

THE OBSERVATORY

A REVIEW OF ASTRONOMY

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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2026 February 13 at 16^h 00^m
in the Geological Society Lecture Theatre, Burlington House

MIKE LOCKWOOD, *President*
in the Chair

The President. This is a hybrid meeting and if you are using Zoom then you should see a little green shield in the corner meaning you are using an up-to-date version. Questions can be put in the Q&A section of the website and they will be read out by Dr. Pam Rowell after each talk.

It is my sad duty to announce the death of Mike Cruise, who passed away this week after a long battle with cancer. He was my boss for a while and he was a great leader and mentor. He has been a great servant of this Society and had served both as Treasurer and President. I will miss his calm wisdom and his sense of humour. Unfortunately, that follows on from the death of Allan Chapman. I remember his lectures here with great fondness. He would stand up and talk about a famous astronomer with no lectern, no microphone, no notes or slides, and just talk in the most beautiful prose and an hour would just fly by. He was one of the most erudite people I ever heard. It is very sad that we have lost those two, so could I ask you all please to stand and observe a short silence in their memory? Thank you.

You will have heard that there is a funding crisis. I did a quick set of calculations and this one is really bad. As a shortfall on the total budget it was 10% in 2002, 12% in 2008, and I estimate 20% this time. The Society has already mobilized a lot of people and I call upon you to write to your MP as soon as possible. I recommend that at the top of the e-mail you put your home address and a personal e-mail address if possible. It does have an impact. All Friends and Fellows have been sent a form letter.

Council has decided to triple the number of fellowships that we offer. We feel it is a powerful gesture and it says that we are fully supportive of our young scientists. We are also going to rationalize the application process. You have a week left before the grant deadline, and the summer-school bursaries are considered only in this round.

We have a new Head of Membership, Elaine Ellis, joining us from the Music Publishers Association. We reckon if she can deal with rock stars, song writers, and friends, she can deal with astronomers, geophysicists, and friends.

More good news. The Vale of Dedham in Suffolk has become a designated dark-sky community. That is now the seventh in the UK but the first in England.

The Editor-in-Chief of *Monthly Notices*, David Flowers, is retiring after 15 outstanding years of service. We will be interviewing candidates for his replacement this month. You may have also noted that *Monthly Notices* and *Monthly Notices Letters* have amalgamated, but that was not our decision. We have a new Deputy Editor-in-Chief for *Geophysical Journal International* — Dr. Stefano Lorito of INGV, Italy.

We need a venue for the NAM for the next four years beginning in 2027. If you think your university might be interested in hosting the NAM, we would like to hear from you.

Mr. Horace Regnart. Can I just mention a letter I have written to the League Against Cruel Sports of which I am a member? I've listed astronomers as a threatened species and have laid out 17 reasons why they should not be endangered. I intend to invite my local MP to have lunch with me and propagandize her!

The President. Our first speaker is Dr. Chris Osborne of the University of Glasgow. Chris Osborne is an RAS Norman Lockyer Research Fellow at the University of Glasgow developing techniques to merge modern non-equilibrium radiative transfer for magnetohydrodynamic modelling to study the formation and evolution of cool condensations in the solar corona. Chris obtained a PhD from the University of Glasgow in 2021 on radiative transfer in solar flares, and has also worked as a research software engineer.

Dr. Chris Osborne. Thanks for having me here and to the RAS for funding this work. Spectroscopic observations provide a wealth of information on remote objects where *in-situ* measurements are not feasible. Our observations are governed by the physics of light formation and propagation: radiative transfer. In particular, atomic spectral lines — electronic transitions between bound levels of atoms and ions — can provide very powerful diagnostics for the plasma where they are emitted or absorbed. In the general case, it is necessary to understand the distribution of the atomic population throughout its bound energy levels. That is determined both by collisional processes in the local environment, and also by absorption and scattering of radiation. In many regimes, the latter is negligible, and the material is often described as being in local thermodynamic equilibrium (LTE); however, the general case is termed non-LTE, and is key to the formation of many strong spectral lines between the ultraviolet and infrared. In the non-LTE case, the atomic-energy distribution is a global function of the radiation field in the region of interest, but equally that distribution affects the radiation field, leading to strong coupling between those quantities.

The techniques commonly employed in solar radiative transfer to handle those regimes need to be efficient in order to handle the large numbers of iterative solutions needed to converge to a self-consistent set of atomic-energy distributions and radiation field. To that end, the short-characteristics method has become the workhorse of the field, due to its deterministic nature and efficient scaling. That method, however, is built around the implicit requirement that in multiple dimensions, the atmospheric model must be sufficiently scattering to prevent the appearance of 'ray effects', a class of artefacts where straight rays appear with voids in between them due to the discrete nature of the angular quadrature. For the radiative modelling of complex structures, such as those produced by modern realistic magnetohydrodynamic models, structures of high opacity may be embedded within optically thin regions (such as the solar corona), and models employing short-characteristics solvers may be plagued with ray effects.

Astronomy and physics are not the only fields that require accurate and efficient solutions to radiative-transfer problems: the field of computer graphics, which provides the techniques employed in rendering modern movies and video games, must also solve those problems efficiently, and with an increasing level of physical accuracy to provide visually realistic results to audiences. In particular, we focus on the radiance-cascades technique, first introduced by A. Sannikov in 2023*, and brought to astronomical radiative transfer by Osborne and Sannikov†. That technique builds on the so-called penumbra criterion, which allows for the derivation of a necessary set of scaling laws to represent penumbras (partially occluded regions) correctly in discretized models, and thus efficiently compute the radiation field due to nested shells around sample points. Under that scheme, contributions in more distant shells are sampled with higher angular resolution, but lower spatial resolution, whilst

*<https://github.com/Raikiri/RadianceCascadesPaper>

†C. Osborne & A. Sannikov, *RASSTI*, 4, 2025, rzae062, <https://doi.org/10.1093/rasti/rzae062>



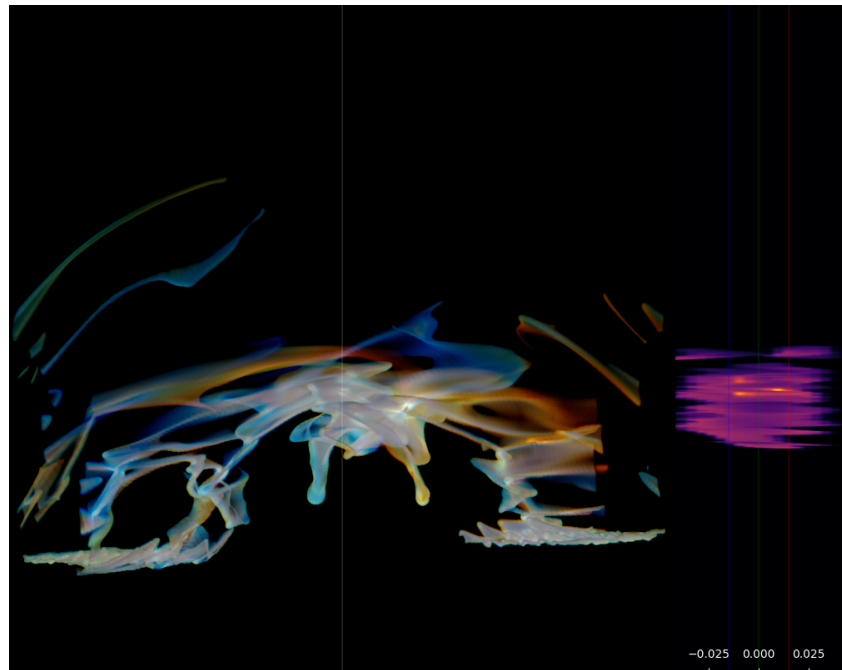


FIG. 1

Mg II *k*-line COCOPLOT. The Colour Collapsed Plot (COCOPLOT) encodes the wavelength variation across the spectral line into the colour channel. Here, blue and red represent the blue and red wings of the spectral line, whilst green represents the core. These are then merged following typical RGB synthesis to compress the 3D data visually. Both axes are spatial (essentially pixels; edge length ≈ 4 Mm) except for the inset at the right where the *x*-axis is in nanometres.

more nearby contributions are sampled with lower angular resolution, but higher spatial resolution. That is a fairly intuitive observation for discretized models, as any slight spatial movement may engender a dramatic variation in radiation due to nearby sources, but those will by definition have a large angular size. On the other hand, distant sources will be small, requiring high angular resolution, but are minimally affected by lateral movement (in essence, their parallax effect is small). The radiance-cascades technique defines a process for interpolating and merging the data stored in those cascaded shells so that many samples of the distant cascades can be efficiently reused, whilst introducing minimal artifacts. In that way, radiance cascades provide an efficient solution for multidimensional radiative-transfer modelling with intermixed optically thick and thin material where avoiding ray effects is key. That is the case, for instance, with coronal condensations, such as prominences — cool structures that form in the outer layer of the solar atmosphere.

The need for efficiency in computer graphics has also led to the development of a large number of accurate and rapid approximations. Our radiative-transfer code builds on ideas presented by the OpenVDB framework* (a two-time Academy-Award-winning software library for efficiently handling and rendering high-resolution volumetric data), along with the recursive spatial-averaging technique known as mipmapping, to provide an ef-

*<https://www.openvdb.org/>

fective adaptive-mesh-refinement technique optimized for traversal along rays integrating the radiative-transfer equation. That provides a typical order-of-magnitude speedup over the core-radiance-cascades method, at minimal additional memory cost. Combining those methods with programming techniques for graphics-processing units (GPUs) enables complex models of solar coronal condensations to be computed both more efficiently and on scales that were not previously feasible. For instance, the prominence model shown in Fig. 1 shows the $\text{Mg II } k$ spectral line in a very high-resolution magnetohydrodynamic model ($1024 \times 768 \times 384$ grid cells), that would previously be a very significant undertaking with existing radiative-transfer codes, but takes less than 30 hours on a single NVIDIA H100 GPU with our new software.

The goal of this talk is less to report on the existence of our code, and present the synthesis of those models, but instead to encourage the astronomical community to look at other fields and discuss with researchers working in those fields. That can be a very difficult process, as different fields have slowly evolved both the same and novel solutions to problems, often with different terms, and it can be challenging to develop a shared vocabulary. When successful, however, it can bring about step changes in methods that are becoming increasingly hard to achieve as the body of knowledge to contribute to the cutting edge of science ever increases.

The President. That is fascinating. We spent a lot of time thinking about how we could use gaming computer graphics in science but it's mainly in outreach and things like that. Do we have any questions for Chris?

Dr. Quentin Stanley. Considering the CUDA cores you get in NVIDIA cards: the RTX 5000/4000 and I think 3000, actually use AI interpolation to increase the frame rate; are you able to use that sort of technology on this sort of problem in the same way?

Dr. Osborne. Yes, there are a few ways in which we can use that sort of technology. One is simply in terms of it acting as a smart interpolator in many ways, so for visualization work in trying to figure out 'what does this look like?', we can take sparse samples through a model, something that is efficient to compute, and fill it in with some scientifically valid science data later on. There is also a lot of work going into small neural networks that approximate expensive physical processes as part of a larger model. Those are difficult things to train but it is something that we are just starting to play around with and we are really focussing on something really small as opposed to the big networks that are common in physics, three layers of 32 neurons, but they encode just enough physics that we can't quite get otherwise.

Dr. Stanley. Could you give an idea of the computational cost?

Dr. Osborne. Yes, it ran on an NVIDIA H100 and it took a day and a bit, so feasible.

The President. Thank you very much. [Applause.]

The next speaker is Dr. Teresa Paneque-Carreño. She is a Chilean astronomer and obtained her PhD in 2014 from Leiden University and ESO. She is currently a 51 Pegasi b and Michigan Society Fellow at the University of Michigan and an Assistant Professor. She combines observations and theoretical models to understand the physical and chemical conditions of planet formation around young stars. As part of her scientific work she has a deep commitment to science communication with an on-line community of over one million people who follow her across various social-media platforms. She is an author of top-selling books and she is recognized as the first female UNICEF ambassador in Chile where she is recognized as a current female youth leader. The title of her talk is 'A recipe for planet formation, dust chemistry, and a bit of luck'.

Dr. Teresa Paneque-Carreño. A fundamental question that people who study planet formation seek to understand is what processes lead to the creation of planetary systems such as our own and how those differ from the forming conditions of the wide variety of other planets that have been detected around various stars. We know that the process starts with the collapse of a molecular cloud and the formation of a protostar. Around the nascent protostar, the accreting material settles down to form a disc structure as a natural consequence of conservation of angular momentum. That disc is labelled as a protoplanetary



or planet-forming disc and my work focusses on studying it when it has become sufficiently isolated from the surrounding cloud, at a stage where the star is labelled as a Class II Young Stellar Object. Usually Class II systems are between one and five million years old and we expect that ten million years after the molecular-cloud collapse, the disc will have been completely dissipated, leaving behind only a debris disc and a planetary system.

Protoplanetary discs are made of dust and gas, with the bulk of the material being the gaseous reservoir. They are three-dimensional structures that extend both radially and vertically for tens, and even hundreds, of astronomical units. They have radial and vertical gradients in temperature and density. The solid reservoir is distributed such that larger, mm-sized pebbles and planetesimals settle towards the midplane of the disc, while smaller micrometre-sized particles are suspended in more elevated layers, as they are well coupled with the gas. Analysing each of those dust components and the distribution of the full gaseous disc is fundamental for tracing the chemical and solid reservoir available for forming planets, as well as interpreting the on-going physical processes that lead to planetary systems.

In this context, my work focusses on understanding the dynamical motions that mix and stir molecules throughout the disc. Those random-velocity motions are called turbulence, and they are essential not only for mixing the bulk gas, but also for driving disc evolution through angular-momentum transport and triggering dust growth towards planetesimal formation. To study turbulence, it is important first to understand that the disc material is rotating following Keplerian motion around the central star. We can study distinct line profiles of rotating gas using high-resolution spectral and spatial observations taken with instruments such as the *Atacama Large Millimeter/sub-millimeter Array (ALMA)*. For each observed molecular-line emission, we are sensitive to the Doppler shift of material moving away from and towards us as it rotates in the disc. That leads to a double-peaked feature, centred at the systemic velocity, that varies depending on the observed inclination of each disc. Most importantly, line profiles have a width that is largely attributed to the velocity dispersion caused by the Doppler effect due to the thermal motion of the observed molecules. The total line-width will be a combination of thermal, opacity, and non-thermal effects. Turbulence is amongst the non-thermal-effect components, therefore lines that appear broader than expected when accounting for thermal and opacity effects may be tracing turbulent motions in the disc.

Turbulence in protoplanetary discs is expected to be an outcome of various instabilities, with distinct theoretical predictions regarding its strength and variation across the three-dimensional disc structure. Magneto-rotational or vertical-shear instabilities will create turbulent motions with higher-velocity fluctuations in the upper layers compared to the midplane, creating a vertical gradient. An inverse effect of the latter may be caused by any perturbation produced by embedded (or forming) planets, where the midplane may become more turbulent than the upper layers. On the contrary, gravitational instability, a scenario that arises when the disc is massive and cold, may create strong turbulence throughout the whole vertical extent.

It is clear, then, that to study both the strength and presence of turbulence, as well as its launching mechanism, one must use molecular-line tracers that emit from constrained and diverse vertical locations of the protoplanetary disc. To that end, CN and N_2H^+ are selected as key tracers of the upper and midplane layers, respectively. CN is a well-studied molecule that requires high-energy photons for its creation as it is a by-product of HCN photodissociation or can be created if vibrationally excited H_2^+ molecules, created through FUV pumping of H_2 , are present. Therefore, CN originates in the upper disc layers, where radiation is higher. N_2H^+ , on the other hand, is an ion that is readily destroyed by gas-phase CO, therefore it can be used as a tracer of the CO snow-surface, which appears at low (<20 K) temperatures, close to the planet-forming midplane.

Using high-resolution spectral *ALMA* observations and non-parametric modelling of the line profile, I am able to measure non-thermal line broadening in CN emission from the disc around the solar-mass star IM Lup. That non-thermal broadening is related to turbulent

motions of 170–190 metres per second, in agreement with theoretical models of various instabilities. In comparison, N_2H^+ shows lower levels of non-thermal broadening for IM Lup, indicating a vertical gradient in turbulence that agrees with prior constraints from mm-sized dust observations. A larger sample of discs with modest-resolution observations of N_2H^+ is also analysed and we detect non-zero upper limits on turbulent motion, signalling that — as expected — some discs may have considerable mixing and stirring of material during the planet-formation phase. Overall, these results present a complex and chaotic view of the earliest stages of planetary systems and compel us to consider all of those simultaneous processes that likely shaped our own Solar System in its very beginning.

The President. You didn't quantify the luck.

Dr. Paneque-Carreño. I didn't quantify the luck — there are several layers of luck, one of which is finding any of those features and being able to trace all of that, and for me I think I had luck because it is my personal view of planet formation. I think a lot of things have to go right or maybe we are complicating it. It seems like a lot of things have to happen that we don't yet fully understand in order to create the number of systems that we know to exist including our own, so it's a lot of little pieces that we are trying to observe from Earth but we need luck to be able to detect them and we also need luck to be in place for them to happen.

The President. You also need luck to study the candidates in the first place.

Dr. Paneque Carreño. Also true, but we need other astronomers to trust in that luck — we can go to systems where it is less likely and see how common they are.

The President. Thank you very much. [Applause.]

The next speaker is Dr. Hannah Wakeford from the University of Bristol who is going to talk about 'The exotic nature of exoplanet clouds'. Hannah is an Associate Professor of Astrophysics at the University of Bristol where she leads a team investigating the atmospheres of exoplanets using space-based telescopes. She is an accomplished researcher and tireless communicator, having won the Philip Leverhulme Prize in Physics in 2004. She has written a nine-billion-year update to the best-selling popular science book *Bang!!* with Drs. Brian May and Chris Lintott. She was the recipient of the 2025 RAS Fowler Award.

Dr. Hannah Wakeford. Clouds are everywhere. Every world in our Solar System from planets to moons and dwarf planets with an atmosphere also has clouds. When we look to distant exoplanets, planets orbiting stars outside our Solar System, is it then surprising that clouds are there too? Well, yes, to some extent. The distant alien worlds are unlike any in our Solar System and their clouds are even more alien for us to imagine.

I am an Associate Professor in Astrophysics at the University of Bristol where I study the atmospheres of exoplanets, planets orbiting stars outside of our Solar System. To study those exoplanet atmospheres, I use the transit method, where the orbiting planet passes in front of the star from our point of view, blocking out a small portion of the star's light — proportional to the ratio of the area of the planet to that of its host star. During the transit some of the starlight is filtered through the atmosphere of the planet, imprinting scattering and absorption signatures on the transmitted light before it reaches our telescopes. Each atom and molecule has a unique spectral signature — the way it blocks the light — and by taking a spectrum of the light from the star during the transit event we can disentangle what is in the atmosphere surrounding the planet. With over a decade of data from the *Hubble Space Telescope* looking at tens of close-in giant planets known as hot Jupiters — due to their hydrogen-helium dominated atmospheres with their radii close to our gas giant Jupiter, but sitting at orbital distances 20 times closer to their star than we are, making their surfaces over 1000°C — we have measured the absorption of water, sodium, and potassium in their atmospheres. But we also saw that the amount those materials absorbed was not as strong as expected. That muting or sometimes complete obscuration of gaseous absorption is due to the presence of clouds in the planetary atmosphere, which block or scatter the light where they sit at high altitudes in their host's atmosphere. Using Mie theory we can show that small cloud particles will preferentially scatter the light at shorter wavelengths while large



particles will block light uniformly at all wavelengths. But what are the clouds made of at those temperatures? For that we need to look at the condensation conditions of different materials and at what temperature would the gas need to be when it becomes saturated and thus liquid or solid particles of that substance form. On the Earth the changing temperature of our atmosphere with altitude crosses the water-condensation line, consequently we have clouds made of water droplets. At the high temperatures of the hot Jupiters they instead cross the condensation lines of material more unusual to think of as clouds. The main cloud-forming species for a hot Jupiter should in fact be magnesium silicates, or sand as we would call it here on Earth. Those silicates condense out of the gas to form solid particles suspended in the atmosphere with their size dictated by the dynamics, chemistry, and temperature of the atmosphere they sit in. In more extreme atmospheres at over 2000°C the clouds are expected to be made of corundum, the aluminium oxide that makes up the basis of rubies and sapphires. The beauty of those materials is that they also interact and absorb light in a characteristic way. For solid minerals that absorption occurs in the mid-infrared (>5 microns) and is caused by the vibration between the main diatomic species that makes up the cloud particle — in the case of magnesium silicates the silicon–oxygen bond which absorbs around nine microns. For decades we have known that those clouds are in exoplanet atmospheres, but only since the launch of *JWST* on Christmas Day 2021 have we had the means to tell you what they are made of.

JWST has already made breakthrough measurements of exoplanet atmospheres with the first detections of carbon dioxide and methane in the gas phase for a handful of planets. Yet the obscuring quality of clouds is still very much present. Excitingly *JWST*'s *MIRI* instrument can measure exoplanet atmospheres over the expected absorption bands of the predicted silicate clouds. But surprises were still in store. My team and collaborators as part of the *JWST* Telescope Scientist Team DREAMS programme used *MIRI* to measure the atmosphere of the hot Jupiter WASP-17b as it transited its star, picking up the absorption signatures of material in its atmosphere. Those measurements revealed a tell-tale absorption spike around nine microns where we expect our sand clouds to interact with the light. But the spike was slightly narrower than expected and shifted to 8.7 microns, that meant it was not our magnesium silicate but instead silica, the more primitive form, SiO_2 , which we call quartz. That detection of silica in the mid-IR combined with scattering measured with *Hubble* in the optical helped us constrain the particle size of those clouds to just 10 nm, suspended high in the planet's atmosphere. What we saw was the first definitive detection of an exoplanet cloud species and what we learnt is that the cloud-formation sequence from corundum down to magnesium silicates and even salts (around 700°C) is more complex than we thought. Additional measurements we have made of WASP-17b have shown that those clouds are forming across the cold side of the planet and being transported by fast winds to the day side where they evaporate into their gas phase and then recondense on their next journey across the nightside. That reveals a silicate cycle very different from our own, crystals of quartz smaller than the width of a human hair raining through an atmosphere over 1000 light years away at temperatures of nearly 2000°C and with supersonic 1000-mph winds. With state-of-the-art telescopes we can bring the true nature of that and other exotic atmospheres and their clouds to light.

The President. It is just amazing the progress that has been made. You were saying that it is 30 years since the first hot Jupiter was discovered and I remember it. We know so much about it now, it's just astonishing. Are there any questions for Hannah? I just make an observation. You were pointing out that Earth-like planets are difficult because their atmosphere is so compacted but their magnetospheres are not and there are some really interesting studies using those techniques on ionized species, separating out the stellar wind from the planetary-origin stuff and they look just like Earth's magnetosphere. It's amazing.

Dr. Stanley. You mentioned the 2% change in atmosphere which is quite intriguing, because that means that you have a low-pressure/high-pressure area. Thinking of the rain

which we are currently suffering, do you end up with one side where it's always raining quartz and the other side where it is nice and sunny?

Dr. Wakeford. The question of weather is something we are interested in and you aren't wrong. We would expect that one part of the planet would be very much inundated with clouds and rain (or quartz) as it sinks down through vertical mixing. Those planets don't have a surface of any kind so it is not something you can stand on and feel as you would on a beach in Wales, say. In essence, what you are saying is actually accurate. We have a point in the atmosphere where we would expect clear skies and it's just gas-phase chemistry going on and we have got the formation of these solid particles suspended high up in the atmosphere that are travelling very fast. Imagine that they are really shards of glass flying at you at thousands of miles an hour. That is what is happening in that atmosphere and as they go around to the day side they get evaporated but that mixing is happening. Deep within the atmosphere we have other clouds that are warming being lofted up into the atmosphere and it's a big dynamical process when you have these spots of weather and we are getting down to the scale where we can tell you not just about the climate of the planet but what the weather is like in a particular location.

Dr. Stanley. So basically you are saying that I'm going to need a bigger umbrella?

Dr. Wakeford. You are going to need a much bigger umbrella and it will need to be very heatproof — 700 to 1000 degrees at that point — and you will be under millibar pressure, equivalent to about the stratosphere on Earth. You are going to need a really good spacesuit.

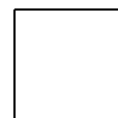
The President. Quentin, your thinking is close to mine. I think that it would be very good if Earth were to manage that trick, burn off the clouds every midday and reappear at night? Thank you very much, Hannah. [Applause.]

The last speaker is Lisa-Marie Zeßner from the Max Planck Institute for Solar System Research in Göttingen. She began studying astrophysics in Heidelberg in 2014, completing Bachelor's and Master's degrees there. During that time, she worked with cosmological simulations and models to study galaxy evolution and cosmic structure formation. At the end of 2020, she started a PhD at the Max Planck Institute for Solar System Research (MPS) in Göttingen and began working with the MURaM code to set up simulations of solar prominences. She finished her PhD thesis last year, and she is now staying at MPS as a postdoc to keep working on new and more advanced setups for her prominence models.

Dr. Lisa-Marie Zeßner. Solar prominences have fascinated people for hundreds of years. During solar eclipses, they can be seen as bright clouds at the edge of the obscured solar disc, meaning they could be observed long before the invention of the telescope. At that time, the nature of those features was unclear: people described them as 'burning holes', 'red flames', or even 'mountains on the Moon', as it was uncertain whether they belonged to the Sun or the Moon. Now, hundreds of years later, we know that solar prominences are plasma clouds that hover in the solar atmosphere, supported against gravity by the solar magnetic field. They can be found all over the Sun and vary in size, structure, and dynamics. Modern ground-based telescopes and satellites now allow us to study them in great detail. Nevertheless, many aspects of their physics remain unclear because the prominence plasma is highly dynamic and can exhibit complex properties. Therefore, theoretical models and numerical simulations are important tools for interpreting observations and understanding solar prominences.

During my PhD, I used the radiative-magnetohydrodynamic code MURaM to set up simulations of prominences in the solar atmosphere. MURaM simulates the solar atmosphere from the top of the convection zone up to the solar corona in a Cartesian box. In this talk, I provide an overview about the formation and properties of the simulated prominences.

We start the simulations by providing a dipped magnetic arcade as the initial condition for the magnetic field in the simulation box. We can vary the parameters of that initial condition to study different versions of the setup. During the simulation runtime, the footpoints of the magnetic arcade are fixed at the bottom boundary of the domain to stabilize the magnetic-field



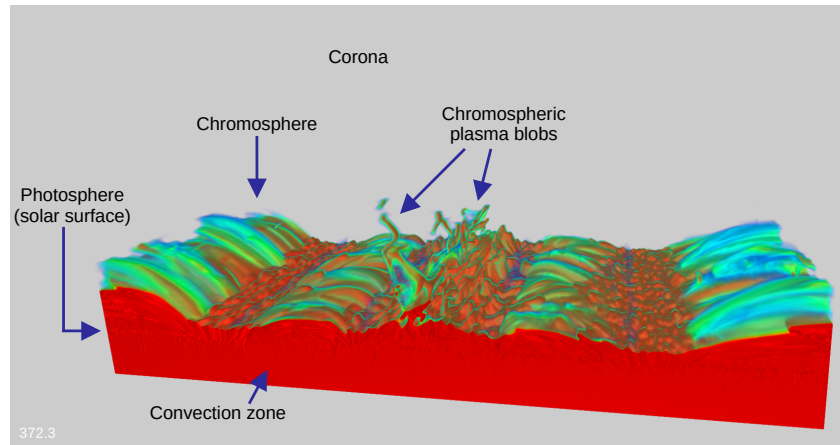


FIG. 2

3-D rendering of the plasma density for the convection zone, photosphere, and chromosphere of the simulated domain before the prominence is formed. The opacity is adjusted such that the corona ($\rho < 10^{-14} \text{ g cm}^{-3}$) is not visible. The corona spans the whole volume above the chromosphere. The visible chromospheric plasma blobs show examples of the injections that can form and feed the prominence.

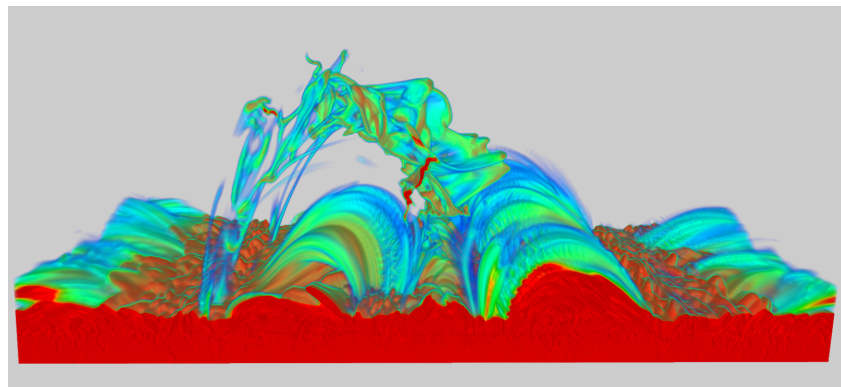


FIG. 3

3-D rendering of the prominence plasma during a draining event. The opacity is adjusted such that the corona ($\rho < 10^{-14} \text{ g cm}^{-3}$) is not visible.

structure against the dynamic convective motions. After some time, a prominence structure starts to form self-consistently by a combination of cool injections from the chromosphere and the condensation of hot coronal material. At the beginning of the prominence-formation process, cool and dense plasma blobs are ejected upwards from the dynamic chromosphere into the hot solar corona (see Fig. 2). Some of those blobs settle in the dips of the magnetic-field configuration, beginning to build up the prominence structure, while others fall back down to the solar surface. If the blobs remain in the corona for long enough, they get cooled by radiative losses, and the pressure at that location drops. That drives inflows of

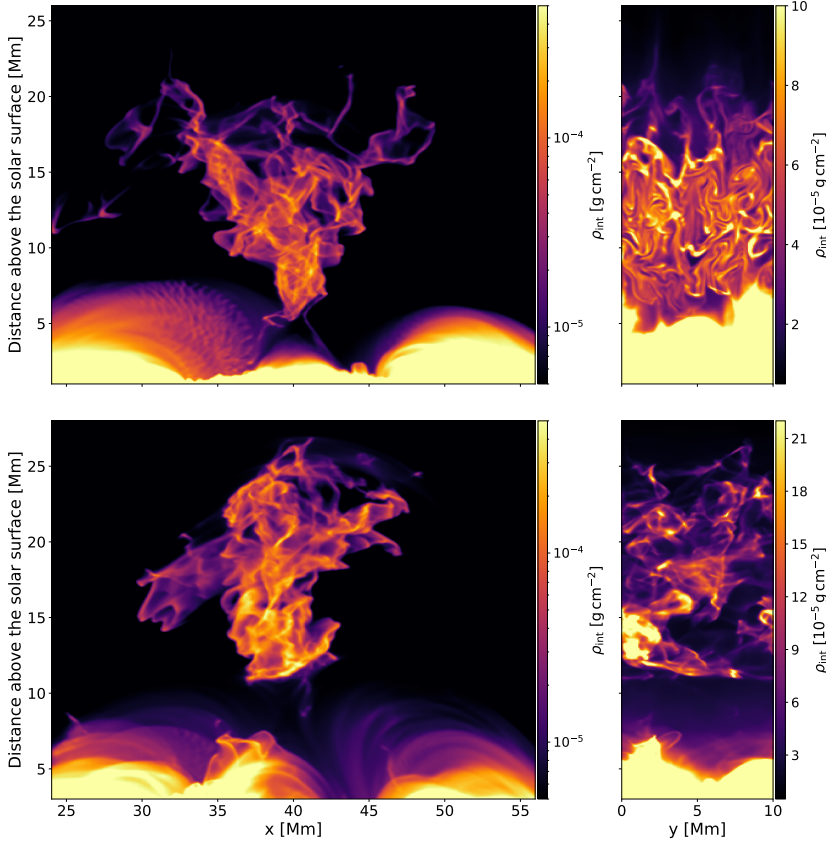


FIG. 4

Structure of two simulated prominences in integrated density. The left panels show the viewing direction from the front (line-of-sight along the y -axis) and the right panels show the viewing direction from the side (line-of-sight along the x -axis), similar to how prominences can be observed on the solar limb.

hot coronal plasma that condense onto the existing cool blobs. The condensation of that hot plasma, along with the continued injection of cool plasma from the chromosphere, feeds the prominence structure. Offsetting that mass build-up, the prominence can also lose mass through plasma draining back to the surface along magnetic-field lines (see Fig. 3). That mass loss can occur to both sides and at the bottom of the prominence.

The simulated prominences are close to the surface and have heights of $\approx 6\text{--}20$ Mm, which is similar to the size of prominences in active regions. The prominence plasma is dynamic and shows an interesting fine structure. The visible fine structures of the prominences can vary depending on the parameters chosen for the setup (see Fig. 4). Depending on the strength and orientation of the magnetic field at the location of the prominence, the structures as viewed from the side (right panels of Fig. 4) can feature horizontal, vertical, and turbulent-looking patterns that qualitatively resemble different types of observed prominences. Furthermore, we compare simulations in which the atmosphere is treated in local thermodynamic equilibrium (LTE) everywhere with simulations that take non-LTE

(NLTE) effects in the chromosphere into account, such as scattering of radiation and non-equilibrium hydrogen ionization. In the NLTE simulations, the average temperature of the prominence plasma is higher, and the temperature structure within the prominence becomes more inhomogeneous compared to the LTE case.

With the current setup, we plan to conduct more extensive parameter studies in order to gain a better understanding of the origin of the visible structures and dynamics. In the future, we intend to expand our simulation setup to include more sophisticated magnetic-field configurations, such as larger sheared arcades and magnetic-flux ropes. By calculating synthesised emission at different wavelengths, we will be able to make more detailed comparisons with observations.

The President. Questions for Lisa? I'm just amazed at the detail you are able to simulate. Some of the simulations look more like things from computer games. I was going to ask about the basis of the field model, but also the pattern of motions — are they prescribed from instrumentation or are they produced by other models?

Dr. Zeßner. The movement in general is produced by the models. You start out with a simple atmosphere and then the model gets heated so you put energy in which tries to match what energy comes out of the Sun and then you naturally get this hot-plate effect that creates granulation cells in the plasma when you heat it from below. You have to define a boundary condition because the convective zone is pretty deep — it makes up about 30% of the solar diameter. We cannot simulate all of that and also we have the problem that we don't really know exactly how the convection cells look deep-down. We simulate only the very top layer so we have to make assumptions.

The President. My question was biased because the movie didn't run. It looked as though the field was sitting within granulation cells. That is why I wondered if they were prescribed. I'm amazed at some of the things that you are able to simulate. Some of them look more like computer games.

Dr. Zeßner. That field was prescribed because it was put in by the initial magnetic-field configuration, but its shape is also affected by the turbulent convective motions.

The President. Are there any other questions? Thank you very much, that was lovely. [Applause.]

There are just two announcements before we close. The next meeting will be on Friday, March 13th and there are drinks next door in the library. Remember to write to your MP.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2026 March 13 at 16^h 00^m
in the Geological Society Lecture Theatre, Burlington House

MIKE LOCKWOOD, *President*
in the Chair

The President. Welcome to today's meeting. This is a hybrid meeting. Questions can be put in the Q& A and they will be asked at the end of each lecture by Dr. Pam Rowell.

I have an unhappy job to do and that is to announce the death of Dame Carole Jordan. [Carole was an Editor of this *Magazine* 1968–1973. — Ed.] She was the first female President of the Society and served in that post from 1994 to 1996. I can tell you that the RAS was incredibly close to her heart. We would often talk both here at the meeting and afterwards

on the train to Oxford, and she would always ask about the Society. She was a genuine trailblazer in making her own way in what was a male-dominated field at the time. She made her name in particular in spectral studies of in the UV from the *IUE* mission and in X-rays. She analysed the spectra in terms of states of ionization and followed through that with work on cool stars. I was asked to talk about her for *Last Words* on Radio 4 and I was looking for a suitable anecdote. Fortunately Roger Davies came up with the perfect example: At a reception at Oxford, she was introduced as Professor Dame Carole Jordan and her response was “Dame Commander — I like the Commander bit”. Can I ask you to take a few moments to remember her? Thank you.

The bad news comes from STFC. There is a major funding crisis with 30% cuts to astronomy-grants projects and teams have been told to plan for 60% cuts. I want to tell you what the Society has been doing and my sincere thanks to Robert Massey, Marieta Lefort, Sam Tonkin, and Jess Shaper who have contributed enormously as has Jim Wild (our President-Elect), and Ian Russell.

They have been trying to improve the situation and I know we have made a definite impact. As soon as the announcement was put out in a press statement we talked to several national media outlets and Jim Wild and I spoke to a large number of journalists. We have created a template letter for Fellows to write to their MP, and if you haven't already done so, please do help to keep the pressure on. I wrote to Lord Vallance the Science Minister for a meeting and we briefed ministers at the Science and Technology Committee. We hosted an emergency astronomy forum where STFC staff were in attendance. We have also talked to Michele Dougherty, Catherine Heymans, Peter Fortune MP, and the Shadow Science Minister. Ian, Robert, and I attended other sessions at advisory Town Hall meetings and the IoP Heads of Physics meeting.

The Society has tabled FOI requests on certain aspects on how this crisis came about and also what the plans are to end it. I'm pleased to say that MPs are now asking those same questions. We have also had an open letter from physics teachers with 120 signatures. They understand the aspirational value of astronomy and getting people into science and technology. RAS Council is doing what it can to help and I remind you that we have tripled the number of fellowships that we offer.

Max Alexander is presenting his ‘Fragile Earth’ exhibition on the growing threat of space debris. The exhibition started at Lloyd's of London and has been to the United Nations, the European Parliament, and is now being hosted by us in the BH courtyard from March 19 to May 16.

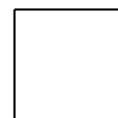
The first speaker today is John Coxon who is an STFC Ernest Rutherford Fellow at Northumbria University and who won the Fowler Award in 2025. His research interests are primarily in terrestrial electrodynamics: he studies electric-current systems that flow at Earth, including the Birkeland currents. He has also contributed to the question of substorm physics, including work in how energy and currents are distributed before and after substorm onset. The title of his talk is ‘Hemispheric asymmetry in terrestrial electrodynamics’.

Dr. John Coxon. Kristian Birkeland produced an instrument called the terrella consisting of a giant magnetized metal ball and he fired electrons at it. He was occupied with the question of how the aurora occurs. It was located under one of the lecture theatres at the University of Oslo, and in 1899 he built an observatory in Norway to make studies of geomagnetic storms.

In 1908 he wrote in a paper “the knowledge gained in radioactivity since 1896 has favoured the view to which I give in that year namely the magnetic disturbances on the Earth and the aurora borealis are due to corpuscular rays emitted by the Sun.”

He built the terrella to test the theory that the aurora borealis was being caused by some sort of emanation of charged particles coming from the Sun. His idea was widely pilloried in Britain and he did not get anywhere near the recognition he deserved during his lifetime.

Birkeland discovered that current flows along the magnetic-field lines at Earth, and he found that by firing electrons at the terrella. The morphology of the Birkeland currents was



first established by Iijima and Potemra in 1978, 70 years later.

I would like to introduce to you the Dungey cycle. The magnetic-field lines are trapped in the solar wind. Effectively there is a circulation of field lines with reconnection and the solar wind drags the field lines around to the night side where reconnection occurs again and the Earth's magnetic-field lines go back to the dayside thus completing the cycle. There are large plasma flows because the plasma is trapped on the field lines and as the field lines move, the plasma moves with them. You have a mass movement of plasma in the Earth's magnetic field, so you end up getting an electric field as a result. If you have a vortex in the plasma flow you get the electric field pointing into the middle of one vortex and out of the middle of the other vortex. Because you have electric fields pointing inwards and electric fields pointing outwards, that implies you have some large-scale current flowing and the magnetic line currents are the currents that Birkeland hypothesized.

We can take snapshots of the current system using a megaconstellation of satellites called *Iridium*, a telecommunications satellite network. There are 66 satellites in six orbital planes and we get data in a ten-minute-long sliding window, evaluated every two minutes. We have 16 years of data at a resolution of 1200 spatial data per time-stamp. We pay the satellite operators for magnetic data and we can get the currents from that.

It turns out that if you look at the total current in the northern hemisphere and subtract the total current in the southern hemisphere you get a sinusoid. In the northern summer, currents are stronger in the north, and stronger in the south in the southern summer, because of the differences in insolation caused by seasons. We expected that the current flowing in each hemisphere during equinox would be equal. What we find is that at the equinox they are absolutely not equal in the two hemispheres. The northern current dominates at all times except during the southern summer and the northern-hemisphere currents are larger than those in the south. We had to decide if that difference was an artefact or was real. Other teams found the same difference in *Swarm* and *DMSP* [the U.S. *Defense Meteorological Satellite Program*] data which was very encouraging.

However, in my 2016 paper, I found that the northern-hemisphere currents were 27% stronger than the southern-hemisphere currents, whereas the asymmetry reported by *Swarm* was 12%, which are inconsistent with one another. In other data sets, Poynting flux and ionospheric conductivity are also asymmetrical whereas neutral winds do not seem to be. Asymmetrical neutral winds might cause an asymmetry in the current because plasma vortices drive vortices in the neutrals which end up counteracting the current you get. If you think about Antarctica and the ocean around it *versus* the Arctic circle, the northern-hemisphere magnetic pole is in the sea, surrounded by land, and in the south it is in a land mass surrounded by sea. A recent paper by Silva *et al.* in 2020 does not find a significant difference between the neutral winds in other hemispheres but that is a difficult observation to make. As such the leading theory for why we see asymmetries in the electrodynamics is that the Earth's dipole itself is asymmetrical.

We recently looked at a solar cycle's worth of data, plotting data *versus* the FACER model* parameterized by a simple consideration — if the plasma vortex results in currents I described earlier and is being driven by magnetic reconnection, you can parameterize the model of the vorticity with magnetic reconnection and estimate the current you should get. The model includes conductance and so it knows about seasons, because the zenith angle is part of the model and it changes with season.

The modelled currents vary with season and so are centred on zero as there is no systematic asymmetry in the model. Another important thing to note is that in 2018 the *Iridium* satellites were replaced. Older *Block-1* satellites were replaced with *Iridium NEXT* satellites, which

*The Field-Aligned Currents Estimated from Reconnection (FACER) model is a model of Birkeland current based on a few simple assumptions; the full model description is at <https://github.com/johncoxon/facer-model>.

carry science payloads and have different magnetometers on board compared to the *Block-1* vehicles. Also, the fitting process has been changed from the WORLD MAGNETIC MODEL to CHAOS 8.1, and now incorporates an extra spherical elementary current step.

In reality you can see that the *Iridium* satellite tracks in the northern hemisphere are much more constrained than they are in the south and you effectively end up with a change in coordinates in the south. That fitting tries to correct for issues with the southern-hemisphere maps, and leads to new maps.

The old fitting method gives a result which was 21% asymmetric for *Block 1* and 19% for *NEXT* whilst the new fitting method applied to *NEXT* data gives an asymmetry of 4% which is interesting because every other data set gives a value between 10% and 12%. The asymmetry has seemingly gone from being overpredicted to underpredicted. There is a problem because it is really hard to do conjugate studies of Earth, particularly if you want to do it from the ground. There are a lot of data in the northern hemisphere but in the Antarctic it is really hard to put magnetometers there because you have far less land mass. If you use spacecraft, even those giant constellations that span the Earth, you are at the mercy of the orbital mechanics and you are going to have to make assumptions as to how to do your fitting in either hemisphere. There is no way, at Earth, of making truly conjugate measurements except for one. We need a dual-hemisphere auroral imager. It has been about two decades since the last time we had an auroral imager taking images of the aurora from space and we've never had a dual-hemisphere auroral imager. Multiple missions have been proposed and all have failed, which is intensely irritating. We know the hemispheres are asymmetrical and we are finding out more and more that the asymmetry manifests itself in many ways.

I'd like to end by thanking all the people who have supported me.

The President. Thank you, John. Questions? Is Peter Cargill here? Peter, the student that we looked after together, Tim Stubbs, looked at polar-hemisphere work.

Professor Peter Cargill. I don't think it was ever submitted.

The President. After he left he went and joined Goddard.

A Fellow. A very intriguing presentation, particularly since most of us simply present saying "here are my results". That not only gives the results but presents the facts that there are questions still to be answered. That really leads us all on further. During the presentation I thought, because of the asymmetry, could it be that the northern hemisphere has far more surface land than the south, though you have suggested that it is the altitude of that land that plays a role.

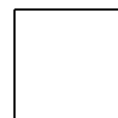
Dr. Coxon. It's possible — it's not the favoured interpretation but it is something that I want to look at. Measuring neutral wind is very difficult and I haven't worked out how to do it yet. I thank you for your kind words. I don't want anyone to think that we have solved the problem, partly because we haven't but partly because I would like more money to work on this!

The President. One thing that you pointed out was that the poles had a different offset. That means that our magnetic field is not geocentric. It really imposes a big UT variation on everything we do and I think that is very related to all that you say. Let us thank John again. [Applause.] In my Presidential address in two months I am going to be producing evidence for the Dungey cycle on an exoplanet.

The next speaker is Mark Lester who is our Senior Secretary. The title of his talk is 'Chance observations with a meteor-scatter radar'.

Professor Mark Lester. Just a comment on John's talk — there will soon be a new auroral imager flying in space, at least providing that the launch of *SMILE* goes to plan next month.

I'm going to talk about some observations taken with a meteor-scatter radar. This is about work that my colleagues Alexander Kozlovsky (Sodankylä Geophysical Observatory) and Gunter Stober at the University of Berne have done in this respect. These are observations that we saw but could not have predicted in any grant proposal. The instrument that I will talk about, *SLICE* [Sodankylä–Leicester Ionospheric Coupling Experiment], has been



operational since 2008. It's not really an ionospheric experiment but a meteor-scatter radar which tends to make observations between 80 and 100 km — that is where meteors tend to leave the bulk of their ionization trail as they fall into the atmosphere. In that region we tend to get constant measures of neutral winds.

The first observation I will talk about was triggered by one of the largest volcanic eruptions since Krakatoa. It happened on the volcano of Hunga Tonga Hunga Ha'apai in the south Pacific and observations were made in Scandinavia where there are four radars at Tromsø, Andøya, Kiruna, and Sodankylä, and *CONDOR* (Chilean Observation Network De Meteor Radars) in Peru. We got five days of data and we have used a data-assimilation algorithm. We see an eastward gravity-wave arrival, followed 48 hours later by a westward one. In the Nordic cluster you see the arrival of eastward and westward gravity waves at the same time. We can then use the five sets of observations in more detail and include a worldwide network of radars. The westward wave moved at 165 metres per second and the eastward component at 240 metres per second. That tells us that the system is acting in a way that was not anticipated. I'm fascinated by the fact that the Nordic array can see both gravity waves. Previously, such southern volcanic events could be seen only in the southern-hemisphere sector.

The second study relates to from an effect which is known as the Tromsø spiral. It was caused by the controlled destruction of a Russian military missile in 2009 December. We know from other studies such as launches of the Space Shuttle that some 350 metric tons of water vapour can be injected between 100 and 115 km on each ascent. We did not have a handle on the neutral winds in that altitude range. You would not normally expect to see anything in the Sodankylä region but from 0900 UT there are extensive clusters of apparent meteor scatter, unusual in itself, but after about 30 minutes, the occurrence rate drops right down for about 2.5 hours. In the sporadic E-layer there are events at 15 MHz. We believe that that is not associated just with neutral winds on their own. We expect to see scattering from the debris of the missile launch. A meteor scatter has a delay of about 1 second. A rocket launch is much more long-lived, so we don't think it's aurora.

In summary, this event occurred in a period of extremely low solar and magnetic activity, so we don't think it's aurora. It's unlikely that the scatter has been moved by electric fields and the observed horizontal transport by neutral winds can't explain this either. There were some suggestions from the Shuttle launches that turbulence could play some role in this and the theoretical estimation suggests that this could be the case, but for me the quenching of the scatter is a real unknown that we still have to resolve.

So, two very different chance events, which we would not have seen were we not operating this system on a continuous basis. In one case, the response to the rocket explosion, the instrument is not well suited to the study due to the limited amount of data that has been saved for each echo, such that we have no idea of the full life history of the scattering bodies. The violent volcanic eruption caused wave activity across the globe in different local-time sectors and hemispheres, so something of that nature, a 1-in-100-year event, does have significant impact elsewhere. One last point, John mentioned constellations — one of the problems with that is that the satellites have to de-orbit and when they do they leave stuff in the mid- and upper atmosphere. That is something that has to be looked at in a great deal more detail.

The President. Any questions for Mark?

Professor Kathy Whaler. Going back to the Hunga Tonga eruption — did you see any evidence for the arrival of a second wave? Was there any evidence, therefore, in your observations for dispersion?

Professor Lester. We didn't see any evidence for the second arrival, and there is a question over the dispersion of the signal. The thing is we did a straight line and there probably is a dispersion of the signal.

The President. Kathy has stolen my question! We saw the tropospheric wave at Reading three times.

Professor Whaler. Yes, we saw that in some of the pressure observations.

Mr. Horace Regnart. A little bit of prehistory from my childhood. The Krakatoa explosion is said to have knocked people unconscious on top of a cliff where they were standing 30 miles away and the sound waves being detectable going three times around the world. A rather unsophisticated precedent to your sophisticated work.

Professor Lester. Kathy just made that comment about the pressure waves that you saw. I should say that we have evidence for a land wave as well but that is a different story.

Rev. Garth Barber. You mentioned the effect of exploding missiles and the Space Shuttle — could you comment on Elon Musk's plan to launch a million satellites to process his AI?

Professor Lester. Apart from the fact that I know all my astronomical colleagues will be very unhappy, I am genuinely concerned about the impact of such a proposal. I also take John's point that if there is a scientific instrument in there we would have a fantastic data set to work with, but it's the de-orbiting from a long-term perspective of the atmosphere; the impact on the atmosphere is still troubling and that needs to be studied in detail.

The President. I think that we can take some comfort in Musk's promise that one of his automatic cars was going coast to coast, and that we are going to have a city on Mars. Neither has happened.*

Dr. Quentin Stanley. You'll find in Max Alexander's photos some photos of debris that has landed and the impact of that is quite an eye-opener.

The President. 120 bits of debris a year fall out of space at the moment.

Professor Lester. And that could change as there is a variation in the number of bits that come in depending on the solar cycle and sunspot maximum.

The President. Strangely, the thing that is working in our favour is climate change. It's cooling the upper atmosphere and reducing the drag so they don't come down quite as quickly.

The President. The Eddington Lecturer today is Dr. Kareem El-Badry. He is an Assistant Professor of Astronomy at the California Institute of Technology. His research focusses on binary stars, black holes, and unusual outcomes of stellar evolution, combining large-scale surveys, targeted observations, and stellar modelling to understand how stars and compact objects form and evolve. He earned his PhD in astrophysics from UC Berkeley in 2021 and was a Junior Fellow at the Harvard-Smithsonian Center for Astrophysics before joining Caltech in 2023. He also holds an adjunct appointment at the Max Planck Institute for Astronomy in Heidelberg, where he has been a frequent visitor since 2016. The title of his talk is 'Black holes and revelations: unseen companions in stellar binaries'.

Dr. Kareem El-Badry. I'm going to talk about astrometry — the small motion of stars on the plane of the sky — and binary stars. William Herschel, along with his sister Caroline, at the end of the 18th Century made many observations of various types of objects and often made sketches. He particularly liked double stars and compiled a catalogue of new companions to single stars mostly of the 8th to 10th magnitude, and he also noticed the motion on the plane of the sky. He assumed that the pairs of stars were chance alignments of a distant star and a nearby foreground star, and he was searching for that in order to measure a parallactic shift which he argued they should exhibit if they were at different distances. Over 25 years he re-observed some of the pairs but found that many of the pairs were physical binaries and had the same parallax. He did discover that some companions moved in curved paths around the primary star.

*[Though not coast to coast, while editing the first version of this talk for publication, I read that astrophysicist Lawrence Krauss had recently completed his "[s]econd trip up the west coast 1k miles without touching steering wheel". I remain sceptical about the latter in the near future, though; see my review of *A City on Mars* in these pages: 144, 210, 2024. — Ed.]

In the 1830s Friedrich Bessel used a heliometer to measure small angles and he observed 61 Cygni. He knew that both components were at the same distance, and he measured both stars with respect to two distant field stars. That was a difficult observation for several reasons, including the effect of a turbulent atmosphere, so he increased the number of observations to beat down the measurement error. He measured a parallax of $0''.31$ with an error of $0''.02$, which corresponds to a distance of ten light years which is within 1.5σ of the result obtained by *Hipparcos*. Bessel noted that the position angle increased two-thirds of a degree per year and calculated that the period of the star was 540 years. Today's figure is around 700 years.

Bessel then looked at Sirius, and when he examined the positions over 50 years he found that the motion was not linear and the same was happening with Procyon. Bessel came up with the bold prediction that the motion was due to an invisible binary companion. Sirius and Procyon are both accompanied by white dwarfs that are much fainter than their bright companions; the latter, however, have masses comparable to the primaries.

Modern application of the method is carried out by *Gaia*, an astrometric satellite located at the L2 Lagrangian Point which has two cameras that scan the sky every six hours. The rotation axis precesses every two months so *Gaia* scans the whole sky. *Gaia* measures every star very precisely once a month and over a period of time the linear motion of the stars can be seen. The parallaxes are also measured along with gravitational effects from any companion. The precision of *Gaia* is 0.01 mas which is the angle subtended by a human hair at a distance of 1500 km, and is also four times smaller than the image of the event horizon of the supermassive black hole in M87.

Bessel had uncertainties of a fraction of an arcsecond and could measure positions in binary-star orbits a few parsecs away. *Gaia* can measure the distances to stars a few tens of kpc away so essentially it can measure orbits across the Milky Way galaxy.

Gaia finished operations last year but over its 11-year working life it measured each star about 120 times, but so far only the first three years of data has been published. The DR4 catalogue will appear in December and will contain six years of data.

The current data release, DR3, was the first to include astrometric orbits, 200 000 of them. The colour-magnitude diagram shows that most stars are like the Sun and also close to its mass. We found 5000 cases where the companion was most likely a white dwarf like Sirius, about 50 with a neutron star, and about five with a black hole. In the last five years we have been following up on those objects and trying to characterize them in more detail. We do that *via* radial velocity using telescopes with high-resolution spectrographs. The astrometry and radial velocities can be combined to produce a Keplerian orbit.

One object which we get excited about is an object called *Gaia* BH1. The visible star is similar to the Sun and the period is half a year and it lies at a distance of about 500 parsecs. The radial-velocity measures confirm the astrometry and we find that the star has a mass $0.9 M_{\odot}$ but the companion has a mass of $9.3 M_{\odot}$ — we think that it is a black hole. Black holes come from massive stars and this object originally had $40 M_{\odot}$. When it evolved into a red supergiant it became too large to fit inside the current orbit without interacting with the companion star. We suppose that the separation between the stars was greater and the progenitor black hole expands and spirals in, releasing gravitational potential energy which could be used to eject the envelope of the massive star. All the envelope gets blown away and the companion star survives next to the core of the progenitor black hole. That, however, works only if the star gets really close to the black hole and in that case the spiral has stalled so it is difficult to explain the current situation.

Several theories have been proposed. Perhaps the massive star remained compact but the mass transfer was stable. Another possibility includes a third star — there is a massive pair of stars which run into each other and there is no expansion which would save the distant star, or maybe the black hole formed on its own and later gathered up the star gravitationally, perhaps in a cluster.

We have found some more of them. In *Gaia* BH2 the star is evolving off the main sequence. The black hole mass is $9 M_{\odot}$, the period is 3.5 years and the separation is 5 AU. Those are the only two black holes in *Gaia* DR3 but there is another, *Gaia* BH3, which has a period of 11 years and it was found during preparations for DR4. The black hole has a mass of $33 M_{\odot}$ and the star is very metal-poor. We think that the star and the black hole formed at the same time and we can see the composition of the star from its spectrum so we can see what sort of star formed the black hole (BH). We are looking for more black holes in the *Gaia* data but we can also find BH binaries from the X-ray binary systems. Most of the X-ray binaries have abundances close to solar and masses around 9 to $10 M_{\odot}$, although Cyg X-1 has $20 M_{\odot}$.

Could we have two BHs in a binary system? We know that they exist from gravitational-wave observations. My student Pranav Nagarajan has modelled a system with a star and a pair of BHs but the motion is not strictly Keplerian and orbital precession is involved. We have used very precise radial velocities from *Keck* and *VLT* to test that model but even with the most precise velocities we find no evidence for non-Keplerian motion so it looks like a single BH. We cannot strictly rule out that BH-binary model as the two objects could be very close but they would merge if the period were <1.5 days. Radial-velocity work is the only way to detect BH binaries.

The three *Gaia* BHs are the three closest BH systems that we know about. We infer that the non-accreting, non-interacting wide binaries are about ten to 100 times more common than the wide X-ray binaries. We expect to see ten X-ray-bright red giants in binaries and we are now looking at red giants associated with a radio source but most do not have a black hole associated with them.

In the case of neutron stars (NS) we have 30 nights of data to yield some orbits. We started with 50 candidates and in 21 cases we confirm the *Gaia* velocity and confirm that the companion is a neutron star based on its mass. The orbits are eccentric and the periods range from ten to 100 days. We have found that the companion stars are often enhanced in lithium (Li) and from that line we can measure the absolute abundances of Li. We don't know what produces the Li but it must be related to the neutron star. The stars must have formed co-evally. In the case of the wide star-NS binaries we think that the star will become a red giant and become X-ray bright and we compared the number of those systems with the number of X-ray-bright binaries. From the close bright X-ray systems 2 kpc away we can infer a space density and a formation rate and we find that the birth rates of the two populations are consistent. When we plot the mass distribution of NSs and BHs we find masses between 1.3 and $2 M_{\odot}$, a couple of BHs at $9 M_{\odot}$, one at $33 M_{\odot}$, and nothing in between. We are learning that those binary systems prefer to make NSs of $1-2 M_{\odot}$ or a BH which is much more massive. If we compare to other kinds of NS that we see such as radio pulsars and BHs to what we see in X-ray binaries then we find a mass bi-modality between BHs and NSs.

In December we will have *Gaia* DR4. We expect the number of binaries to increase and to have longer orbital periods. In DR4 we will be able to fit periods up to 2000 days. The orbit is consequently bigger and the binaries can be seen further away. In DR4 we simulate that we will get 30 BHs mostly at longer orbital periods. We are now writing proposals to get observing time in December mostly for high-resolution spectroscopy and hopefully we'll have lots of spectra of BH systems in DR4.

There is a mission called *Roman* which launches in September this year and also will be good at finding BHs. It is doing a Galactic-bulge survey and will find stars that are gravitationally lensed by BHs passing in front of them. The star gets brighter and deviates in position on the sky. It will also look at other parts of the sky and we will use it to extend the *Gaia* baseline. We think that combining *Roman* astrometry with *Gaia* astrometry will double the known number of BH binaries.

The President. Thank you very much. Questions?



Professor Richard Ellis. The mass gap between the neutron stars and black holes: I presume that we understand it at some level but recently there were some claims that there was an object within the gap. I think it is a neutron star. Do we understand that object?

Dr. El-Badry. It's debatable whether we understand the gap but there are some reasons why we should get a gap. At the end of the star's life you have a core collapse and then you have a supernova, or your supernova fails and a bit of material falls on the star and that is why you get a gap. There are objects that are $2\text{--}3 M_{\odot}$ stellar objects in a globular cluster and we have radio timing of the companion. It could be a massive neutron star or it could be a low-mass black hole. I guess it's a massive neutron star. From the gravitational waves we have a better-sampled mass function so the answer is probably not that there is nothing in the gap but just an order of magnitude fewer objects in the gap than there are on either side. Nature usually finds a way to make objects in all areas of parameter space, it's just that some parts work better than others.

Professor Phil Charles. I was most intrigued by the enhanced Li in some of your neutron stars. That happens to be related to the formation from the SN event but the Li will actually be absorbed and decay with time which implies that those are young objects. Have you looked for radio SN remnants or faint examples of that to support the idea of the recent production?

Dr. El-Badry. We have looked in the radio and not seen anything. We think that those are pretty old stars because they are metal-poor and we didn't find any young stars with those values. Because they are metal-poor they have very thin convective envelopes so anything you dump on the surface effectively stays on the surface, it doesn't get mixed in, and we think the Li will survive for a long time. You can produce Li in a SN in a super AGB star. Young NSs produce high-energy particles which will bombard the surface of the companion and those high-energy particles can make carbon and oxygen by spallation.

The President. Thank you again for a wonderful lecture. [Applause.] To close, nobody in Washington is measuring how thick your hair is! [Laughter.]

I give notice that the AGM will be here on May 8 and the next A&G meeting will be on April 10th in Bristol. Thank you again for the wonderful talks.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 32:
THE ECCENTRIC F-TYPE SYSTEM EY CEPHEI

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EY Cep is a detached eclipsing binary containing two Fo V stars in an orbit with a period of 7.97 d and an eccentricity of 0.440. We determine the physical properties of the system using light-curves from the *Transiting Exoplanet Survey Satellite* and published spectroscopic measurements. We find masses of $1.523 \pm 0.008 M_{\odot}$ and $1.494 \pm 0.014 M_{\odot}$, radii of $1.491 \pm 0.004 R_{\odot}$ and $1.446 \pm 0.004 R_{\odot}$, and temperatures of 7070 ± 170 K and 6990 ± 150 K. We calculate the system's distance to be 300.3 ± 3.8 pc, in excellent agreement with the *Gaia* DR3 parallax, and estimate its age to be 220 Myr. We find no evidence for pulsations, but there are hints of variation in the eclipse times potentially attributable to a third body on a longer-period eccentric orbit.

Introduction

Eclipsing binary star systems (EBs) are of fundamental importance to astrophysics as a direct source of mass and radius measurements of normal stars. Detached eclipsing binaries (dEBs) are particularly useful as their components have evolved as single stars so can be used to check and calibrate theoretical models of single-star evolution^{1,2}. The current work is part of a series of papers³ in which primarily space-based light-curves⁴ are used to refine the properties of known dEBs. The properties of those objects are collected in the *Detached Eclipsing Binary Catalogue*⁵ (DEBCat^{*}).

In this work we present an analysis of EY Cephei (see Table I), which contains two Fo V stars on an eccentric orbit. The target was originally chosen as possibly containing pulsating stars, although that was not confirmed. We summarize the observational history of the system, present the new observational material, analyse the available light- and radial-velocity (RV) curves, and determine the physical properties and age of the component stars.

EY Cephei

Eclipses in the EY Cep system were reported in 1958 by Strohmeier⁶. Strohmeier⁷ gave an orbital period of 5.51672 d, which has turned out to be incorrect. Lacy^{8,9} reported the discovery of double lines in the spectrum of EY Cep, with the lines from the two stars having approximately equal widths and depths. Lacy¹⁰ measured its *V* magnitude, and *B* – *V* and *U* – *B* colour indices outside eclipse. Lacy¹¹ provided magnitudes and colour indices in the *uvby*β system.

Lacy *et al.*¹² (hereafter Lo6) presented the only detailed analysis of EY Cep published so far, including a revision and confirmation of the orbital period of 7.971 d. Their spectrographic material comprised five spectra from the 2.1-m telescope and coudé spectrometer at the Kitt Peak National Observatory (KPNO), and 47 from the 1.5-m Tillinghast reflector, échelle spectrograph, and Reticon detector at the Fred Lawrence Whipple Observatory (FLWO). Each yielded RV measurements for both stars. The projected rotational velocities were found to be $10 \pm 1 \text{ km s}^{-1}$ for both stars. From the *UBV* and *uvby*β photometry Lo6 deduced spectral types of Fo V for both components, a temperature of $T_{\text{eff,A}} = 7090 \pm 150 \text{ K}$ for star A (the star eclipsed at phase zero), and a temperature of $T_{\text{eff,B}} = 6970 \pm 150 \text{ K}$ for star B (its companion).

Lo6 obtained light-curves comprising 6907 measurements in the *V*-band using a 28-cm telescope and modelled using the EBOP code^{18,19}. They found night-to-night magnitude offsets in those data, concluded that they were likely of instrumental origin, and removed them before analysis. They determined the physical properties of the component stars and found them to be consistent with theoretical predictions for a solar metallicity and a young age (40 Myr but with a large uncertainty). Finally, they suspected δ Scuti pulsations in star A due to the night-to-night offsets and its much larger scatter in the RVs compared to those for star B.

EY Cep has been mentioned in several other works, and additional times of mid-eclipse have been published. However, Lo6 remains the only detailed analysis of the system prior to the current work.

Photometric observations

EY Cep was observed by the *Transiting Exoplanet Survey Satellite* (TESS²⁰) mission during eight sectors. Light-curves from the TESS Science Processing Center (SPOC²¹) at a cadence of 120 s are available for seven of the sectors (19, 25, 53, 59, 60, 73, and 79). Quick Look Pipeline (QLP²²) data at 200-s cadence are available for the last sector (86).

^{*}<https://www.astro.keele.ac.uk/jkt/debcats/>

TABLE I

Basic information on EY Cephei. The BV magnitudes are each the mean of 115 individual measurements¹³ distributed approximately randomly in orbital phase. The JHK_s magnitudes from 2MASS¹⁴ were obtained at an orbital phase of 0.947, which is close to but confidently before the beginning of primary eclipse.

Property	Value	Reference
Right ascension (J2000)	03 ^h 40 ^m 04 ^s .07	15
Declination (J2000)	+81°1'9".0	15
<i>Gaia</i> DR3 designation	568183560050534016	16
<i>Gaia</i> DR3 parallax (mas)	3.3202 ± 0.0135	16
<i>TESS</i> Input Catalog designation	TIC 297899564	17
<i>U</i> magnitude	10.126 ± 0.010	10
<i>B</i> magnitude	10.162 ± 0.009	10
<i>V</i> magnitude	9.795 ± 0.007	10
<i>J</i> magnitude	9.035 ± 0.030	14
<i>H</i> magnitude	8.977 ± 0.031	14
<i>K_s</i> magnitude	8.841 ± 0.020	14
Spectral type	F0 V + F0 V	12

We downloaded those data from the *Mikulski Archive for Space Telescopes* (MAST*) using the *LIGHTKURVE* package²³, with the ‘hard’ flag to reject data of lower quality. The light-curve from each sector was then converted into differential magnitudes and the median magnitude was subtracted to normalize the data to zero outside eclipse. The light-curves are shown in Fig. 1.

We queried the *Gaia* DR3 database[†] for sources within 2 arcmin of EY Cep, finding 41 including the dEB itself. The brightest of those is 5.3 mag fainter than EY Cep in the G_{RP} band, suggesting that contamination of the *TESS* light-curve by nearby stars is negligible.

Light-curve analysis

The *TESS* light-curves for each sector all have full coverage of at least two primary and two secondary eclipses, with the exception of sector 73 for which there are two primary but only one secondary eclipse. We therefore modelled the light-curves from each sector independently. Prior to that, we extracted the data for each fully-observed eclipse from the *TESS* light-curves in order to reject data which were not useful but would still incur computational overhead. We included an additional 0.2 d of data before the start and after the end of each eclipse, to which we fitted a straight line. That fit was then subtracted from the data to normalize each eclipse to zero differential magnitude.

The light-curve for each sector was then modelled using version 45 of the *JKTEBOP*[‡] code^{24,25}. We fitted for the orbital period (P), a reference time of primary minimum (T_0) selected as the primary eclipse closest to the midpoint of the sector, the sum and ratio of the fractional radii ($r_A + r_B$ and $k = r_B/r_A$), the central-surface-brightness ratio (J), third light (L_3), and orbital inclination (i). We included orbital eccentricity (e) by fitting for $e \cos \omega$ and $e \sin \omega$, where ω is the argument of periastron.

Limb darkening (LD) was incorporated using the power-2 law^{26–28}. The two stars have very similar properties so we used the same LD coefficients for both. We fitted for the linear coefficient (c) and fixed the nonlinear coefficient (α) at a theoretical value^{29,30}. The best fit

*<https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

†<https://vizier.cds.unistra.fr/viz-bin/VizieR-3?-source=I/355/gaiadr3>

‡<http://www.astro.keele.ac.uk/jkt/codes/jktebop.html>

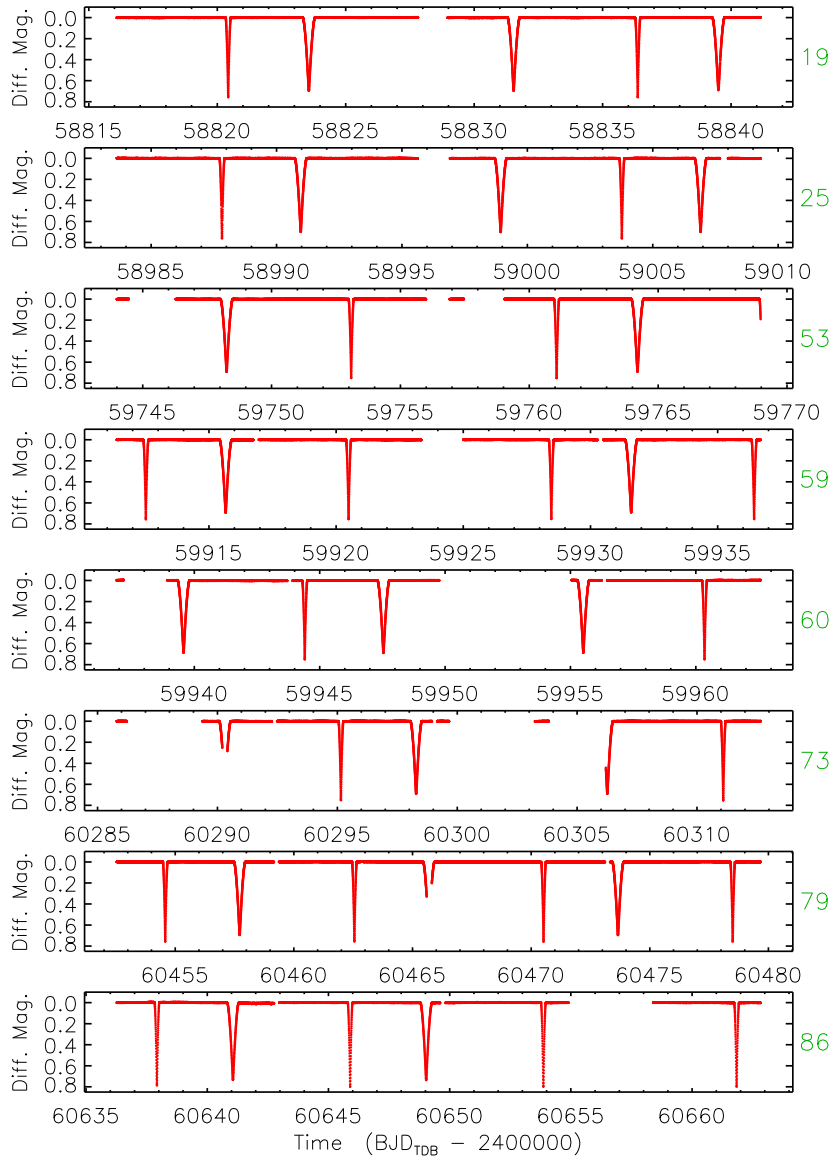


FIG. 1

Light-curves of EY Cep from all eight *TESS* sectors. The flux measurements have been converted to magnitude units and the median subtracted.

for the data from sector 19 is shown in Fig. 2; other sectors are similar. The fitted parameters are given in Table II and are the unweighted mean of the individual values for each parameter.

We determined three sets of uncertainties for the fitted and derived parameters. The first

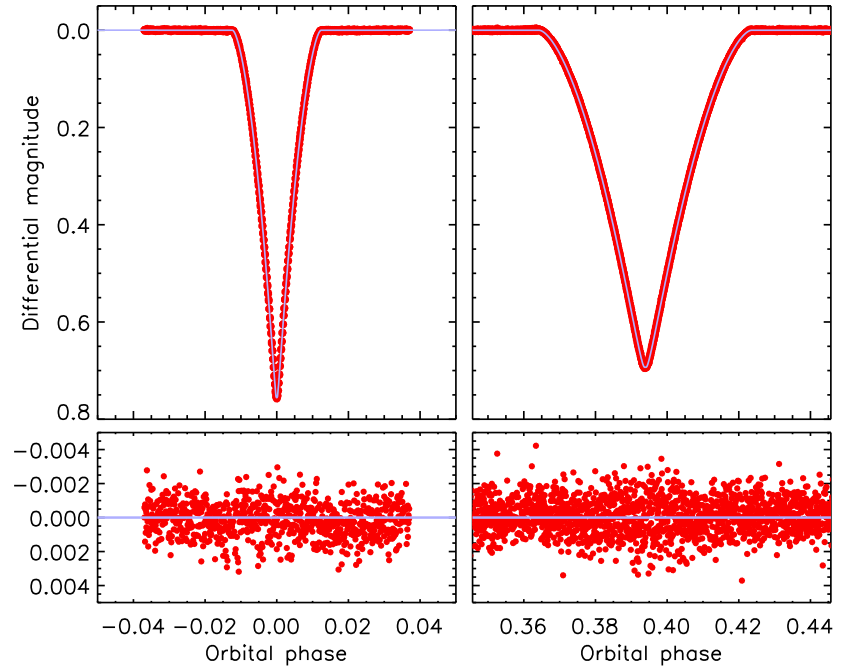


FIG. 2

JKTEBOP best fit to the light-curve of EY Cep from TESS sector 19 for the primary eclipse (left panels) and secondary eclipse (right panels). The data are shown as filled red circles and the best fit as a light-blue solid line. The residuals are shown on an enlarged scale in the lower panels.

TABLE II

Photometric parameters of EY Cep measured using JKTEBOP from the TESS light-curves. The error bars are 1σ and are the largest of three options calculated for each parameter. Values from Lo6 (their table 6) are shown for comparison; the two bracketed quantities came instead from their table 5.

Parameter	This work	Lo6
<i>Fitted parameters:</i>		
Orbital inclination ($^{\circ}$)	89.903 ± 0.013	89.89 ± 0.03
Sum of the fractional radii	0.12102 ± 0.00008	
Ratio of the radii	0.9701 ± 0.0017	1.005 ± 0.012
Central-surface-brightness ratio	-0.9577 ± 0.0010	0.931 ± 0.005
Third light	-0.0001 ± 0.0149	
$e \cos \omega$	-0.15291 ± 0.00028	-0.14897 ± 0.00013
$e \sin \omega$	0.41275 ± 0.00037	0.4224 ± 0.0017
LD coefficient c	0.597 ± 0.014	
LD coefficient α	0.4555 (fixed)	
<i>Derived parameters:</i>		
Fractional radius of star A	0.06143 ± 0.00006	0.0603 ± 0.0004
Fractional radius of star B	0.05959 ± 0.00008	
Light ratio ℓ_B/ℓ_A	0.9013 ± 0.0028	0.961 ± 0.026
Orbital eccentricity	0.44017 ± 0.00035	(0.4415 ± 0.012)
Argument of periastron ($^{\circ}$)	110.328 ± 0.041	(109.78 ± 0.07)

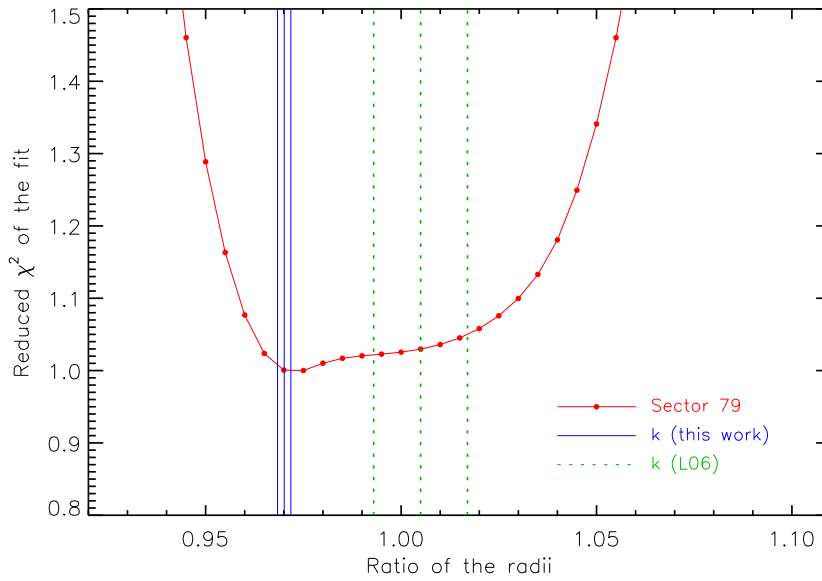


FIG. 3

Quality of the fit, χ^2_{ν} , to the *TESS* sector 79 light-curve of EY Cep as a function of ratio of the radii, k (red lines and filled circles). The blue solid lines indicate the value and its uncertainty from the current work (based on all eight *TESS* sectors, not just sector 79), and the green dotted lines show the best value and uncertainty found by Lo6.

set is the r.m.s. scatter of the fitted values from the different sectors, the second set was obtained by running 1000 Monte Carlo simulations for each sector, and the third set was from running residual-permutation simulations for each sector³¹. We took the largest of the three options for each parameter, which in most cases was from the scatter of the fitted values. Those are also given in Table II. We did not divide by $\sqrt{8}$ to obtain the standard error because that led to error bars which are smaller than the limits to which our modelling code has been proven³².

The parameter values we measured are significantly different from those of Lo6. The latter are collected in Table II for convenience, along with our own. The most obvious discrepancies are for k and the light ratio, which of course are physically related. We investigated that by running a set of JKTEBOP fits to the data from *TESS* sector 79, with k fixed at a grid of values between 0.6 and 1.5. The quality of the fit is shown in Fig. 3, together with the k found in this work and by Lo6 (Table II). It can be seen that our k measurement is much more precise and also significantly different from that of Lo6, driven primarily by the much better quality of the *TESS* data.

The light ratio we find (0.901 ± 0.003) does not match either of the spectroscopic light ratios measured by Lo6 (1.06 ± 0.06 from their KPNO spectra and 1.32 ± 0.02 from their FLWO spectra). It is also moderately different from Lo6's photometric value (0.96 ± 0.03), which can be attributed to the different k we obtain as discussed above. The two spectroscopic light ratios are inconsistent with each other and with the photometric values, as noted by Lo6. A plausible explanation would be that one component is a metallic-lined star, thus the ratio of spectral-line strengths differs from the continuum light ratio, but that is ruled out by Lo6's observation that the two stars are chemically normal. The discrepancy remains unexplained.

TABLE III

Times of mid-eclipse for EY Cep and their residuals versus the fitted ephemeris.

<i>Orbital cycle</i>	<i>Eclipse time (BJD_{TDB})</i>	<i>Uncertainty (d)</i>	<i>Residual (d)</i>	<i>TESS sector</i>
-139.0	2458836.367724	0.000012	0.000057	19
-118.0	2459003.768820	0.000014	-0.000003	25
-23.0	2459761.059727	0.000012	-0.000039	53
-2.0	2459928.460878	0.000007	-0.000043	59
0.0	2459944.403874	0.000012	-0.000015	60
44.0	2460295.149249	0.000012	0.000082	73
66.0	2460470.521820	0.000007	0.000013	79
89.0	2460653.865933	0.000010	0.000003	86

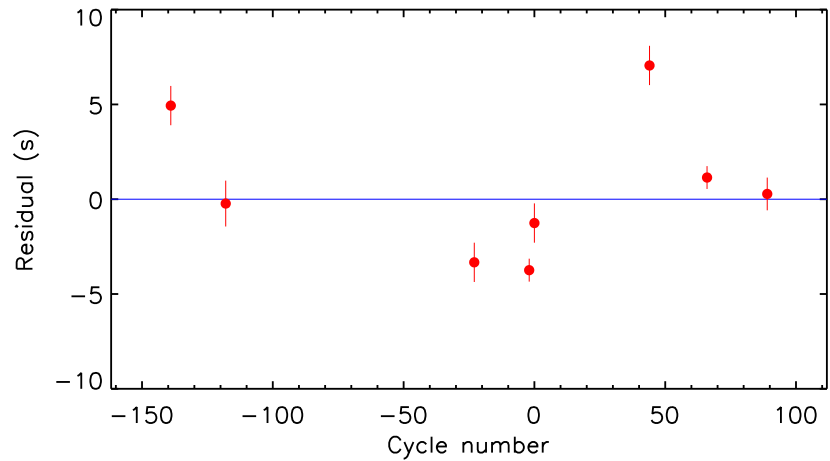


FIG. 4

Residuals of the times of minimum light from Table III *versus* the best-fitting ephemeris. Red open circles indicate the values calculated from *TESS* data in the current work. The blue solid line indicates a residual of zero.

Orbital ephemeris

We determined a new orbital ephemeris for EY Cep using the times of effective primary eclipse found in the fits to the individual *TESS* sectors above. A straight line fitted to these data gives the ephemeris

$$\text{Min I} = BJD_{TDB} \ 2459944.403889(14) + 7.97148361(20)E \quad (1)$$

where E is the number of cycles since the reference time of minimum and the bracketed quantities indicate the uncertainty in the final digits of the previous number. The times of minimum and residuals of the fit are reported in Table III.

The residuals of the fit are plotted in Fig. 4 and show a scatter which is small in absolute terms (the r.m.s. is 3.6 s) but bigger than the error bars. The reduced χ^2 of the fit is 15.3 and there are hints of a periodic variation which could be explained by the light-time effect due to a third body on an eccentric orbit. The uncertainties in the ephemeris above have been

increased by $\sqrt{15.3}$ to account for that excess scatter. Further measurements are required to investigate the possible light-time effect.

We tested including eclipse timings from the literature to see if those might support the third-body hypothesis. The measurement errors from the seven individual timings given by Lo6 are too large to constrain the solution, given the high quality of the *TESS* data. The time system used for those timings is also not clear: they are labelled as HJD but without indication of whether they are UTC or TDB*. The difference between those two time systems is much larger than the size of the prospective light-time effect. Five more timings exist in the literature^{33–37} but all are for secondary eclipses and have a larger measurement error than the Lo6 timings. We thus leave confirmation or refutation of that effect to future work.

Radial-velocity analysis

Lo6 tabulated RVs for both components of EY Cep from their five KPNO spectra and 47 FLWO spectra. We reanalysed the RVs using *JKTEBOP*, fixing the values of P , T_0 , $e \cos \omega$, and $e \sin \omega$ to those in Table II. We fitted for the velocity amplitudes (K_A and K_B) and the systemic velocities ($V_{\gamma,A}$ and $V_{\gamma,B}$) of the two stars. We also allowed for an orbital-phase offset, which in all cases was very small and consistent with the difference between the TDB time-scale used in the current work and the UTC time-scale probably used by Lo6. We calculated orbits based on only the FLWO RVs, and on all RVs assuming the two sources are on a consistent velocity scale. The results are given in Table IV and a representative orbit is plotted in Fig. 5

All spectroscopic orbits in Table IV agree within their uncertainties, making it unimportant which is adopted for the rest of the analysis. We chose to use the orbits based on only the FLWO data — to avoid exposure to any velocity offsets between the two spectrographs — and with separate systemic velocities for the two stars. Our results confirm the observation of Lo6 that the scatter of the RVs for star A is much larger than that for star B.

Physical properties and distance to EY Cep

We calculated the physical properties of EY Cep using our usual method: the *JKTABS-DIM* code³⁸ fed with the results of the photometric and spectroscopic analyses above. The properties are collected in Table V. The masses of the two stars are measured to 0.5% and 0.9% precision, respectively, and agree very well with the values from Lo6 (as expected). The radii are measured to 0.3% precision and do not agree with those from Lo6 because we found a smaller k (as discussed above).

Lo6 found a mean effective temperature of the system of 7030 ± 150 K. We determined individual temperatures from that, the radius and surface-brightness ratios, and the equations derived in our study of V454 Aur³⁹. The values are also given in Table II.

Table V also reports the synchronous and pseudo-synchronous rotational velocities of the stars. The former is the rotational velocity giving one stellar rotation per orbital period. The latter is the rotational velocity resulting in synchronous rotation at periastron, calculated using equation (44) from Hut⁴¹. Because tidal effects are strongest at periastron (as that is when the stars are closest), it is expected that the stars are rotating pseudo-synchronously. However, their measured rotational velocities are consistent with synchronous rather than pseudo-synchronous rotation. The reason for that is unclear. The age of the system (see below) puts it much older than the rotational synchronization time-scale (40 Myr) but much younger than the orbital circularization time-scale (20 Gyr) according to the theory of Zahn⁴².

We determined the distance to the system using the *UBV* magnitudes from Lacy¹⁰, the *JHK_s* magnitudes from 2MASS¹⁴ transformed onto the Johnson system, and the bolometric corrections from Girardi *et al.*⁴³. A small interstellar reddening of $E(B - V) = 0.025 \pm 0.015$

*TDB stands for *Temps Dynamique Barycentrique*, Barycentric Dynamical Time.

TABLE IV

Spectroscopic orbits for EY Cep from the literature and from the current work. All quantities are given in km s⁻¹. We give both sets of orbits from Lo6 (a) based on all (KPNO and FLMO) RVs; (b) based on all RVs and times of minimum light. The orbits from the current work were calculated using either the FLMO RVs or all RVs.

Source	K_A	K_B	V_γ	$V_{\gamma,A}$	$V_{\gamma,B}$	σ_A	σ_B
Lo6 (a)	85.27 ± 0.41	86.64 ± 0.15	-6.79 ± 0.10			2.07	0.64
Lo6 (b)	85.23 ± 0.39	86.62 ± 0.14	-6.77 ± 0.10				
This work (FLMO)	84.94 ± 0.39	86.57 ± 0.13		-6.28 ± 0.28	-6.90 ± 0.09	1.91	0.65
This work (FLMO)	85.06 ± 0.42	86.58 ± 0.14	-6.84 ± 0.09			2.00	0.65
This work (KPNO + FLMO)	85.07 ± 0.38	86.56 ± 0.13		-6.27 ± 0.27	-6.89 ± 0.10	1.88	0.76
This work (KPNO + FLMO)	85.22 ± 0.38	86.58 ± 0.13	-6.83 ± 0.09			1.96	0.76

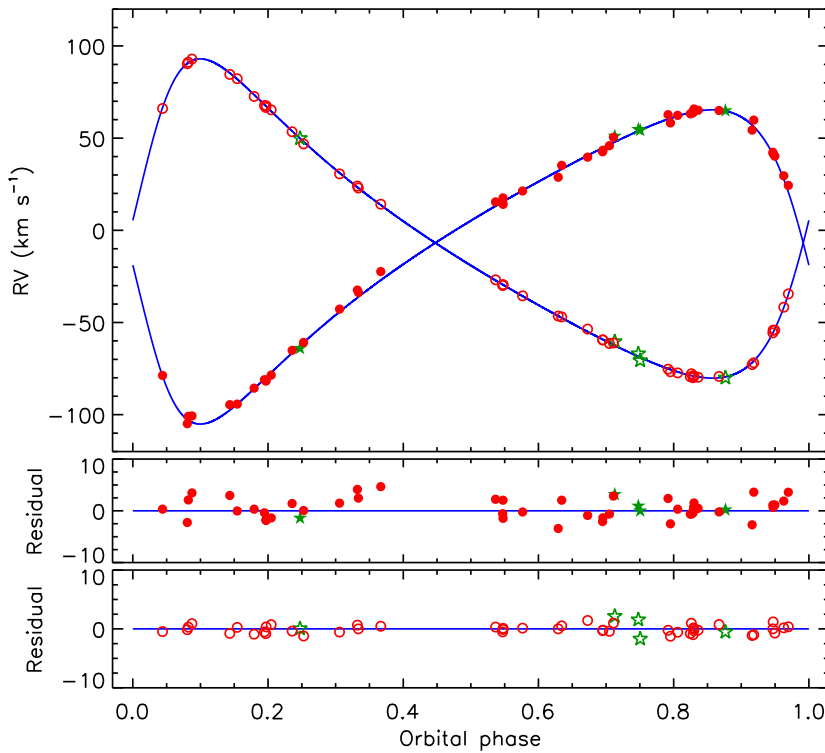


FIG. 5

RVs of EY Cep from Lo6 compared to the best fit from JKTEBOP (solid blue lines). The RVs for star A are shown with filled symbols, and for star B with open symbols. The RVs from the FLWO spectra are shown as red circles, and from the KPNO spectra as green stars. The residuals are given in the lower panels separately for the two components.

was needed to bring the optical distances into agreement with the infrared ones. Our final distance measurement is from the K -band and is 300.3 ± 3.8 pc, which is in excellent agreement with the distance of 301.2 ± 1.2 pc from inverting the *Gaia* DR3 parallax.

We compared the masses, radii, and temperatures of the components of EY Cep to the predictions of the PARSEC 1.2 evolutionary models⁴⁴. The mass–radius relation defined by the two stars is steeper than that predicted by the models, but agreement within 1σ can be obtained for a metal abundance fraction by mass of $Z = 0.020$ and an age of 220 Myr. The predicted temperatures for that age and Z are approximately 50 K higher than observed, so are well within the error bars. Our results here differ from those of Lo6, who required the system to be on or around the zero-age main sequence in order to explain their measurement of a larger radius and lower surface gravity for star B *versus* star A.

Summary and conclusions

EY Cep is a dEB containing two Fo V stars in an orbit of period 7.97 d and eccentricity 0.44. We have determined the physical properties of the component stars using light-curves from eight *TESS* sectors and the RVs from Lo6. The masses are measured to 1% and the

TABLE V

Physical properties of EY Cep defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 40).

Parameter	Star A	Star B
Mass ratio M_B/M_A	0.9811 ± 0.0047	
Semimajor axis of relative orbit ($R_\odot^N$)	24.265 ± 0.058	
Mass ($M_\odot^N$)	1.523 ± 0.008	1.494 ± 0.014
Radius ($R_\odot^N$)	1.4906 ± 0.0039	1.4460 ± 0.0040
Surface gravity (log[cgs])	4.2740 ± 0.0011	4.2921 ± 0.0023
Density ($\rho_\odot$)	0.4600 ± 0.0017	0.4942 ± 0.0023
Synchronous rotational velocity (km/s)	9.461 ± 0.025	9.177 ± 0.025
Pseudo-synchronous rotational velocity (kms/s)	27.104 ± 0.073	26.293 ± 0.076
Effective temperature (K)	7070 ± 150	6990 ± 150
Luminosity log($L/L_\odot^N$)	0.699 ± 0.037	0.653 ± 0.037
M_{bol} (mag)	2.99 ± 0.09	3.11 ± 0.09
Interstellar reddening $E(B - V)$ (mag)	0.025 ± 0.015	
Distance (pc)	300.3 ± 3.8	

radii to 0.3%. We find the less massive star to have a smaller radius than its companion, as expected from stellar-evolution theory, resolving a discrepancy found in previous work. Our measured distance to the system agrees well with that from the *Gaia* DR3 parallax. The properties of the stars are consistent with theoretical predictions for a slightly super-solar metallicity and an age of 220 Myr. There is a hint of periodic variation in the times of minimum light suggestive of the light-time effect from a third component on an eccentric orbit.

Our original interest in this object was piqued by the possibility of pulsations in its light-curve. We investigated that by fitting the most suitable dataset, *TESS* sectors 59 and 60, with JKTEBOP and calculating a periodogram of the residuals. The highest frequency in the amplitude spectrum was at 0.546 d^{−1} and had an amplitude of 0.26 mmag and a signal-to-noise ratio of 4.4. That signal-to-noise ratio is below that required for the detection to be significant⁴⁵. We therefore analysed the data from sectors 79 and 86 as well to see if they could confirm the detection. We did not find the signal present in either sector. We conclude that pulsations are not detectable in the currently available data of EY Cep.

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^{*}<https://www.cosmos.esa.int/gaia>

[†]<https://www.cosmos.esa.int/web/gaia/dpac/consortium>

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TEARS OF ANDROMEDA: THE CELESTIAL SOLUTION TO AN
EARTHLY MYSTERY

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The abandonment of the American merchant brigantine *Mary Celeste* in 1872 November remains the most celebrated unsolved mystery in maritime history. Found adrift and crewless in the North Atlantic with her cargo undisturbed and her ample provisions intact, *Mary Celeste* has resisted explanation for 150 years. Every theory advanced so far fails on one ground or another. Most require us to imagine that her captain, Benjamin Briggs, an experienced and highly regarded mariner, behaved irrationally or incompetently.

This paper solves the mystery and restores Captain Briggs's reputation. It identifies, for the first time, the singular essential clue concerning the most probable date of *Mary Celeste*'s abandonment. For a century and a half, investigators have overlooked the fact that an atmospheric phenomenon of stupendous scale was observed and documented worldwide on that exact same date. Drawing on modern scientific knowledge and reviewing the evidence in the light of this fact, the paper explains what may have happened to *Mary Celeste*.

'The game is afoot': A star-crossed encounter

On the morning of 1872 December 4, British brigantine *Dei Gratia* encountered a vessel behaving strangely some 600 miles west of Portugal. The slowly rotating mystery ship was *Mary Celeste*, an American merchant brigantine one month out of New York, bound for Genoa with a cargo of 1701 barrels of industrial alcohol.

Dei Gratia's captain, David Morehouse, knew *Mary Celeste*'s captain personally and was immediately alarmed. He sent a boarding party. What they found has puzzled the world ever since. *Mary Celeste* was intact and seaworthy. Her cargo, undisturbed. Food, water, and provisions were ample. The crew's personal belongings were there — clothing, pipes, the captain's pocket watch — but the ship was utterly deserted. Captain Benjamin Briggs, his wife Sarah, their two-year-old daughter Sophia, and seven crewmen had simply vanished without a trace. No bodies were ever found.²⁻⁵

The clues they left behind were maddeningly contradictory. The ship's one lifeboat was gone, and the marine chronometer and sextant were missing — suggesting deliberate, cautious preparation to leave. Yet personal valuables remained — suggesting sudden, urgent departure. A length of rope trailed in the water behind *Mary Celeste*, which to investigators meant only one thing: the lifeboat must have been tethered to the ship. The binnacle — the housing for the ship's compass — had been knocked from its mounting, compass glass shattered. Water had found its way throughout the ship; everything in the cabins was wet, the skylight open to the sea air.³ Yet she remained entirely seaworthy. The ship's log slate — the chalkboard on which Briggs made his navigational notations — showed *Mary Celeste*'s last recorded position as six nautical miles northeast of Saint Mary's Island in the Azores on November 25th. She was discovered one week later.⁶

Mary Celeste had drifted, crewless, for some number of the days in between. How many is not known precisely. But if she had continued eastward under sail for a day or two after pausing near Saint Mary's, and then drifted with the currents for about a week, that would



FIG. 1

An engraving of *Mary Celeste* as she was found abandoned. Artist unknown.

easily account for her position when she was spotted by Captain Morehouse.⁶ So, a tragedy may likely have occurred on or about the evening of 27 November. I ask you now to make careful note of that date: 1872 November 27. It is historically significant — and in a directly relevant way.

Every explanation that has been suggested — piracy, mutiny, waterspout, cargo explosion, insurance fraud — fails on one ground or another, and usually on several grounds. Most require us to imagine Captain Briggs behaving incompetently, even irrationally. That is an assumption his professional record does not support. He was experienced, respected, and devout — a man who by all accounts kept a steady head. He brought his wife and daughter aboard, which tells us something about his confidence in his own seamanship.

The question, then, is not merely what happened, but what on Earth could possibly have been terrifying enough to justify the captain's decision to abandon ship?

'When you have eliminated the impossible': The last extremity

No experienced mariner abandons a seaworthy ship for a small open boat in the Atlantic without overwhelming reason. A ship not sinking, a ship not engulfed in uncontrollable fire, a ship that is trim and navigable, is shelter, stability, and survival. The lifeboat is a last resort. Whatever drove Benjamin Briggs off *Mary Celeste* and into that small boat with his family and crew, it was something he judged to be far more dangerous than the expanse of ocean around them. On-board calamities would have been confronted and remedied on board. External threats such as typhoons or seaquakes would have been far more threatening



in a lifeboat.

There is only one circumstance in which abandoning such a seaworthy ship into a small open boat on a vast ocean becomes obviously the only rational choice — and that is if the seaworthy ship herself has become the target of an attack. What might an attack have looked like? Flashes in the darkness or fog. The crack and boom of naval guns. The splash of shot in the water nearby. And the terrible uncertainty. Is this aimed at us? Will the next salvo rupture the top deck or hull? Are we sitting on 1700 barrels of combustible cargo that is about to become our funeral pyre?

This is at first glance a very plausible scenario. The waters Captain Briggs was crossing were not without menace. Spain was in a civil war in 1872, and the routes sailed may well have served arms smugglers supplying one faction or another. A merchant brigantine running in the dark might conceivably have attracted the attention of vessels enforcing an arms blockade.

But the scenario fails for one insurmountable reason: no record of any such attack exists. No naval warship ever reported such an engagement. No government acknowledged one. At the lengthy and meticulous salvage hearings in Gibraltar, no whisper of a military explanation for *Mary Celeste*'s abandonment ever surfaced.³

And so, we are forced to look elsewhere. But if a naval attack is the one thing that would drive a competent captain to order his people off a seaworthy ship, and no such attack by human hands occurred, then we must ask: could there be some natural phenomenon that has, in every practical respect, the same impact on human observers? Does something natural replicate so precisely the flash, the concussion, the sustained thunder of naval gunfire as to be, for every purpose that mattered to Benjamin Briggs, indistinguishable from a naval attack?

Volcanism will not do. Briggs would have known of volcanoes, and he would not have thought for a moment that some distant reverberation or crimson glow imperilled his ship. A seaquake will not do either. There is simply no phenomenon known to occur on this Earth that produces such terrifying war-like flashes, blast, turbulence and prolonged, rolling cannonade. We are at an end. Or . . . are we? Perhaps the phenomenon we are looking for is *not of this Earth*.

'Whatever remains, however improbable, must be the truth': Fire from the heavens

Nearly five years before the fateful voyage of *Mary Celeste* — or, to be precise, at 7:00 pm local time on the evening of 1868 January 30 — residents of a quiet Polish village saw the sky suddenly aglow.⁷ Neighbours' houses, people thought, must be aflame. Then came the sound — a sustained, rolling thunder, like cannon fire, that went on and on, boom after boom, long after any single explosion should have faded into silence. People ran out into the streets. What was happening? Who was firing cannon? Where were the flames?

Then, stones fell. Thousands of them. Descending across the snow-covered countryside were tiny fragments of iron and rock from beyond the atmosphere, an estimated 68 780 of what have come to be known as 'Pultusk peas,' the largest number of meteorite fragments ever recorded.^{7–9} These were the shattered remnants of a meteoroid that had screamed through the sky and detonated in the air above Poland. Residents of Pultusk had witnessed what we now call a meteoric airburst. They had mistaken the flash for fire and the rolling echo, sonic booms, and secondary explosions for artillery. They simply had no other framework, no other word for what they were seeing, and no prior experience of anything like what they had witnessed.

Neither did anyone else in 1868. Nor, for that matter, in 1872.

But today, we know all about these phenomena. On 2013 February 15, a super bolide — a meteoroid estimated at twenty metres across and half a million tons — entered the skies over Chelyabinsk, Russia. Travelling at nearly 40 000 miles per hour, it did not reach the

ground. It slammed into the pressure built up by the lower atmosphere and exploded as if it had struck an impenetrable wall, at an altitude of about 18 miles. The explosion released energy equivalent to thirty times the force of the atomic bomb dropped on Hiroshima. The flash was brighter than the Sun. Windows shattered across six cities. Nearly 1500 people were injured, most by flying glass. The shockwave had arrived silently — travelling faster than sound — well before the roar of the thunderous detonation that rattled buildings across thousands of square miles.¹⁰

And Chelyabinsk was not even a large event by cosmic standards! In 1908 June, something far more powerful detonated above the remote Tunguska river basin in Siberia — flattening approximately 2000 square kilometres of forest, scorching trees for miles in every direction, and generating a shockwave felt hundreds of miles away. Eyewitnesses reported a blinding column of fire, searing heat, and a blast that knocked people from their feet. To this day, no impact crater has been found. Whatever it was, it never reached the ground.¹¹

Pultusk, Chelyabinsk, and Tunguska were visitors from outer space — meteoroids that entered our atmosphere without warning, without precedent in human records. All produced, in every practical respect, the flash, the concussion, and the sustained cannonade of war that no earthly natural phenomenon can replicate.

And another thing we know today that nobody could have imagined in 1872 is how frequently such events occur. Satellite monitoring in recent decades has revealed that meteoric airbursts of significant energy occur roughly thirty times each year, on average.^{12,13} The great majority pass entirely unwitnessed over the vast oceans and uninhabited wilderness that cover most of our planet. But back in the 19th Century, the idea that even a single large extraterrestrial body, let alone many of them each year, could detonate in the atmosphere with the force of a naval bombardment and leave no trace was so far outside the experience of any investigator — maritime, legal, or scientific — that it simply could not occur to them to look for it.

But did such an airburst occur over the Atlantic Ocean east of the Azores in 1872 November? Let us now look more closely.

Andromeda's tears: The comet that died

I invite you now to travel back with me in time and place again — not to the North Atlantic in 1872, but much further back, in time, and very, very much further, in space — to meet a comet, and to understand what became of it.

In 1772, French astronomers Jacques Montaigne and Charles Messier independently discovered a faint smudge of light moving slowly against the stars. It was unremarkable at first, just one of many comets that were catalogued in that golden era of celestial inventory. It was later named for Wilhelm von Biela, an Austrian army officer who observed it in 1826 and was the first to recognize that it was a periodic visitor, one that returned to the inner Solar System every six-and-one-half years. Astronomers immediately began to look forward to its next appearance. It was, in the language of the observatory, a known quantity.^{14–16}

But it made astronomers uneasy. The comet's path was known to intersect Earth's path, and in 1832 that fact was enough to send the popular press into hysteria. Rumours flew that a world-ending collision was imminent. A Parisian play of the time featured a character announcing that the world was about to be turned to ashes. Astronomers calmly reassured the public that Earth and comet would miss each other that year by a full month.^{17,18} The paths did cross. But, at least for the return of 1832, the Earth was still safe.

However, in 1846, the known quantity did something quite unexpected, something no comet had ever before been observed to do. It split in two.^{14–16} It was now a pair of large observable chunks, quite unimaginatively designated 'Comet A' and 'Comet B.'

Astronomers watching through their telescopes that winter saw the pair of glowing fragments travelling side by side through space, like companions on a long journey. The couple



FIG. 2

Shower of Andromedids, 1872 November 27th, as observed over France. From Amedée Guillemin, *Le Ciel*, Paris, 1877.

returned together in 1852, just a little further apart and still visible. And then, they did not return at all. Neither fragment could be found on their predicted return in 1859 — an unfavourable year for observation in any case. The return of 1866 was eagerly anticipated and carefully watched from observatories across Europe. The sky was empty.^{14–16,19} Astronomers, with one exception, gave up in despair. Biela's Comet — both parts of it — had simply ceased to exist as a coherent body. It had, astronomers concluded, disintegrated into a vast dispersing cloud of fragments, dust, and debris stretching along its former orbital path. It took on the new official designation 3D/Biela — the 'D' standing for disappeared, the '3' marking it as only the third periodic comet ever identified. It was the first to vanish entirely.^{14–16}

What no one yet knew was where its debris had gone, or what would happen when the Earth crossed the path where Biela's Comet had once travelled.

Then, in the Fall of 1872, everyone found out.

The sky, as one contemporary observer described it, appeared to be on fire. From New York to London to Paris to Peking, astronomers and ordinary citizens alike stepped outside and stared upward in disbelief. Meteors — not dozens, not hundreds, but thousands upon thousands — streaked across the heavens in a display that defied description. Estimates of the rate varied wildly, but a renowned English astronomer, Edward Joseph Lowe, reported that 58 600 of these meteoric 'shooting stars' fell in under five hours at the storm's peak.²⁰ It was, and remains, one of the most spectacular and intense meteor storms ever recorded in human history — the dying signature of Biela's shattered comet, its dispersed remains burning up in Earth's atmosphere in a magnificent farewell.^{14–16,20}

The meteors of that night radiated from the direction of Andromeda, the constellation

named for the princess of Greek mythology who was sacrificially chained to a rock at the ocean's edge while the sea monster, Cetus, bore down upon her. Astronomers thus named the storm 'the Andromedids'. "Stars fell like rain"²⁰ was the way a contemporary Chinese scholar described the equally Olympian scale when the Andromedids returned as predicted in 1885.

Lovers of mythology might well have been deeply moved, seeing in that evening's streaks of fire the tears of Andromeda — or perhaps even the fury of Cetus. As for the astronomers, they were deeply moved as well, and equally as awestruck. And more, they were thrilled. They had long suspected meteor showers were associated with cometary debris — and now the Andromedids had solidified that theory beyond doubt. Papers were written. Journals filled. The event was meticulously documented around the globe.

Have you surmised the significance of the date that I asked you to take note of and remember? I said that it was a historically significant date. And so, it was. 1872 November 27, just two days after Captain Briggs' final log entry aboard *Mary Celeste*, was the very peak of the first great Andromedids meteor storm, the most spectacular display of celestial fireworks ever before witnessed in human history.

'Elementary': The solution

Meteor showers are not typically associated with airbursts or with meteorite falls. The luminous streaks that delight us are almost without exception vanishingly small fragments — grains of dust and grit shed by comets long since dead. They burn away completely high in the atmosphere.

But Biela's Comet was not long since dead. It was very recently alive, fully intact. No other comet in the history of human observation had ever been observed to break apart as Biela's did in the early 1840s. Its fragments were not ancient dust ground fine by millennia of solar radiation. They were substantial enough to be observed for years. The debris field that Earth sailed through on the night of 1872 November 27 was the wreckage of a comet that had been whole within living memory. Solid fragments capable of penetrating to the lower atmosphere were present in that stream and may still be out there even today.

On the deck of his merchant brigantine carrying 1701 barrels of industrial alcohol, Captain Benjamin Briggs would have watched the same sky as the enthralled observers in New York and in Paris. He had no scientific papers. No journals. No framework of understanding that might have told him what he was witnessing. He knew only what his senses reported — and what they reported, on that extraordinary night, was unlike anything his considerable maritime experience had prepared him for. The storm sent fragments deep enough into the atmosphere to produce sounds that may have seemed quite alarming to Briggs and to his crew. An English observer on land that same evening confirmed this as he carefully noted hearing what he described as distant gunshots, several times, to the north-west.²⁰ And so certain was the German astronomer Klinkerfues that Biela's debris had made contact with the Earth and still likely contained substantial fragments that within three days he telegraphed an observatory in Madras: "Biela touched Earth on 27th. Search near Theta Centauri."^{14-16,20} He was directing southern-hemisphere observers to search the sky for surviving segments of the shattered comet. No one connected his telegram to the empty, drifting hulk of *Mary Celeste*. No one could have. The two facts lay in separate worlds — the maritime and the astronomical — each waiting for the other.

Until now.

And so, here we are. I can now explain what may have happened.

The evening of 1872 November 27 began like any other at sea. *Mary Celeste* was making progress, her cargo secure, her crew at their stations. Captain Briggs had every reason to be satisfied. The Azores were behind him. Genoa lay ahead. The North Atlantic in late

November could be brutal, but Briggs had sailed worse waters in worse weather. He was, by all accounts, exactly where he wanted to be.

But that night the sky above *Mary Celeste* was alive with shooting stars — dozens, then hundreds of luminous trails streaking across the heavens in every direction. Briggs had seen meteor showers before, though nothing like this. And then, from somewhere to the south, came faint sounds like distant gunfire. How very odd. Briggs would have frowned. Gunfire? Fireworks? Heard way out here? How very, very odd.

Then the sky to the south began to brighten.

It was not the slow brightening of a distant ship's lantern, nor the familiar arc of a shooting star. This was something else — a growing, pulsing luminescence that turned the night sky the colour of dawn, then brighter than dawn, then brighter than anything Briggs or any man aboard had ever seen. There was no sound. Not yet. Only light — savage, sourceless light, filling the sky.

Then came the heat wave. Blistering heat. Were they to burn alive? There was only a split second of such terror before their world came apart.

The pressure shockwave then struck *Mary Celeste* silently. The wall of compressed air moving faster than sound lifted the ship, heeled her savagely, and swept the deck with a torrent of white water drenching every cabin, every corner, every crevice below. Men were thrown from their feet. The binnacle — that sturdy, familiar housing of the ship's compass — was knocked from its mounting and crashed to the deck, glass shattered, compass ruined. Sails tore at their lashings. Lines ran free.

And then — silence again! A few seconds of terrible, ringing silence.

And, at last, the sound came. It came at them from everywhere and nowhere — a rolling, concussive thunder unlike anything produced by storm or sea or any natural force they had ever encountered. Not one explosion but many, boom following boom following boom, like the broadside of a man-of-war, then another, then another, going on and on and on in a sustained cannonade that simply refused to end. The night sky above was alive with streaking fire — hundreds, thousands of luminous trails burning across the heavens in every direction, the dying fragments of a comet that had begun to break apart 30 years before, millions of miles away.

Benjamin Briggs did not know about comets. He knew only what his senses told him.

His ship had been struck by something of incomprehensible violence. His compass was destroyed. Beneath his feet lay 1701 barrels of industrial alcohol. Whatever monstrous power had just hit them was still happening — the booming went on, and on, and the sky continued to burn. Was his ship a target? Would another blow rupture the hull? Would his cargo ignite?

He made his decision. It was the decision any competent, rational, experienced captain would have made with the information available to him in that moment. He ordered his family and crew into the lifeboat. He ordered a line made fast between the boat and the ship — he was not abandoning *Mary Celeste*, not yet, not permanently. He was buying distance. He was keeping his people alive until whatever was happening had passed, and then he would go back aboard.

The crew worked fast and efficiently — not in panic, but with the focussed urgency of trained sailors following a captain they trusted. The lifeboat was freed. The tether was secured. Briggs helped his wife and his two-year-old daughter into the boat. The crew followed. They pushed off from the hull of *Mary Celeste* and rowed clear, watching her, waiting.

We will never know how long they waited. We will never know what they said to one another in that small boat on that enormous sea, or what Sarah Briggs thought as she held her daughter and watched the sky burn. We know only that at some point — in a swell, in the darkness, in the confusion of that impossible night — the tether line parted.

And *Mary Celeste* sailed on without them.

She was found nine days later, crewless and intact, drifting in the light of a cold December morning — her cargo undisturbed, her provisions untouched, her log-slate carrying its last notation in a doomed man's hand.

Benjamin Briggs had not panicked. He had not lost his mind. He had not conspired in any crime, nor suffered any mutiny, nor made any foolish error. He had done exactly what any sane, sober, experienced captain would have done.

Unavoidable though it was, he had simply made the wrong choice.

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REVIEWS

Out of This World, by Peter Bond (Reaktion), 2026. Pp. 376, 24.5 × 16.5 cm. Price £25 (hardbound; ISBN 978 1 83639 199 9).

Is there a need for another book about humans' adventures in space? As the author Peter Bond recognizes in the acknowledgements, many books have been written about the Space Age, and indeed as he says those have provided much of the background information for this book. Bond's book is a bit different: although it covers much of the same ground as many others, it deals with the subject matter thematically rather than directly historically as is usual. In nine readable chapters, he deals with the particular issues and concerns that must be answered in order to enable humans to live and work in space.

There are chapters covering such topics as the development of suitable rockets, astronaut selection and training, crew health and happiness, and one emphatically dealing with the risks involved. Within each chapter a particular topic is covered semi-historically, illustrated with examples chosen from all of the nations either currently involved or who have previously contributed to the project of humanity's efforts in space. That is an interesting approach which allows for a wide-ranging appreciation of each country's ambitions and concerns, to act almost as a glimpse of national philosophies as well as building a much more global overview of human achievements in space. Some light asides from that international approach involve the food choices available to those early space pioneers — in 1982 the French astronaut Jean-Loup Chrétien brought French cuisine to the Russian three-man Soyuz spacecraft; that included jugged hare, crab soup, and lobster pilaf and must have been an interesting zero-g eating experience. Two years later the first Indian to fly in space, Rakesh Sharma, provided curry, Ravi Shankar music, and Bollywood films, another atmospheric experience. Bond does not record any menu items supplied by Britain's first astronaut, Helen Sharman, who spent a week on the *Mir* space station in 1991 — maybe a couple of those dense, calorie-rich chocolate bars manufactured by Mars, her employer at the time?

Peter Bond tells us that at the time of writing this book, in 2025, 637 people have orbited around the Earth, and another 119 have taken suborbital flights beyond the 80-km altitude recognized by the US as the boundary to space, with many of those above the higher internationally recognised 100-km Kármán line. Those people came from most varieties of humanity, ranging in age from 18 to 90 and from almost all walks of life — artists, pop singers, politicians, as well as the expected cohort of test pilots, scientists, and engineers. The one excluded exception would seem to be the poor — although as Bond reminds us, for their initial flights the Russians used the homeless as test subjects: the stray dog Laika became the first living creature to orbit the Earth, and within a few hours, the first to die there from shock and heat exhaustion. Spaceflight, as well as being dangerous, is an expensive business, so those without government funding, or who are not the CEOs or friends of one of the world's tech giants, must spend vast sums of money to buy a seat as a tourist. \$20 million is reported as the ticket price Dennis Tito, an investment manager, paid for Star City training and a trip in a *Soyuz* craft to spend eight days on board the *ISS* in 2001. At the government-employee end of the business, US astronauts do their work on a salary of up to \$152 258 per year.

Outside the relative safety of their spacecraft, astronauts have made 483 space walks, in space jargon EVA (Extra Vehicular Activity), into the raw, unforgiving, vast vacuum of space; 277 of those space walks were related to the assembly and maintenance of the *ISS* which totalled thousands of hours in that unimaginably challenging immensity. There have also memorably been 12 men who walked on the surface of the Moon, in a total of 14 excursions, some lasting more than seven hours. In Bryan Burrough's book about working in the *Mir* space station, *Dragonfly*, one astronaut describes the first moments of paralysing fear on stepping out from the spacecraft into the constant falling nothingness of orbit and the extreme effort of will required to overcome that brain-numbing effect. Some very dangerous EVAs are described by Bond — for example the Gemini astronauts getting to grips with docking procedures in preparation for the Apollo Moon-landing missions. Those exercises involved practising linking with the seemingly unreliable Agena rocket upper stage. On one occasion, NASA astronaut Richard Gordon had to grasp the Agena and bring it under control by mounting it much as a cowboy on a wild bronco. Several times astronauts have rescued stricken satellites, including on occasions those in which a live rocket motor has failed to fire. Did those guys never read the instructions on the back of a packet of fireworks about never returning to a failed firework?

For all of the seemingly everyday, run-of-the-mill nature of spaceflight which seems to exist in the current era of the space station, Bond's book constantly reminds us just how dangerous that endeavour actually has been and indeed still is. The last two chapters on going to the Moon and the risks involved in human spaceflight are engrossing reads full of

additional detail about Apollo, and other more current programmes, and it has to be said some rather ghoulish accident information.

After over 60 years of human excursions beyond the atmosphere of our planet, perhaps it is time to make an evaluation of what we have learned; what benefits have accrued to those left on the ground, and to make a judgement on whether it has all been worth the vast outlay of earthly resources and to answer the question; is the project worth continuing? With his wide experience in communicating space science, Peter Bond is perhaps a well-placed writer to do that. I lost count of the number of times he reports astronauts taking part in experiments to do with human physiology, or making use of various furnaces and electron guns to study metallurgy or crystallography, although rather few results are described. Experiments to test antibacterial and antiviral materials are apparently useful for application in the design of lift buttons. However, other than those examples and some generic statements about the development of high-tech industry and associated jobs and of course the few satellite-repair missions, this book does not address any major developments that have resulted from people doing science in microgravity.

Space research is currently being funded by national governments and the four wealthiest private-enterprise organizations the world has ever seen. This book does not tell us how any of those organizations suggest putting people into space will assist in solving the major problem currently facing humanity: the relentlessly warming planet. In the 65 years since Gagarin's flight the world annual CO₂ emissions from fossil fuels have increased from around eight billion tonnes to 38 billion tonnes and the average global temperature during the summer months has increased from 15.6 °C to 16.8 °C and with each decade that increase is accelerating. Space research has certainly been absolutely central to our knowledge of those numbers but almost exclusively by the use of sophisticated unmanned satellites. There is a very good case to be made that humanity has gained enormous benefits from the use of unmanned satellites through all sorts of remote sensing: Earth observation, astronomy, telecommunications, navigation, *etc.*, *etc.* — it is less clear that such obvious returns can be seen from manned spaceflight.

The case is not made in this book, which does not claim to be a book of analysis but a very thorough compilation of historical facts arranged in thematic chapters and as such it is a very good and often surprising resource. One must admire the research involved in assembling this detailed listing of components, processes, and interactions; there is, however, no attempt at understanding of purpose other than getting done the job of putting humans into space — there is no 'why'. It is a book of comprehensive listing and description of salient facts without addressing the current overarching purpose, and perhaps that is a true reflection of the space agencies' and private-enterprise ambitions. To use the coarse language of our times: is manned spaceflight any more than expensive 'willy wagging'?

In a book so full of facts I spotted just a few errors, and really only one worthy of comment. Unfortunately, it is on the first page of the first chapter, where we read that rocket propulsion is based on the principle of "Sir Isaac Newton's third law of *thermodynamics*" [my emphasis]. I guess an autofill-suggested word had slipped in, unnoticed by the author, it was then missed by the copy editor, and also missed again at the pre-publication proof stage. Maybe it is churlish to complain that in a book overflowing with facts I found only a few that bothered me — but but but, "Newton's third law of thermodynamics". Mr. Bond, I was "shaken and not stirred". Hopefully it will be corrected for the paperback edition of this thoroughly enjoyable, excellent compendium of the whole range of human space adventures. — BARRY KENT.

The Physics of Interstellar Travel, by Coryn A. L. Bailer-Jones (Cambridge University Press), 2026. Pp. 358, 26 × 21 cm. Price £55 (hardbound; ISBN 978 1 009 68392 8).

For many years now, unmanned space probes have been traversing the Solar System. Some have landed on, or gone into orbit around, some of the planets and their satellites. The very



earliest, *Voyager 1*, is already (since 2012) moving into the interstellar medium (ISM) but will take some 77 000 years to get to the distance of our nearest star. Manned spaceflight is currently largely confined to the Moon, although there are ambitions to build a base on Mars.

Interstellar travel is still a dream, despite *Voyager 1*, but of course if humans are ever to emulate science fiction and journey to other stars then we should be thinking about what it would involve. That's precisely what Bailer-Jones's book addresses. The author makes a systematic study of the physics of the medium through which any space probe would pass and the hazards that it would encounter. The treatment is mathematical and is suitable for a reader with a good understanding of physics at the level of an undergraduate degree.

There is a short introductory chapter, setting the scene and outlining the contents of all 17 chapters, before moving on to Chapter 2, which considers motivations for interstellar exploration, gives essential background information, and talks briefly about the nearest stars and time-scales. It becomes clear that any chance of reaching other stars in a reasonable time requires interstellar probes to be moving at some fraction of the speed of light, say 0.1 *c*.

Chapters 3 and 4 cover the theory of rockets and discuss orbital mechanics while chapters 5, 6, and 8 discuss various types of rocket engine, from thermal- and ion- to nuclear-powered, with relativistic effects on motion (with a clear discussion of the twin paradox) and on their effects on what we see (aberration and the Doppler effect) covered in chapters 7 and 9. Chapter 10 introduces the concept of solar sails, with a clear discussion of the practical difficulties. The next chapter considers using a laser rather than the Sun as a driving mechanism for the sails.

Of course, that kind of probe is light and easily affected by the ISM so the author here inserts a chapter on the ISM, considering the effects of impacts and the resultant drag and explaining the principle of the ramjet, which he regards as very speculative at this stage. Chapter 13 covers more exotic forms of sails, involving magnetic and electric fields.

The next question that arises is how to make sure the interstellar probe goes in the right direction and knows where it is in some inertial frame. Bailer-Jones spends Chapter 14 discussing navigation in general. Within the Solar System, where light-travel times are relatively short, it is a solved problem, with an agreed reference frame (ICRF — the International Celestial Reference Frame) based on the Solar System barycentre (SSB), using radar ranging. Out in the ISM ranging becomes impractical and the probe must do its own navigation. Instead of ranging, the probe must use other reference points, such as bright stars with precisely known positions and velocities in the ICRF. Alternatively, it is possible to use pulsars, but that is more complicated, as he explains.

Back on Earth, meanwhile, we would like to know what the probe is finding, so the final problem is getting the information back. Once the probe is well out into the ISM, two-way communication is unrealistic and even getting data back is slow — it may take months or years to send the information back at a low bit rate because the probe doesn't have the power to transmit faster. Chapter 15 discusses all the ramifications. Chapter 16 discusses possible payloads, including what instruments might be used. The mass of those instruments would have to be small, especially for sail-driven probes, so one option might be to send out swarms of probes, each with a different instrument, and some redundancy built in to avoid losing everything if a probe is lost.

Finally, Chapter 17, 'Outlook', starts by considering very briefly (and dismissing) wilder ideas such as wormholes before going on to real-life challenges and possible solutions. Bailer-Jones then considers broader issues: Should we undertake interstellar travel? Is it ethical? Is it dangerous? And — where do we go from here? None of the technology required currently exists, but some is within reach in the next half-century or so.

This book is clearly written, with useful summaries at the end of each chapter. The mathematics is deliberately simplified to enable the basic principles to be explained without obscuring them by the detail that would be needed in a realistic description. One comment

is that, although he does occasionally mention the power needed to make and send such probes, he does not discuss the fact that it is well beyond current world power usage. But that would be straying into politics, so he's probably wise to avoid that. The book is really an answer to the question: if we want to send out probes into space at 0.1 c, what are the physical requirements? This would be a useful book for anyone thinking about a career in astronautics, and is also of general interest. — ROBERT CONNON SMITH.

The Multiverse: When One Universe Isn't Enough: Uncovering a Universal Mystery.
by Brian Clegg (Icon Books), 2025. Pp. 190, 20 × 13 cm. Price £10.99 (paperback; ISBN 978 1 8377 3236 7).

Brian Clegg is a well-known popular-science writer and I've reviewed^{1,2} a couple of his previous books^{3,4} in these pages. The Multiverse is the subject of several books^{5–10} reviewed^{11–16} in this *Magazine*, so this book was an obvious choice for one of the dozen books I bought at an English-language bookstore after attending a thesis defence in Amsterdam a few weeks ago. Already in the acknowledgements (which is mostly a preface), Clegg mentions his sceptical stance on the Multiverse. Perhaps because he is not trying to convince the reader of the reality of the Multiverse, the chapters illuminate various ideas related to the Multiverse rather than working together towards some goal. We get brief descriptions of a motley collection of topics: the idea of the Multiverse, our Universe (one definition of the Multiverse is the sum of observable universes — the sum being Tegmark's Level I Multiverse —, each of which is smaller than the (possibly infinite) ensemble, though usually as used by other authors 'Universe' refers to Tegmark's Level I Multiverse), the simulation hypothesis, imaginary numbers and quaternions, fine-tuning, inflation, the many-worlds interpretation of quantum mechanics, string theory, the ekpyrotic model, the holographic principle, Tegmark's mathematical universe, and pop-science YouTube personality Sabine Hossenfelder. Sometimes I agree with Clegg's sceptical take, *e.g.*, when discussing inflation (though he omits the strongest argument for inflation: a mechanism for the origin of primordial density fluctuations). More often, though, his scepticism seems to be due mostly to a matter of taste (in the acknowledgements/preface, he mentions his sadness when the Steady State model was ruled out, possibly because he was a fan of Hoyle's science fiction).

The book is well-written with few typos; Clegg knows his trade. On the whole, the book is a good (but very brief) introduction to the topics mentioned above. However, whether intentionally or not, the combination of the trivially true, very speculative, and everything in between tends to cast a too sceptical light on things which are almost consensus; maybe Clegg hopes that the reader will come to dislike the same things he does once they've become tainted by association with the Multiverse. There are also a few common misconceptions, such as the ideas that dark energy causes the expansion of the Universe (and it seems to be implied that a negative cosmological constant would lead to contraction) and that inflation is basically faster-than-light expansion. The discussion of the Strong Anthropic Principle is confusing at best. His discussion of the inverse gambler's fallacy is somewhat unorthodox, perhaps to aid his comparison of it to the idea of the Multiverse (while at the same time not even mentioning other reasons for believing in some sort of Multiverse). That discussion is inspired by Philip Goff, who is known primarily for his belief in panpsychism. While people can be right about some things and wrong about others, Goff seems like a strange bedfellow for someone like Clegg pushing a less speculative and more down-to-Earth view.

There are a few footnotes, no photos, and the main text is followed by three pages of suggestions for further reading (many by Clegg, but also many presenting different points of view on the idea of the Multiverse) and a four-page small-print index.

In a review of another book by Clegg, I wrote "I would like to give the book a better recommendation, since it is generally well written and manages to give a good overview". My desire with regard to this book is somewhat less, because in addition to mistakes I detect an agenda. It's not a problem that I disagree with his opinion; rather, my impression is that

the account is intentionally somewhat biased. On the other hand, it's an easy introduction to some complicated topics and sometimes it is good to be exposed to a different point of view.

— PHILLIP HELBIG.

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Gravitation for Theorists, by Piljin Yi (Cambridge University Press), 2026. Pp. 338, 24.4 × 17 cm. Price £70 (hardbound; ISBN 978 1 009 57564 5).

This book grew out of a single-semester graduate course taught by the author at Seoul National University and at the Korea Advanced Institute of Science and Technology (the author's affiliation is the Korea Institute for Advanced Study). To allow comparison with other books on General Relativity (GR) which I've reviewed in these pages, I assign it a relativity-book signature of 000+++.* As such, it is good for someone who wants to work through the mathematical details at a fairly high level. It is atypical for GR books in that Part III (three chapters) is about 'Canonical Field Theories with Gravity' (including a chapter on the ADM formalism) and there is an appendix on 'Fiber Bundles'; much more than most broadly similar books, it highlights connections between General Relativity and other branches of physics. (Parts I and II are 'Relativity and Geometry' and 'General Relativity', five and six chapters, respectively.) Except for some background on Special Relativity and Maxwell's equations, the book has practically nothing on the history of General Relativity.† I can't improve on the author's summary: "This book is intended as a self-contained handbook on the foundation of General Relativity. The content shies away from a comprehensive treatise that would cover all the nooks and crannies of gravitational phenomena. The emphasis is instead given to incremental developments of the underlying mathematics, explicit derivations of key formulae, and, in particular, examples and sidetracks that are meant to solidify the concepts and to prepare the readers for further applications."

Although, as expected, Chapter 7 on 'Cosmology in Brief' is indeed brief, there is nothing misleading or wrong in it. Non-flat cosmological models are also discussed, and even the Multiverse gets a few paragraphs. The discussion of the flatness problem (though restricted to the fine-tuning problem, *i.e.*, why was the Universe extremely flat immediately after the

*The characters indicate maths-first or physics-first, breadth, depth, level, difficulty of maths, mathematical detail shown. (+ indicates maths-first or more than average, – physics-first or less than average; 0 neither or about average.)

†For that, see another book¹ reviewed² in these pages.

Big Bang) and the effects of inflation is good (though I disagree that the flatness problem is actually a problem (*e.g.*, ref. 3 and references therein)). In my review⁴ of a cosmology textbook⁵, I praised the author for explicitly introducing various forms of the Robertson–Walker metric. Something similar is done in this book for various representations of S^3 in the chapter on the Maurer–Cartan description (and the connection to the RW metric in cosmology is mentioned). The author is also aware that it is the Lorenz gauge (though there is no such entry in the six-page small-print index, though there are three Lorentz-related entries.) Apart from the usual topics and those already mentioned, the discussion of black holes (Schwarzschild, Reissner–Nordström, Kerr, Kerr–Newman) also includes the cosmological constant, and there is an entire chapter on the Maurer–Cartan description.

The book is a good introduction at a reasonably high level for someone who wants the work shown and is happy to forego the history of the topic. However, I found the book rather difficult to read, primarily because of the lack of definite and indefinite articles when they should be there and *vice versa*. In general, the book could have benefitted from editing by a native (or otherwise very good) speaker of English. There is also one instance (p. 223) where some text has obviously been left out. Similarly to the previous book on General Relativity⁶ I reviewed⁷ in these pages (also from Cambridge University Press), the wider margins are always on the left; more practical is to have them always on the outside. Several pages of my copy also became unattached; hopefully that is a one-off problem and doesn't affect the entire print run.

There are only a few black-and-white diagrams, scattered throughout the text. There are neither footnotes nor endnotes nor any sort of bibliography; only preface, main text (including appendix), and index. This is a no-frills detailed introduction to General Relativity and good for those who want to learn the subject by following worked-out derivations — PHILLIP HELBIG.

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Radio Universe: How to Explore Space Without Leaving Earth, by Emma Chapman (John Murray), 2026. Pp. 242, 23.5 × 15 cm. Price £18.99 (paperback; ISBN 978 1 529 39899 1).

I've read many popular-science books on astronomy, but this is probably the first which is mainly about radio astronomy. The author is a Royal Society Dorothy Hodgkin Research Fellow at the University of Nottingham and recipient of several awards; this is her second popular-science book about astronomy (thus only two books so far; there is another author named Emma Chapman; to add to the confusion, in the US this book is entitled *Echoing Universe*). Chapman was raised on radio, but in the BBC sense; she became interested in radio astronomy as a result of her PhD project, which involved radio observations from the Netherlands. An introduction mentions that project, tells a very brief history of radio astronomy, describes how radio telescopes work, and offers a somewhat longer exposition of the electromagnetic spectrum (including an obsolete reference to the colour indigo on p. 7). There is little about radio astronomy in the technical sense in the book; rather, it discusses the science which can be done *via* radio astronomy, sometimes containing asides about other radio-related topics.

The first six chapters are confined to the Solar System: the Moon (Apollo programme, radar, radio communications), the Sun (sunspots, James Stanley Hey, coronal mass-ejection events), Mercury (detailed discussions of its rotation, the presence of ice, why there have been only three missions), Venus (temperature, rotation, vulcanism, craters, lack of plate tectonics, high-resolution mapping), Mars (extraterrestrial life, orbital mechanics, the ill-fated *Beagle 2* lander), and the asteroid belt (introduced *via* Saturn's rings, Saturn being the current limit of radar astronomy), detecting potentially dangerous asteroids, and some history involving (later Sir) Bernard Lovell at Jodrell Bank. We then move further away to the Milky Way (the *Voyager* probes, Grote Reber, the 21-cm line, the structure of the Milky Way, astrophysical masers, *Meerkat*), black holes (detection, gravitational waves, Special and General Relativity, Schwarzschild's life (and death) and work, the *Event Horizon Telescope*, stellar-mass black holes), neutron stars (discovery of pulsars, neutron-star physics, pulsar astronomy, controversy around Jocelyn Bell (Burnell)), gravitational waves (the Hulse–Taylor binary pulsar, *LIGO*, the *Pulsar Timing Array*, kilonovae), exoplanets (formation, T Tauri stars, *ALMA*, molecular clouds), contact with extraterrestrial intelligence (SETI, TRAPPIST 1e, the Drake equation, the *Allen Telescope Array*, funding, Sagan, Tartar, METI), the high-redshift Universe (discovery of the CMB, 20th-Century astronomy including some wrong turns and dead ends, radio-source counts, physics of the CMB, first stars, the *Square Kilometre Array*), dark matter (cosmology, history of dark matter, Purcell & Ewen, modern structure-formation simulations), dark energy (more cosmology, baryon acoustic oscillations, intensity mapping), and the 'dark' side of the Moon (putting a radio telescope on the far side of the Moon). Finally we get a tourist's guide to radio telescopes, with brief descriptions of eleven such potential travel destinations. There are no figures and a few footnotes. The back matter includes extensive acknowledgements, notes (which are actually numbered references corresponding to numbered citations in the text, about eight per chapter), suggestions for further reading (both in general and a few suggestions for most chapters; I noted five which I intend to read; some should be updated to reflect more recent editions), and a ten-page small-print index.

While the topics are chosen because of the role played by radio astronomy in them, that is a jumping-off point for more general descriptions, such as a detailed account of the determination of the rotation of Mercury and Venus and the mapping of the latter.* While much of the material was familiar, I was happy to get more details on Hey and Purcell & Ewen. It is also good to have a nice overview of SETI and related topics; Chapman notes that some authors shy away from such discussions for no good reason. (Recently, SETI has become more respectable, and Michael Garrett, a prominent SETI advocate, has been the Sir Bernard Lovell Professor of Astrophysics and Director of the Jodrell Bank Centre for Astrophysics since 2016, after having been Director of the Joint Institute for VLBI in Europe and the General & Scientific Director at ASTRON.) Considering the large number of diverse topics, balance might be hard to achieve, but she does a good job, usually going into more depth only when mentioning less common (but important) details. A minor point is that I found there to be a bit too much detail on the physics behind the CMB (and to some extent on the history of the topic), but too little on why it is so important for cosmology today, *i.e.*, what one can learn from the power spectrum, though arguably that is too much physics and too little radio astronomy.

I noticed only a few mistakes. Some are easy to explain. For instance (p. 40), "Six missions carried a total of twenty-four American men to lunar orbit between 1969 and 1972, and of those, twelve set foot on the surface." There were eight, not six missions, but only six included a Moon landing. (The ill-fated *Apollo 13* went around the Moon, but didn't orbit it in the

*The most recent space-probe mapping is from the *Magellan* mission 1990–1994, with a resolution of 100 m. In 1978, the *Pioneer Venus Orbiter* had achieved one of 2 km. Amazingly, only ten years later, technology at the *Arecibo Telescope* was able to achieve that from Earth.

stricter sense.) Some are common misconceptions, *e.g.*, Special Relativity (SR) cannot deal with acceleration (p. 157) — the main difference is that SR is restricted to (flat) Minkowski space and General Relativity (GR) allows for curved space–time (to be sure, gravity curves space–time, and the Equivalence Principle relates acceleration and gravity, but nonetheless SR can describe acceleration). It is at least implied that Schwarzschild died on the battlefield; he died in hospital, away from the front, and of an auto-immune disease, not war wounds (p. 160). (She does get the history of the term ‘black hole’ correct, crediting Dicke and not Wheeler, p. 160.) Bell wasn’t yet Bell Burnell when she discovered pulsars (p. 172). The last sentence in the first paragraph of the last section in the chapter on neutron stars (p. 182) states “Sadly, Bell Burnell is less known for her scientific breakthrough than for the controversy that surrounds it.” That might well be true, but I wonder if devoting eight paragraphs to said controversy will improve the situation. At the risk of doing the same, I note that the actual discussion agrees with my assessment and correctly differentiates the question of whether she should have received a share of the Nobel Prize (including placing the decision in the context of the time and Bell Burnell’s own take on the matter) from the silly reporting by many journalists at the time. While GR indeed describes changes in the gravitational field propagating at the speed of light, not all such changes correspond to gravitational waves as usually thought of (p. 189). Since this is the third book in which I have noticed it, the idea that astronomers can somehow *measure* the radial velocity of extragalactic objects is becoming a common misconception (p. 248).

Others are more bizarre: Drake’s choice of 1679 pixels for his Arecibo message was due to it being the product of the two primes 23 and 73, but of course 1679 itself is not prime (p. 235). The description of the Hubble law is at best confused (p. 247). It is at least strongly implied that Einstein was aware of Friedmann’s work (which was done some years later) when the former added the cosmological constant in order to have a static universe (p. 248). The history of dark matter is at best too brief. P. 263: “Dark energy was proposed in the 1990s, when observations of distant supernovae revealed that the expansion of the Universe is not slowing down as expected, but accelerating.” That is literally true, but it was not *first* proposed (which seems to be implied) then, and though the *term* ‘dark energy’ was proposed then the idea is older. (Sometimes ‘dark energy’ is used to contrast it with a cosmological constant, the former having an equation of state other than $p = -\rho$ and/or the value or even the equation of state changing with time, though none of those were needed in the 1990s and probably none is needed today.) Further discussion of supernova cosmology is at best muddled (pp. 278–279).

However, most of the mistakes are related to cosmology, with which only a small part of the book is concerned, and are rather common, both of which are true of many books reviewed in these pages. I think that it is important to mention them, but at the same time the space devoted to them in this review exaggerates their importance. The rest of the book is not only (as far as I can tell) technically correct, but is well written and conveys the author’s love of radio astronomy, a topic which should get much more attention in books at this level; perhaps this book can be a step in that direction. I certainly enjoyed reading it and, despite being an honorary radio astronomer, learned many new things. — PHILLIP HELBIG.

On Time: The Physics That Makes the Universe Tick, by Jim Al-Khalili (Princeton University Press), 2026. Pp. 359, 24 × 16 cm. Price £28/\$32 (hardbound; ISBN 978 0 691 26703 6).

Al-Khalili is a well-known popular-science writer and presenter on radio and television with a background in theoretical nuclear physics; he is a professor of physics at the University of Surrey, where he also holds a chair in the public engagement of science. This is the first book by him that I have read. I’ve read many books on the nature of time and reviewed some in these pages, though they were usually more technical and/or edited volumes with several authors. In particular, this book — with an important exception mentioned below —

could be seen as something like a popular-science version of a book¹ reviewed² in the 2026 August issue of this *Magazine*. It's more than just a typical popular-science book, though, as some of its contents reflect research done by Al-Khalili and colleagues in the context of a large research grant, in an area (the philosophy of time) somewhat removed from his earlier specialization. While there are many popular-science books on time itself (including an excellent one³ reviewed in these pages⁴), there are few on the philosophy of time.

The preface notes that the book is concerned with physical time, not “mystic or poetic notions”. That does not exclude our perception of time, ‘manifest time’. That and basic questions are discussed in the introduction, such as whether time is an illusion, whether (and if so how) it flows, whether it is continuous, why it has a direction, and so on. The two philosophical problems of time are why we perceive it to flow and why we perceive the past to be different from the future, given that those facts aren't obvious from the equations of physics. The two physical problems are the connection between the coordinate time of classical or quantum physics and the time which is part of space–time in relativity, and reconciling time-symmetric dynamical equations with the irreversibility of thermodynamics.

There are so many concepts involving (the philosophy of) time that some structure is needed. The four parts of the book provide some of that, reflecting time as a label, as a dimension, as an arrow, and the reality of time. The first, with four chapters, discusses the basic concept of time as a coordinate which indicates when something happened, as in Newtonian or quantum mechanics, and how it is measured. The philosophy of time becomes important when psychological time and the question of free will *versus* determinism are discussed. The second, with five chapters, covers Special and General Relativity, including cosmological time, the idea of the block Universe, and the fact that ‘now’ is not clearly defined in a relativistic context. The third (four chapters) discusses various arrows of time: psychological, entropy, causal, cosmological, quantum, *etc.* Al-Khalili sees statistical mechanics on an equal footing with Quantum Mechanics (or dynamical physical equations in general) and Relativity with respect to its role in the foundations of physics, and there is a good discussion of various types of entropy, Loschmidt's paradox, and so on.

The closest thing to a consensus on the topic of the arrow of time is that all arrows of time are ultimately derived from the cosmological arrow of time, which is due to the Universe having started in a state of very low entropy, which is difficult to explain. (One might think that radiation would have a high entropy; that is true in the absence of gravity, but with gravity the high-entropy state is with everything in black holes.) Thus, the importance of the Past Hypothesis, which is just a statement of that fact, without explanation. Most discussions, at least most I am familiar with, are concerned with ‘traditional’ entropy (*e.g.*, that of particles of matter or radiation) or gravitational entropy. Al-Khalili emphasizes the importance of a third type of entropy, namely that connected with nuclear fusion. It is the increase of entropy as the result of fusion which ultimately responsible for most entropy-related phenomena. Since the possibility of such fusion is merely one of many aspects dependent on the fine-tuning of our Universe (*e.g.*, ref. 5 and references therein, reviewed⁷ in these pages), Al-Khalili also introduces the interesting twist that no extra Past Hypothesis is actually needed; it is merely one aspect of the fine-tuning of our Universe for life, which is hard to dispute, though there is disagreement about its explanation (*e.g.*, refs. 5,6). Considering that many have deemed the problem of the origin of the low-entropy Big Bang the most important outstanding problem in physics, such a simple explanation — which I haven't seen anywhere else — is at least very interesting.* With the beginning out of the way, the reader is then presented with various ideas about a possible end of time. Contemplating extremely long periods of time leads to the idea of ‘Boltzmann brains’, conscious observers which arise due to fluctuations. Whatever one thinks of them (the author apparently doesn't think much of the idea), as a serious area

*Al-Khalili does point out what are the author's own ideas and what is his summary of the field, always something worth doing when a popular-science book includes the former as well as the latter.

of research I would have liked to have had a bit more discussion than the short shrift they are given here.

The fourth part is intended to convince the reader that time is real, with one chapter discussing the idea of time as an emergent concept within the context of quantum gravity, and the other introducing Al-Khalili's concept of entanglement entropy. The interrelated concepts of quantum measurement, entanglement, and decoherence are discussed. It is, correctly, pointed out that entanglement is not limited to the special cases we read about in laboratory experiments, but is actually the rule, and that decoherence is extremely important. The two chestnuts that the laws of physics are time-symmetric and that entropy almost always increases both apply only to isolated systems. Of course, no system in the Universe is truly isolated, but that is not appreciated enough. I remember John Barrow's example of aiming a cue ball at the other 15 balls at the start of a game of pool with the maximum precision allowed by the uncertainty principle; after just 15 collisions the uncertainty in the balls' positions would be larger than the size of the table. We are reminded of a similar but more impressive argument due to Michael Berry already mentioned in Chapter 4: Take the classic molecules-in-a-box thought experiment from a typical discussion of statistical physics, which is alone in the Universe except for one electron at the limit of the observable Universe — but we don't know in which direction. Even if we could measure the position and momentum of each molecule in the box *exactly*, after 50 collisions, *i.e.*, within a tiny fraction of a microsecond, we would lose predictability due to our lack of knowledge of the position of the electron. With the smallest imaginable perturbation having such an effect so quickly, no system can be described as even approximately isolated, thus giving great importance to decoherence. The irreversibility of quantum decoherence, together with an initially non-entangled Universe is thus the ultimate source of arrows of time. The fly in the ointment is that a new Past Hypothesis regarding a non-entangled Big Bang seems to be needed, since fine-tuning doesn't seem to explain it as it does the traditional Past Hypothesis. (After such heavy going, the bonus chapter on time travel after the afterword is almost light relief! There is nothing novel here, but it is included because it seems to belong in a book on time.)

As with many books I've reviewed, there are a few blunders relating to cosmology, but fewer and more harmless than is usually the case and not important for the main narrative. There are a few black-and-white drawings scattered throughout the book and a few footnotes; the nine pages of small-print endnotes after the acknowledgements are references — unusual for a popular-science book, but appreciated. The two pages (also in small print) of about 50 suggestions for further reading are particularly interesting: I've reviewed some of the books, just read others, some were already on my ever-growing list of books to read, others I've added to it. A nine-page small-print index and a note on the type end the book. The book is a nice combination of the familiar and the new, well researched, and thought-provoking; anyone interested in time should find the time to read it. — PHILLIP HELBIG.

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(2) D. Mihalas, *Stellar Atmospheres* (2nd Edn.) (Freeman, San Francisco), 1978.

(3) R. Kudritzki *et al.*, in C. Leitherer *et al.* (eds.), *Massive Stars in Starbursts* (Cambridge University Press), 1991, p. 59.

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