and in cosmological questions, such as the 'Hubble Tension'. Lloyd-Ronning begins with some introductory material, outlining the 'scientific method', and how we observe the Universe — astronomy now being very much a multi-messenger enterprise. As we might expect, there are many analogies, a great many of them cake- and fruit-based. The role of serendipity and perseverance in scientific progress is noted, suggesting that, very often, the best bit of software is that stored in the hardware that sits between our ears.

Stephen Hawking was famously warned that, for every equation in *A Brief History of Time*, the readership would be halved, hence it includes only a single equation, $E=mc^2$. Lloyd-Ronning has no such qualms, and pulls no punches in presenting difficult technical material (for example the field equations of General Relativity appear at the beginning of Chapter 4). Some more quantitative material is enclosed in boxes throughout the text, and the contents of some of these are more challenging than others. The book is consequently written in such a way that the whole gamut of physics abilities can expect to gain something by reading it: there is something here for everyone.

The book concludes by exploring some of the wilder shores of theoretical physics, such as string theory and loop quantum gravity, but so far neither of these has made testable predictions, the essence of any theory. It ends with some discussion of more general topics such as Space Law, and the concerns expressed by indigenous peoples that their sacred lands are being defiled by telescope building. Each chapter ends with a short reference list. Some of these are references to popular works, aimed at a general readership, while some are very technical (for example, to papers in *ApJ*). The latter are likely to challenge the general reader.

There are, as always, one or two niggles, but these are not serious. There is a profusion of footnotes (which can be a little distracting, and not all of which are necessary), and the exclamation mark is overused (so that it loses its impact). Also one or two of the figures, especially those on a dark background, are rather difficult to see, some panels are rather small, while Fig 8.3 doesn't match the text.

In summary, Lloyd-Ronning's book is a thoroughly good (if in some places, demanding) read, and at £30/$50, is excellent value for money. Your library should have a copy, and the book should appeal to a wide spectrum of physics and mathematics abilities. I'd recommend it to professionals who are interested in getting to know more about the latest in high-energy astrophysics, and to the adventurous novice who is keen to know how scientists in general, and astrophysicists in particular, conduct their business. — A. Evans.

Stellar Structure and Evolution, by Marc Pinsonneault & Barbara Ryden (Cambridge University Press), 2023. Pp. 324, 24·5 × 17 cm. Price £39·99 (paperback; ISBN 978 1 108 79882 2).

This is a wonderful book for its purpose! I could almost wish I had written it myself. Come to think of it, I almost did, about 19 years ago, and the present authors are generous enough to include Hansen, Kavaler, and Trimble (2004) in their list of further reading, ahead (only for alphabetic reasons) of volumes credited to Rudi Kippenhahn *et al.*, Dina Prialnik, and Achim Weiss. The purpose is to be a textbook for the course on stellar structure and evolution for advanced undergraduate and beginning graduate students that every American astronomy department feels it must offer, even though every faculty member works on exoplanets or cosmology and large-scale structure in the Universe.

The 12 chapters are aimed at a 15-week semester (such as that at Ohio State where the authors reside) rather than a 10-week quarter (like that at U California Irvine where your reviewer resides), and so we will never get to rotating, pulsating, and binary stars.

Of course, the things I might complain about are all omissions, so that 3rd virtual author Trimble would have made the volume too long even for a semester (and indeed H, K, and T were aiming for a full year of stars, not found in many curricula these days). Some missing pieces include: pulsating white dwarfs, of types DAV (prototype ZZ Ceti), DBV (prototype left as an exercise for the reader), and DOV (prototype PG 1159 = GW Vir). Indeed the Cepheid instability strip in the Pinsonneault–Ryden HR diagram does not extend below the main sequence (Fig. 11.1, p. 256).

Also not mentioned is the *p* process from among those responsible for synthesizing elements beyond the iron peak, though *s* and *r* are well described (and the latter honourably credited to core-collapse supernovae as well as neutron-star mergers). And well-known corrections to the mixing-length theory of convection: we meet convective overshoot (which happens because rising and falling gas blobs can't stop instantly when the temperature gradient drops below the adiabatic one) but are deprived of semi-convection, the blurring of a sharp composition discontinuity when it encounters, or is encountered by, the edge of a convective zone.

As for credit to the pioneers, the bibliography includes Baade and Zwicky, Bethe (but von Weizsäcker is relegated to a footnote), Annie J. Cannon, Cowling, Chandrasekhar, Eddington, Emden, Gamow, Hayashi, Henyey, Holmes, Jeans, Kelvin, Homer Lane, Morgan, Öpik, Pickering, Rosseland, Saha, Salpeter, Schwarzschild both K. and M., T. J. J. See (before he became obstreperous), and von Zeipel, not always for the papers that get referenced most often. Thus E. M. Burbidge and F. Hoyle are here, but not B^2FH nor Cameron for overall nucleosynthesis.

Most items are well up to date, with lots of *Gaia* data from Data Release 3. Each chapter is followed by exercises, some of which require careful thinking about an issue, some of which require careful calculation, and some of which need both. Among the 'fun' items in the exercises is the calculation of the Eddington limiting luminosity of the black hole at the centre of the Milky Way. Omitted is estimating the level of violation of the Eddington limit for an energetically working horse and the probable consequences if horses were held together only by gravitational forces. Reasons for buying this book: you are going to be teaching That Class; you are going to be taking That Class (maybe with a less cheerful text); it has been a long time since you took or taught That Class, and fear the subject might have gotten away from you. It probably has, but not nearly so much so as exoplanets or large-scale cosmic structure if those lie a few decades in your past. But whichever box you feel is yours, I hope you will remember to fill in and keep safe at hand the most egregious omission — the 1925 demonstration by Cecilia Helena Payne (later Gaposchkin) that stars are made mostly of hydrogen, without which none of the processes in the other chapters would work properly. — VIRGINIA TRIMBLE.

Forks in the Road: A Life in Physics, by Stanley Deser (World Scientific), 2022. Pp. 155, 22·5 × 17 cm. Price £20 (paperback; ISBN 0780811235665).

According to the Astrophysics Data System, Stanley Deser (1930–2023) was very close to a half-astrophysicist*, with 217 out of 413 listed papers coming up if you ask just for astronomy. And he has left us a wonderful book! The title, lest I forget, comes from Yogi Berra's advice "when you come to a fork in the road, take it." This, says the author, is also the basic law of Quantum Mechanics. Deser was born in 1931 in a city (Rovno/Rivne) now in the Ukraine. By the time he arrived in the United States a decade later, he had lived in Poland, Palestine, Paris, and Portugal, coming to terms with their languages†, and was

*Who first coined this phrase, with syllables accented to get a laugh, is lost in the grime of time. But I first heard it from John Bahcall, who was by the ADS criterion, a nine-tenths astrophysicist, with 690 out of 728 items called up as astronomy.

†He soon added English and later Danish, the latter in connection with his marriage to Elsbeth Klein, daughter of Oskar (of the Klein–Nishina cross section, Klein–Gordon equation, and Kaluza–Klein five-dimensional theory). Deser, however, bowed to the language skills of Murray Gell-Mann, who recited a Hans Christian Andersen story in flawless Danish, without having any personal connections to the country.

about to receive his third given name, having started as Salomon, become Lucien in France, and choosing Stanley from among the alternatives offered by the immigration inspectors on Staten Island. His chemist father Nachman became Norman, while mother Miriam was allowed to keep her name. And we have reached only page 12! Leaping quickly to the end of the book, we find the author revealing the soul of an observer when he writes about "…so-called dark matter. This is another word for observational deviations from the expected gravitational interactions at the galactic and cosmic level, which has proved all-too-fertile ground for crazy theories."*

In between comes a cast of dozens of physicists who have revealed (or maybe invented) the theoretical underpinnings of our Universe. Many are accompanied by revealing anecdotes. Oppenheimer speaks of "the old fool down the hall" (meaning Einstein) and warns Deser away from working on General Relativity (advice he wisely ignored). We meet von Neumann at his citizenship hearing about to point out a logical inconsistency (category error) in Article V of the US constitution, and I will offer a small prize to any reader who figures out what that particular logical error is. There are no Dirac stories, though P. A. M. appears as one of Deser's class of "Martians" among the mathematical physicists. The original Martians of science were the Hungarian quintet (not all from the same high school), Theodore von Karman, Leo Szilard, Eugene Wigner, John von Neumann, and Edward Teller. Deser adds Gerard 't Hooft, Julian Schwinger, and Dirac (also not all from the same high school, or even the same country), and one has to know a good bit of physics to understand the issues about which these three had instantaneous, correct insights.

The author has fascinating things to say about prizes, supersymmetry, supergravity, and superstrings (not total enthusiasm about any); a brief word about how Arnowitt and Deser became Arnowitt, Deser, and Misner, while the last was still a graduate student, working with John Wheeler, and about the relationship between mathematics and physics. His view is more like that of Viktor Weisskopf, who marvelled at how well the former fit the latter, than that of another sage who, scheduled to speak about mathematics and physics, walked to the podium, said they had nothing to do with each other, and sat down again. From the ends of the alphabet, Luis Alvarez and Yakov Zeldovich make cameo appearances, along with Chandrasekhar, Ed Purcell, and (Baron) Stueckeberg, this last as a contributor to scaling as a development from renormalization. Deser ends that section (called 'The Idea of Progress') by saying "it is really turtles, but very different turtles, all the way down." This ought to be the last word, but I wish to extend hearty thanks to Stan, who sent me an advance copy of the pages dealing with the 1955 Bern conference (which he had attended) that had been meant to honour Einstein on the 50th anniversary of his "miraculous year," but became instead a memorial and the zeroth of the now-numerous triennial international conferences on General Relativity and Gravitation. — VIRGINIA TRIMBLE.

* My own oft-proclaimed version is that dark matter is shorthand for a whole bunch of observations on scales from the disc of our Milky Way to the observable Universe. I'm pretty sure I didn't borrow this idea from Stan Deser and very sure he did not borrow it from me!

THESIS ABSTRACT

On the Evolution of Gaseous Haloes in Cosmological Simulations of Galaxy Formation

By Jake Bennett

The study of gaseous haloes holds the key to understanding gas flows in and out of galaxies, which in turn determines how galaxies form and evolve. However, recent observations have revealed them to be very complex, with the presence of significant amounts of multiphase gas, driven by a range of physical process within galaxies as well as by the larger-scale environment. Simulations that realistically model this gas are therefore crucial to interpreting this new data, and ultimately helping us understand how galaxies assemble. However, many cosmological simulations sacrifice resolution in gaseous haloes to reduce their computational cost, meaning their ability to resolve accurately some of the key physical processes, such as turbulence and instabilities, can be limited.

Using cosmological simulations in my thesis, I have investigated how gaseous haloes evolve over time. I have implemented a new shock-refinement scheme to boost numerical resolution in gaseous haloes. Applied to a massive cluster progenitor, I found significant increases in cold gas mass in filaments and clumps, leading to more widespread star formation. In the hot halo there is a notable boost in turbulent velocities, leading to a doubling of non-thermal pressure support. With the FABLE simulation suite, I studied how the hydrostatic mass bias and turbulent pressure support level in galaxy clusters change as they undergo major mergers and are host to powerful feedback episodes. I found that clusters rarely tend to be in hydrostatic equilibrium for long, with variations being driven by both merger activity and interestingly, at higher redshift, AGN feedback. Such insights could be important for future cluster mass estimates from X-ray and SZ observations, for use as cosmological probes. Finally, I simulated the growth of an ultramassive black hole of mass $\sim 10^{10}\,M_{\odot}$ by $z = 6$. I have studied its impact on the gaseous halo around it, including how powerful AGN feedback can disrupt inflowing cold filaments and increase the thermal pressure of the surrounding gas. I found that strong AGN-driven outflows can deposit significant quantities of metals at very large distances from the central galaxy, which could be a unique signature of the presence of such ultramassive black holes in the very early Universe.

Many of the effects predicted by the simulations described in my thesis have the potential to be observed (or ruled out) in the coming decade or two, with an incoming wealth of observational data from observatories like *JWST*, *Athena*, *CMB-S4*, *SKA*, and *LISA*. These data, combined with further developments in theory and simulation, will therefore revolutionize our understanding of gaseous haloes. — *University of Cambridge; accepted 2022 September.*

Here and There

TEA OR COFFEE?

Contributing Editor CHUCK WOOD will be spending many evenings pouring over these new [lunar] maps. — *Sky & Telescope*, 2023 August, page 53.