THE OBSERVATORY

A REVIEW OF ASTRONOMY

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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2026 January 9 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 those on Zoom should see a small green shield which means you are using the most up-to-date version of Zoom. Please put questions in the Q&A and they will be read out by Dr. Pam Rowell at the end of each talk.

I'm going to show one of the latest Christmas cards in history. It is a diagram produced by Annie and Edward Maunder which first appeared in *MN* in 1904. It's commonly called a Butterfly diagram and it shows solar latitude *versus* time, and you can see sunspots moving to lower latitude as each solar cycle progresses. If you extend it a few years and turn it through 90 degrees you get a Christmas tree. [Laughter.] That is to thank you for all the support that you give to the RAS. Although it's too late to wish you a happy Christmas it's not too late to hope that you have the very best of what is left in 2026.

Now for the best job that the President gets to do and that is to announce the annual awards. I'd like to thank the members of the Education Outreach panel, the Agnes Mary Clerke Medal panel, the Astronomy panel and the Geophysics panel, and also Nush Cole who managed much of the administrative support for us. Thanks also to those who put in nominations. The James Dungey Lecture will be given by Professor Andy Hillier (Exeter), the Harold Jeffreys Lecture by Professor Andy Biggin (Liverpool), the George Darwin Lecture by Professor Suzanne Aigrain (Oxford), and the Gerald Whitrow Lecture by Professor Richard Battye (Manchester). Early Career Awards go to Dr. Ke Zhu (Bristol, Geophysics) and Dr. Deaglan Bartlett (Oxford, Astronomy). The Fowler Award for Geophysics goes to Professor Paula Koelemeijer (Oxford) and that for Astronomy is awarded to Dr. Ingrid Pelisoli (Warwick). The Service Award (G) goes to Professor Mark Burchell (Kent). The Ian Robson Lifetime Achievement Award goes to Professor Raman Prinja (UCL). The Higher Education Award goes to Dr. Kurt Froebrich (Kent), whilst the Secondary Education Award goes to Mrs. Vicky Dean (The King's Academy, Middlesborough). The Agnes Mary Clerke Medal is awarded to Dr. Edward Gomez (Cardiff), the Jackson–Gwilt Medal to Professor Alistair Glasse (Edinburgh), the Chapman Medal is awarded to Professor Matthew Owen (Reading), and the Eddington Medal goes to Professor Debora Šijački (Cambridge). The Herschel Medal is awarded to Professor Andrew Bunker (Oxford). The Gold Medal for Geophysics is awarded to Professor Andrew Jackson (ETH, Zurich) and the Gold Medal for Astronomy goes to Professor Shrinivas Kulkarni (California Institute of Technology).

Our first speaker is Dr. Stephen Thorp. He is a postdoctoral researcher at the Institute of Astronomy and Kavli Institute for Cosmology, Cambridge, where he works with Professor

Hiranya Peiris. He spent the first three years of his postdoctoral position in the Oskar Klein Centre at Stockholm University, and relocated to Cambridge in 2025 September. From 2018 to 2022 he was a PhD student at the Institute of Astronomy, Cambridge, working with Professor Kaisey Mandel. Before that he studied physics at the University of Birmingham. Stephen has broad interests in statistics and machine learning applied to astronomy problems, particularly in the fields of galaxy evolution (which he'll be talking about today), strongly lensed transients, and supernova cosmology. The title of his talk is 'POP-COSMOS: Machine-learning the galaxy population for large cosmological surveys'.

Dr. Stephen Thorp. Thank you for having us here. We have had a really nice Specialist Discussion Meeting on Machine Learning Applied to Astronomy and I will be presenting a broader view of some work that I presented earlier.

This presentation introduces the 'POP-COSMOS' framework, a generative model for the galaxy population probed by large cosmological surveys. We will look at what it means to build a generative model, how we can build such a model for the galaxy population, the challenges involved, and how we can overcome those challenges. We will conclude by applying this framework to data from the Cosmic Evolution Survey (COSMOS).

Our motivation is cosmological surveys — particularly photometric ones — that seek to map the matter distribution and large-scale structure (LSS) in the Universe by observing billions of galaxies. The matter-density field in the Universe — and the underlying cosmology — is traced by the clustering of galaxies in 3D space, and/or distortion of their observed shapes due to weak gravitational lensing. Those tracers are the primary way today's large surveys probe the nature of dark energy.

Two of the largest photometric surveys ever undertaken are now in progress: the *Vera C. Rubin Observatory* Legacy Survey of Space and Time (LSST), and the European Space Agency's *Euclid* mission. The cosmological data sets produced will consist of four-band (*Euclid*) or six-band (LSST) photometry, and the measured shapes and positions of billions of galaxies over thousands of square degrees. We will not have 3D positions for all galaxies — only spectroscopy can provide that by measuring redshift precisely — so our cosmological analyses will be done *via* tomography. That means sorting galaxies into redshift bins based on their photometry; that is sufficient for cosmology, but relies on detailed modelling of the sorting process. We need to understand the true redshift distributions of galaxies sorted into each of our tomographic bins.

With that context in mind, we will switch gears to talk about generative modelling. The goal of any generative model is to design an end-to-end simulator that is able to replicate a target data set. We will work through what that means conceptually, how we can build a model for the galaxy population, and why that will help us with tomographic binning. The accompanying Fig. 1 shows three sketches of the model building process.

The first panel **(a)** shows the general model structure we will follow. At the deepest layer of the model, we have a population distribution. The intrinsic (physical) properties of any finite sample of objects will be a random draw from the underlying population distribution. The intrinsic properties will often not be directly observable; a physical model or process will be needed to translate those into observable features. Finally, to generate realistic simulated observations, we will require a model for the noise and selection effects in our target data set.

To 'train' our generative model, we will need to specify some measure of similarity between our simulated observations and the target data set. We will then simultaneously optimize any degrees of freedom or tuneable parameters in the layers of our model, until our simulated observations match the data. The largest degree of freedom will be the underlying population distribution; if we can learn that, we will have learned something about the true population underlying our data.

To adapt that general model structure to the galaxy population, there will be several challenges:

1. What set of physical properties is sufficient to parametrize a galaxy, and how do we map those to observables (photometric fluxes)?
2. Will our model be computationally scaleable for billion-galaxy data sets?
3. What is a sufficiently flexible form for the population distribution?
4. Can we realistically replicate any relevant observational effects?

To tackle the first challenge, we will use stellar-population synthesis (SPS). Pioneered by Beatrice Tinsley, that is a detailed framework for synthesizing galaxy spectral-energy distributions (SEDs). SPS models assemble SEDs from component stellar populations, incorporating effects such as dust, chemical evolution, nebular emission, and active galactic

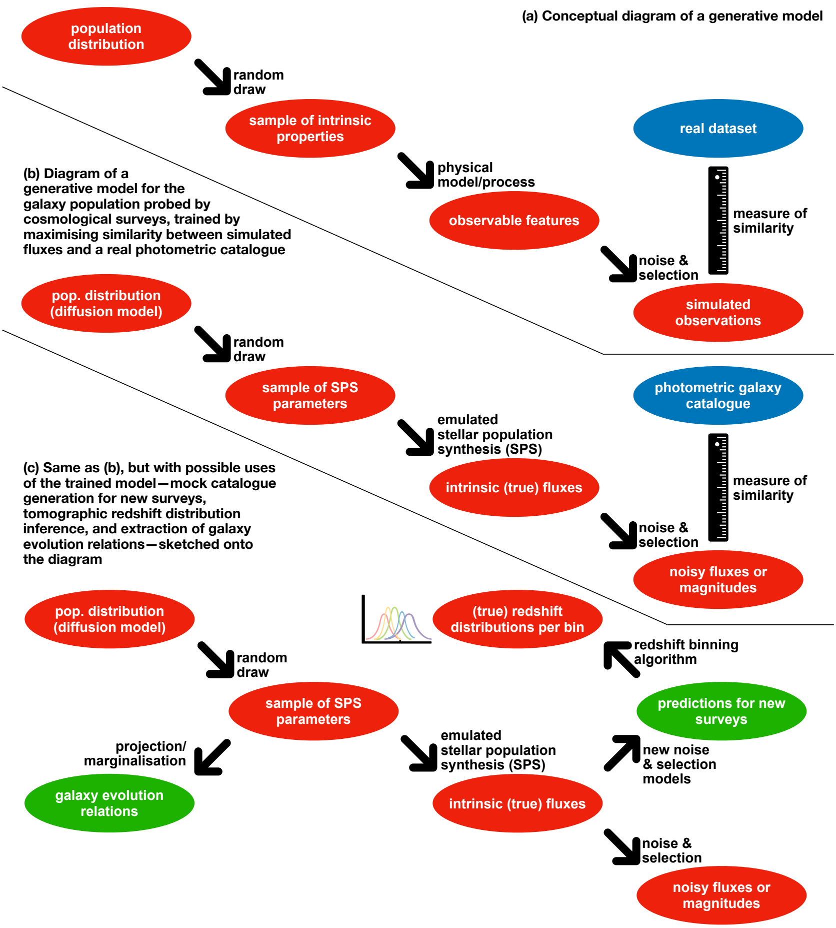

FIG. 1
Diagrams sketching a generative model for the galaxy population. The top panel **(a)** shows a problem-agnostic conceptual diagram. The second panel **(b)** shows our model design for photometric galaxy survey data. The final panel **(c)** shows possible uses.

nuclei. Modern SPS models represent a diversity of galaxy SEDs with a handful of parameters such as stellar mass, metallicity, star-formation rate (SFR), redshift, and dust optical depth. We will use a 16-parameter SPS model.

We now face a computational challenge. Detailed SPS models are inherently complicated, including many components, slow underlying calculations, and time-consuming I/O operations (*e.g.*, loading spectral templates). Additionally, many 'industry standard' SPS codes are not optimally suited for GPU-based high-performance computing (HPC) systems. To scale SPS to billion-galaxy data sets, we can use 'neural emulation'. That involves training an artificial neural network to learn the mapping between parameters and SEDs (or photometric fluxes) that is provided by SPS. A neural emulator will be able to replicate the output of an SPS code to very high accuracy (fluxes approximated within 1%), with a fraction of the computational cost (≈10 000× faster). Our emulator code, 'SPECULATOR', is publicly available on-line.*

Our third challenge is to find a sufficiently flexible way of representing the underlying population distribution over our 16 SPS parameters. Two possible routes are: (*i*) to take a classical hierarchical Bayesian approach and make assumptions to write down an explicit form; or (*ii*) to use a flexible density estimator as in generative artificial intelligence (AI). We will take the second route here, using a class of models called 'diffusion models'. Those represent a complex 'target' distribution as a continuous deformation of a simple 'base' distribution (often an isotropic Gaussian). Rather than explicitly learning a functional form for the target distribution, one instead learns the transformation. Those kinds of models have been workhorses for tasks such as AI image generation. We have a lightweight code, 'FLOWFUSION', available for building diffusion models.†

Our final challenge is applying realistic observational effects: transforming our intrinsic model fluxes or SEDs into simulated observations by adding appropriate noise and selection effects. Adding realistic noise can be framed as another density-estimation task — learning the distribution of flux errors conditional on true fluxes — which can be solved using a diffusion model (or similar). Sample selection criteria (*e.g.*, magnitude limits) will usually be known from the survey design, but can in principle be represented probabilistically and learned during training.

The second panel **(b)** of Fig. 1 shows our full generative model design. That is the recipe we implement in the 'POP-COSMOS' framework.‡ We train the model — optimizing the diffusion model that represents the underlying population distribution — by maximizing the similarity between simulated noisy fluxes and a deep photometric galaxy catalogue.

The final panel **(c)** of Fig. 1 shows two possible uses of our trained model. For example, we can simulate realistic photometric galaxy catalogues for wide-area surveys (*e.g.*, LSST or *Euclid*), and can subsequently apply a tomographic redshift-binning algorithm to our simulated photometry. That lets us infer the underlying redshift distribution in each tomographic bin, necessary for accurate cosmology. Estimating those distributions *via* generative modelling sidesteps challenges associated with stacking per-galaxy redshift estimates, or using unrepresentative spectroscopic calibration samples. The second use-case we highlight is the inference of galaxy-evolution relationships. Since the learned population distribution will encompass the evolution of galaxy properties across cosmic history, we can 'slice' it in different ways — by projecting or marginalizing over parameters — to extract key relationships.

We have trained the POP-COSMOS model on data from the ≈2 deg² COSMOS field; specifically the *COSMOS2020* catalogue's 26-band ultraviolet–infrared photometry. We have in our training set ≈420 000 *COSMOS2020* galaxies brighter than ≈26 mag in *Spitzer IRAC*

*https://github.com/Cosmo-Pop/speculator

†https://github.com/Cosmo-Pop/flowfusion

‡https://github.com/Cosmo-Pop/pop-cosmos

[*Infrared Array Camera*] Channel 1 (≈3·6 μm). We validate the trained model by comparing simulated colours and magnitudes to the real catalogue, and by comparing the learned galaxy evolution relations to literature results from other surveys or tracers. Some key results we extract include:

- colour–redshift relations;
- the redshift distribution of galaxies with $r < 25$ mag;
- the SFR *vs.* stellar-mass relation (star-forming sequence);
- the cosmic SFR density; and
- the stellar-mass and redshift-dependent fraction of quiescent galaxies.

To conclude, we have designed a recipe for interpretable generative models, combining machine-learning tools with a physically motivated parameterization. We have applied that approach to building a generative model for the galaxy population probed by wide and deep surveys, and have examined the galaxy evolution results one can extract from the model (detailed fully by Thorp *et al*. in *ApJ*, **993**, 240).

Professor Ofer Lahav. Experience from surveys shows that it really depends on what you do with it rather than the application. Specifically, some groups just use point estimation of the redshifts and others use the whole PDF or distribution function. I just wonder about the application of your method.

Dr. Thorp. This is attempting to be a third way of getting redshift distributions, rather than stacking or averaging point estimates or per-galaxy posteriors — which we know isn't strictly speaking correct in a Bayesian sense. We're trying to get the redshift distributions in tomographic bins in a third way by building a forward simulator and applying our real-observations noise model and observational selection effects along with whatever point estimator is being used to do the target on the real galaxies. When we apply that to the model galaxies we obviously know their true underlying z so we can see what was the redshift distribution of the galaxies that made it into our 'top-hat' bins as it were.

The President. You glossed over random selection of the stuff when you were showing that iteration in the training; do you do the selection every time or is it for that random selection?

Dr. Thorp. When you are matching the real data you just want to draw enough model galaxies from the underlying distribution that it's capturing the whole structure.

The President. Are you using the same selection through the whole of that process?

Dr. Thorp. We are using the same magnitude limit because we are trying to model a survey with one magnitude limit although, in principle, if you have reason to believe that there is some varying depth across the sky you could fold that in.

The President. For the computer time that you are using you probably don't want to be doing a sensitivity study to check that your selection is random enough and large enough.

Dr. Thorp. Most of that is done with stochastic optimization. There is a degree of randomness anyway. Every time you adjust something in your population model you take a fresh draw and push it through the whole thing and there is a stochasticity there anyway.

The President. Any other questions? Thank you very much, Stephen. [Applause.]

The next speaker, Dr. Francesco Scotto di Uccio, is currently a postdoctoral researcher at the Department of Physics of the University of Naples Federico II, where he obtained his Master's and Bachelor's degrees in Physics, followed by a PhD in Structural, Geotechnical, and Seismic-Risk Engineering (awarded on 2025 February 21), with a thesis entitled 'Detection and characterization of microseismicity using advanced techniques' (supervisors: Prof. Gaetano Festa and Prof. Matteo Picozzi). During his PhD programme, he carried out research periods as a Visiting Student at Stanford University and at the GFZ German Research Centre for Geosciences in Potsdam, where he had the opportunity to develop and apply advanced techniques for microseismicity detection, also using fibre-optic sensors for seismic monitoring. The title of his talk is 'From background seismicity to seismic crises: What can we learn from machine-learning-enhanced catalogues?'

Dr. Francesco Scotto di Uccio. Microseismicity continuously occurs along the seismogenic structures that can also host larger, destructive earthquakes. Therefore, its characterization can potentially provide crucial information on the geometry and mechanical state of the underlying faults, before the occurrence of notable events. However, conventional catalogues are limited in size, since many small events are hidden in the noise. Therefore, discovering such events calls for advances in both earthquake-detection techniques and monitoring infrastructures.

We showcase how the integration of machine learning and similarity-based detection techniques can increase the content of seismic catalogues both for background seismicity and seismic sequences, up to one order of magnitude as compared to conventional manual catalogues in Southern Italy. In that framework, machine-learning models provide an enhanced set of events as compared to the standard catalogue, which can be used as templates to detect effectively lower-magnitude, colocated events, also with a short interevent time. Following that strategy, seismic catalogues can also be enriched by nearly one order of magnitude. The location of the earthquakes in the enhanced catalogue revealed the activated fault patches, while the determination of source properties enabled the definition of evolutive models for the seismic sequences. In the case of seismic sequences, relocated seismicity clearly identifies local patches on kilometre-scale structures, featuring an orientation coherent with the main faults of the area. To monitor background seismicity, we integrated the standard seismic network with 200 stations deployed in dense arrays for one year, demonstrating the possibility of consistently detecting small-magnitude earthquakes with the use of short-term dense arrays and established machine-learning models. Moreover, that configuration enables the downscaling of the seismicity characteristics to small, decametre-size events, achieving resolution as from multiple years of conventional monitoring. We estimated focal mechanisms using a CNN [convolutional neural network] for evaluating P-wave polarities and we inverted the data set of fault planes for determining the characteristic of the stress field. The orientation of the stress field resulting from the inversion of the fault planes agrees with previous estimates, based on six years of microseismic events. The stress field obtained has a vertical most compressive stress σ_1 and horizontal intermediate and least compressive stresses, σ_2 and σ_3, respectively, the latter azimuth lying in the direction of the anti-Apenninic extensional stress, featuring coherent values of the relative stress magnitude as compared to former studies. From a spatio-temporal analysis, we observed a spatial homogeneity of stress field in the area on ≈20-km scale, while the time distribution of the stress ratio reports lower values observed up to the end of January and higher values up to June, modulated by the occurrence of the oblique faulting. That result correlates with seasonal variations in the regional strain.

We finally focussed on the characterization of the 2025 Santorini seismic sequence, revealing the intense level of seismic activity during the crisis and demonstrating how deep-learning approaches can support near-real-time tracking of the evolution and dynamics of the sequence. Advanced detection techniques can increase standard catalogues by ≈12× (≈48k events), identifying five stages of the crisis according to hourly rate (≈70 earthquakes per hour) on February 6 when an emergency was declared. Deep catalogues enable the investigation of moment tensors and tomographic models, potentially identifying magmatic sources.

Dr. Pam Rowell. This question has come in from Kathy Whaler. "Do you think there is scope to use machine learning in attempts to infer temporal changes in tomographic models, *e.g.*, associated with magma movement?"

Dr. Scotto di Uccio. That tomographic model was not one of my main activities in this work but actually we are still not so much involved in the tomographic models in that way, but given the huge seismic activity that we were able to recognize by machine learning we can use more traditional approaches to try and get some variation in the velocity in the vents in the area.

Dr. Quentin Stanley. That was absolutely fascinating. It puts me in mind of a discussion that we had some years ago in a Discussion Meeting looking at the difficulty of understanding earthquakes. Two comments: are you able to use your machine learning to put it on edge compute so that your seismic stations are able to say what is going on rather than post analysis? Would that be a possibility in the future?

Dr. Scotto di Uccio. Simple techniques as algorithms that identify earthquakes based on the energy evaluation of the seismic signals are running, in real-time, on dedicated servers that receive the collected data, with a latency lower than one second. In their standard configuration, machine-learning models for earthquake detection are based on more extended windows (*e.g.*, 30 s), therefore are not fully applicable to real-time monitoring. In the future, we can eventually retrain the model with shorter windows.

Dr. Stanley. That would be a tremendous advantage going forward and the other little bit is because you have that amount of data coming through are you able to analyze it or is it coming through too fast?

Dr. Scotto di Uccio. To get information we integrated results from seismic modelling but also from GNS stations and, of course, seismic information can provide the tools for understanding the loading.

Professor Mark Lester. Thank you, Francesco. Could I just ask: in the Santorini data towards the end of that period in the final phase, the distribution of the magnitudes seems to start to become quite banded so you have values at the highest level and then at two other levels. Is there a physical reason for that compared with the distribution that you see earlier?

Dr. Scotto di Uccio. Actually it does not report the magnitude but that is the distance along a profile, *e.g.*, the lower bands are closer to Santorini's area and the higher bands closer to the Amalfi coast. That has a physical meaning because, typically, after an earthquake we expect lower-magnitude events to be more frequent than larger-magnitude events associated with the same earthquake. Here everything was quite complex because we had large earthquakes, hundreds of events. It was difficult to disentangle which was the decay rate for which earthquake in the case of Santorini; it is very overlapping. It means that the seismicity is occurring in some particular spots on the basin.

The President. I'd like to ask you about the situation after the Florence earthquake but we should carry on with the next speaker. Zahra Zali is a postdoctoral researcher in seismology at GFZ Helmholtz Centre for Geosciences. Her research focusses on the analysis of continuous seismic and strain data to study transient processes in faults and volcanoes, with an emphasis on developing machine-based methods. She has worked on volcanic eruptions, slow deformation, and earthquake-related signals across a range of tectonic settings. Her current research aims to detect and characterize the preparatory processes preceding earthquakes and volcanic eruptions.

Dr. Zahra Zali. The Earth is constantly active, even when nothing dramatic appears to be happening. Subtle ground motions, slow deformation, and weak vibrations carry information about how volcanoes and faults evolve over time. Modern geophysical networks are designed to monitor that activity continuously, recording the planet's behaviour day and night with increasing sensitivity and coverage. Seismometers, strainmeters, and other geophysical sensors therefore produce vast streams of data. Yet much of our traditional analysis still treats the Earth as if it only speaks in short, discrete events: earthquakes, explosions, eruptions. Anything slower, weaker, or more ambiguous is often filtered out, averaged away, or simply ignored.

In this talk, I explore how machine learning, particularly unsupervised methods, can help us listen differently. Instead of asking only *when* an event happened, we can ask *how* signals evolve through time, and whether systematic patterns emerge before major changes in the system.

The challenge is not a lack of data. Modern seismic and geodetic networks generate terabytes of continuous recordings. The difficulty is that those signals are noisy, overlapping, and non-stationary. Important processes, such as magma migration or slow fault slip, may unfold gradually and leave only subtle fingerprints. Event-based approaches, by design, are not well suited to capturing such behaviour.

Machine learning offers a way forward, not as a replacement for physical understanding, but as a tool for organizing complexity. In particular, unsupervised learning allows us to explore continuous data without predefined labels or templates, something that is often unavailable in volcanic or tectonic settings.

A central idea in my work is to transform continuous signals into a form where patterns can be compared objectively. Seismic or strain data are first converted into frequency representations, using wavelet transforms or spectrograms. Those representations are high-dimensional and difficult to analyze directly. Autoencoders, a class of neural networks, address that problem by learning compact, nonlinear representations of the data. In effect, they learn how to describe complex signals using a small number of latent variables. Once the data are mapped into that latent space, clustering becomes meaningful. Similar signal patterns group together, and their temporal evolution can be tracked. That process is automated and does not rely on human-defined signal categories.

I first illustrated that approach using volcanic data from the 2021 Geldingadalir eruption in Iceland, a well-monitored event that produced a rich mixture of earthquakes, continuous tremor, episodic tremor, and changes in eruptive style. Fig. 2 shows the evolution of clustered seismic signals during that eruption. Each point represents a short window of continuous seismic data, mapped into a low-dimensional space using an autoencoder and then grouped according to signal similarity.

Several distinct regimes emerge naturally from the data. Before the eruption onset, the signal space is dominated by earthquake-related activity. After the eruption begins, a cluster associated with continuous tremor becomes prominent. That is followed by a separate cluster linked to episodic tremor during phases of lava fountaining, and later by another form of continuous tremor accompanying sustained lava outflow.

What is particularly striking is that a coherent tremor cluster appears several days before the eruption starts. Those signals are subtle and are often missed by classical analyses. By using a deep-based representation of the data, subtle changes and recurring patterns in the signals can be captured and tracked more systematically through time. The timing of that transition is consistent with independent geodetic evidence for shallow magma emplacement prior to eruption onset. Later in the eruption, the same clustering framework captures a distinct change in signal behaviour in late April, before the onset of lava fountaining on May 2. In other words, the machine-learning model identifies a weak but coherent pattern in the seismic data that precedes the observable transition in eruptive style.

The same philosophy can be applied to tectonic systems. I next showed results from the 2023 7·8-Mw Kahramanmaraş earthquake in Turkey, where months of elevated, tremor-like activity were observed before the main shock. Clustering reveals episodes dominated by low-frequency signals that increase about six months prior to failure. Those episodes consist of many small, repetitive pulses.

Source locations show a spatial association with industrial sites, indicating that that activity is related to anthropogenic processes. That observation is important from several perspectives. First, it demonstrates that such activities can generate tremor-like signals that are recorded by seismometers. Second, it raises questions about the potential influence of those processes on the local stress state of the region. Third, it serves as a reminder that patterns identified by machine-learning methods require careful physical analysis and independent investigation before being interpreted.

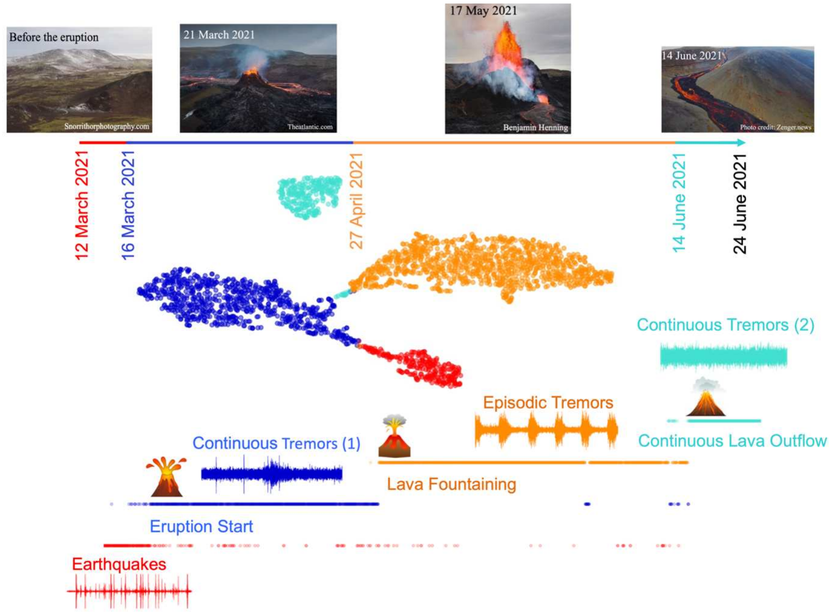

FIG. 2

Evolution of clustered continuous seismic signals during the 2021 Geldingadalir eruption, Iceland. The central panel shows a low-dimensional representation of continuous seismic data produced by an autoencoder, with colours indicating distinct clusters. Those clusters correspond to different eruptive regimes, including pre-eruptive seismicity, continuous tremor, episodic tremor during lava fountaining, and a later phase of sustained lava outflow. Photographs and dates above illustrate the close correspondence between cluster transitions and observed changes in eruptive behaviour.

The final part of the talk focusses on fault-slip processes at Parkfield on the San Andreas Fault, a long-studied transition zone between creeping and locked fault segments. Here, dense borehole strainmeter networks allow us to observe deformation with extremely high sensitivity. Using a deep-learning workflow adapted for strain data, we can automatically detect transient strain signals associated with short-duration slow-slip events.

Those slow-slip events are subtle, often lasting only minutes, and are easily masked by tides, atmospheric-pressure changes, and instrumental effects. After careful preprocessing, the machine-learning model identifies coherent strain transients that appear consistently across multiple stations. Their scaling behaviour extends known earthquake relationships into the aseismic domain, suggesting that slow-slip and earthquakes may be governed by related physical principles. Moreover, these slow-slip events modulate nearby low-frequency seismicity, possibly transferring stress along the fault. That highlights an important point: continuous deformation processes can actively shape the seismic cycle.

Across both volcanic and tectonic examples, a common picture emerges. Machine learning provides a unifying framework to detect, organize, and track transient processes in continuous Earth data. It excels at revealing structure where human intuition struggles, especially in high-dimensional, noisy signals. But interpretation remains essential. The clusters themselves are not explanations; they are tools for asking sharper physical questions.

In closing, listening to the Earth requires both sensitive instruments and flexible analysis methods. As our data sets continue to grow, approaches that embrace continuity rather than discretization will become increasingly important. Used carefully, machine learning allows us to hear parts of the Earth's story that were previously lost in the noise.

The President. Questions for Zahra?

Dr. Rowell. This question is also from Kathy Whaler who asks "You mentioned in the introduction also the large quantities of geodetic data that are now available. Are you currently analyzing them or have plans to analyze them with ML methods?"

Dr. Zali. I'm not currently working on that. I'm currently working on strain data. I might work in that direction to try and develop an algorithm for automatic analysis of GNS data as well.

The President. Any more questions? Quentin?

Dr. Stanley. With the clustering that you have done which has revealed a lot of that, how sensistive is this analysis to the clustering if you do it in a slightly different way?

Dr. Zali. The model is very sensitive in terms of small changes to the signal. We hope that what the model will do will be to find everything in the data. In terms of sensitivity to the data the model is seeing, it is very powerful. If you think about unseen data, that is a challenge and and we are trying to develop an algorithm for clustering done close to real time. We have not done that yet but we are hoping to.

Dr. Stanley. We look forward to the next exciting episode!

The President. Thank you very much, Zahra. [Applause.] As we have had a late speaker cancellation I have prepared a talk on the train on the way here today. I can promise that there is no machine learning involved in this talk. Here ML stands for Mike Lockwood. [Laughter.] The title of my talk is 'Semi-annual variation and the Russell–McPherron effect in geomagnetic activity'.

Geomagnetic activity peaks at the two equinoxes: we see it in all geomagnetic indices, we see it in aurorae and space weather. I am going to talk about the Russell–McPherron effect. We can break it down by looking at the time of calendar year *versus* the time of day because the Earth's magnetic field is spinning and we see a UT variation. The pattern is in the shape of an hour glass which we see in all global geomagnetic indices.

There have been three proposals for explaining the semi-annual variation. One is the so-called axial effect which was first suggested back in 1912, the equinoctial effect was first suggested by Bartels, also called the McIntosh effect, and then there is the Russell–McPherron effect. The solar magnetic equator is inclined to the ecliptic plane by seven degrees so that the Earth travels up and down in heliographic latitude and so the pattern depends on the time of year.

Ulysses has plotted the magnetic field and the velocity of the solar wind and you can see that the velocity is larger over the poles at sunspot minimum but relatively slow down the streamer belt which is close to the ecliptic but actually orientated to the magnetic equator of the Sun. At solar minimum we can go up and down in terms of solar-wind speed — that is a very sharp gradient. As Earth goes up and down in heliographic latitude we might see an effect that is known as the axial effect.

The McIntosh effect, first proposed by Bartels, says that the Earth's magnetic axis is rotating around the rotational axes because the poles are offset. Our magnetic field is not actually geocentric which is used in almost all models. It does not pass through the centre of the Earth so that adds a complication. McIntosh and Bartels proposed that the angle ψ between the direction towards the Sun and our magnetic axis which has both a time-of-year and time-of-day variation gives a pattern which is named after McIntosh.

The last one is called the Russell–McPherron effect and we have a rotating Earth and a rotating magnetic axis which varies. That works on the idea that the magnetic field we receive from the Sun is just about in the solar magnetic equatorial plane — any north or south field as it left the Sun is completely wiped out by the time it reaches us. We are interested in what component of Earth's magnetic field points southwards in Earth's magnetic frame, because we may get magnetic reconnection and energy coupling within the magnetosphere when it points southwards in a magnetic frame and that gives a semi-annual variation pattern, but the UT of the two peaks is quite different.

Looking at the three patterns that we observe appear equinoctial, the big surprise is that, although there is an equinoctial effect, the most important factor is the Russell–McPherron [RM] effect. That has caused years of misunderstanding. How do we know it is the most important? Looking from the Sun at the Earth the field is normally in this equatorial plane and at the September equinox the magnetic axis of the Earth is tilted over so we actually require negative B_z and to get that we require positive B_y and GSEQ [geocentric solar equatorial coordinate system], whilst in March it is the other way round. Is the solar field E or W? The big surprise is that that really matters.

We can see that the RM effect really matters if we look at the southward field in the magnetic frame against the southward field in the solar frame. What gives the large southward field in the Earth's magnetic frame is the large southward field in GSEQ. It's actually the large southward field from the Sun and coronal mass ejection that is giving us the southward field in Earth's frame and the RM effect is very small compared to the effect of the transient events.

Why has that led to confusion? There are indices such as the DST [disturbance storm time] index that show an axial effect to add to the confusion. What that is about is time-scale, taking the RM pattern over one-hour data and averaging over six hours it still looks RM-like. Average over 12 hours and it turns into an axial pattern; DST has a response time of more than 12 hours and that is why the axial effect sometimes crops up. It's just a matter of averaging the data makes it look axial, you have averaged out the UT variation.

Where does the equinoctial pattern come from? If we take the pressure of the solar wind and we look at the equinoctial pattern in our geomagnetic data, we find that it emerges as the pressure of the solar wind goes up; the pattern amplitude is a function of pressure. It is something to do with squeezing the magnetosphere and what we think happens is the component of the solar-wind pressure which squeezes the near-Earth tail and you squeeze it more if the solar-wind dynamical pressure is higher. That gives us a clue about where that equinoctial pattern is coming from. It is to do with the tail. What we find from models is that if we get a bending of the tail in the northern summer, it affects the stability of the tail and that is where the equinoctial path is coming from. It's nothing to do with transfer of energy into the magnetosphere — that is all RM. The modulation that confused us is how that energy which is stored as the magnetic field in the tail and how that is released and deposited — that is where the equinoctial pattern comes from and we know that because of the effect of squeezing.

Recently I have been working on the density of the thermosphere at a satellite altitude of 400 km put together from a time series of orbital decay measurements from spacecraft such as *SWARM*. Looking at the annual variations in that density, you see the equinoctial peaks and at the times you expect for the RM effect. There is an annual variation because it depends on UV illumination, so if I subtract the annual variation out, I start to see an equinoctial peak which has nothing to do with the sense of B_y so it's not RM but there is an additional RM effect on top of it. The bending of the tail affects the stability of the tail and that is really where the equinoctial pattern is coming from. If I take the threshold for sorting the IMF B_y component you see that that difference starts to grow so it depends on the strength of the IMF. People have proposed all sorts of reasons for the equinoctial peaks in photospheric densities and they have not really looked at the space-weather element which might be more important than we thought. [Applause.]

The President. I meant to say at the beginning that we were the only Society not to have a licence but Geological Society has one so we will have a drinks reception and it will be next door. The next meeting will be on Friday, February 13. What can possibly go wrong?

REDISCUSSION OF ECLIPSING BINARIES. PAPER 31: THE SLOWLY-PULSATING B-STAR SYSTEM CV VELORUM IN THE *PLATO* SOUTHERN FIELD

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CV Vel is a detached eclipsing binary containing two B2·5 V stars in a circular orbit of period 6·889 d. Both stars show line-profile variations arising from g-mode oscillations, characteristic of slowly-pulsating B (SPB) stars, and rotational axes misaligned with the orbital axis. We present the first photometric analysis of the system based on light-curves from a space telescope. By combining our results with published spectroscopic observations we determine the stars' masses to be 6·065 ± 0·015 $M_\odot$ and 5·950 ± 0·012 $M_\odot$, and their radii to be 4·094 ± 0·056 $R_\odot$ and 3·978 ± 0·049 $R_\odot$. The precision of the radius measurements is limited by the pulsations in the light-curves. We identify two confirmed (0·4886 d^{-1} and 0·3695 d^{-1}) and two candidate (0·7468 d^{-1} and 0·7048 d^{-1}) pulsation frequencies but cannot reliably identify further frequencies due to the short duration of the available light-curves (approximately 50 d). CV Vel is in the first field to be observed by the *PLATO* satellite so in future may become the first EB containing an SPB star for which we have a light-curve with a high photometric precision and a duration of over one year.

Introduction

Eclipsing binaries (EBs) are our primary source of directly measured properties of normal stars[1,2] because their masses and radii can be measured to high precision and accuracy using only light- and radial-velocity (RV) curves[3]. Detached eclipsing binaries (dEBs) are of particular value as benchmarks against which the predictions of single-star evolutionary theory can be tested. The current work is part of a project[4] to reanalyse known dEBs using published spectroscopy and new space-based light-curves[5], for inclusion in the *Detached Eclipsing Binary Catalog*[6] (*DEBCat*[*]).

In this work we present an analysis of CV Velorum (Table I), which consists of two B2·5 V stars in an orbit of period 6·889 d. A rare — possibly unique — feature of CV Vel is that both stars belong to the class of slowly pulsating B stars. SPB stars are gravity-mode pulsators with masses of approximately 3 $M_\odot$ to 8 $M_\odot$ lying within the main-sequence band[7,8]. They show multi-periodic g-mode pulsations of high radial order and frequencies normally from 0·25 d^{-1} to 1 d^{-1}, excited by the heat-engine mechanism[9]. SPB pulsations can be used to constrain interior properties such as the efficiencies of mixing and angular-momentum transport[10,11].

Only a few SPB stars are known in dEBs: that list includes V539 Ara[12], μ Eri[13], AR Cas, and AS Cam (papers in preparation), and a few others found in surveys[14,15]. The combination of pulsations and eclipses is expected to lead to new insights into the physics governing the evolution of massive stars[16], but light-curves of sufficient duration (several years) to study SPB stars in EBs remain unavailable. That may soon change, because CV Vel is in the southern field of the forthcoming *PLATO* mission[17]. Here we present a photometric study

*https://www.astro.keele.ac.uk/jkt/debcat/

TABLE I

Basic information on CV Velorum. The BV magnitudes are each the mean of 151 individual measurements [18] distributed approximately randomly in orbital phase. The JHK_s magnitudes from 2MASS [19] were obtained at an orbital phase of 0·76.

Property	*Value*	*Reference*
Right ascension (J2000)	$09^h00^m37^s.99$	20
Declination (J2000)	$-51°33'20''.1$	20
Henry Draper designation	HD 77464	21
Tycho designation	TYC 8177-1750-1	18
Gaia DR3 designation	5323799125200766592	22
Gaia DR3 parallax (mas)	1·7652 ± 0·0333	22
TESS Input Catalog designation	TIC 401238440	23
B magnitude	6·507 ± 0·012	18
V magnitude	6·679 ± 0·012	18
J magnitude	6·963 ± 0·024	19
H magnitude	7·016 ± 0·033	19
K_s magnitude	7·061 ± 0·020	19
Spectral type	B2·5 V + B2·5 V	24

of CV Vel using space-based photometry, measuring pulsation frequencies in this object for the first time.

CV Velorum

CV Vel was discovered to be eclipsing by van Houten in 1950 [25] in the course of a search for new variable stars using 18 photographic plates and a blink comparator. He found a period of 3·445 d and reported its spectral type to be B3.

Feast [26] discovered CV Vel to be a double-lined spectroscopic binary. He obtained the first spectroscopic orbit, based on 34 photographic spectra with reciprocal dispersions of 49 or 29 Å mm^{-1}, with a period of 6·892 d. That doubling of the orbital period is due to the primary and secondary eclipses being of very similar depth.

Gaposchkin [27] presented a photographic light-curve. He confirmed Feast's period measurement and, using Feast's RVs, provided the first determination of the masses and radii of the component stars.

Andersen [24] presented a spectroscopic study of CV Vel based on 32 photographic spectra [28] covering 3700–4700 Å with a reciprocal dispersion of 12·3 Å mm^{-1}. He found that "the two components appear virtually indistinguishable in both spectral type and luminosity" and adopted spectral types of B2·5 V for both. The lines were ideal for RV measurement due to their strength and low rotational broadening (given as 28 km s^{-1} ±10% for both components). Andersen measured RVs from 31 different absorption lines and demonstrated that line-blending causes an underestimation of the RVs of the stars measured from H and diffuse He lines. His final spectroscopic orbit rested on RVs from a set of ten strong and unblended lines arising from C, Ca, Si, Mg, and sharp He lines.

Clausen & Grønbech [29] observed CV Vel using the 50-cm Copenhagen telescope at ESO La Silla [30], obtaining complete coverage of the eclipses in the Strömgren u, b, v, and y bands. They found the secondary eclipse to occur slightly before phase 0·5, indicating a small but non-zero eccentricity. They modelled the data using the WINK code [31] and determined the masses and radii of the component stars. A light ratio of 0·90 ± 0·02, obtained on request by Andersen from his spectra, was used to constrain the light-curve solution and obtain a determinate value of the ratio of the radii of the stars.

Yakut *et al.* [32] obtained 30 high-quality échelle spectra of CV Vel and used them to determine new spectroscopic orbits and physical properties of the stars.* They found the secondary star (hereafter star B) to rotate faster than the primary (star A): $v_A \sin i = 31 \pm 2\,\mathrm{km\,s^{-1}}$ and $v_B \sin i = 19 \pm 1\,\mathrm{km\,s^{-1}}$. They also found both stars to show line-profile variations (stronger in star B than star A), with periods very uncertain but close to the orbital period. The physical properties of both stars are consistent with those of SPB stars. They found effective temperatures of 19000 ± 500 K and chemical abundances close to solar.

Finally, Albrecht *et al.*[33] obtained spectra of CV Vel during both eclipses to study the Rossiter–McLaughlin effect in the system[34,35]. They found star A to be misaligned with the orbit (sky-projected orbital obliquity $\beta = -52^\circ \pm 6^\circ$) and star B to be possibly aligned ($\beta = 3^\circ \pm 7^\circ$). In that model the precession of the spin axis of star A causes its $V \sin i$ to vary with a period of approximately 140 yr. The observed change in the rotational broadening of star B suggests it too has a significant true orbital obliquity, and that the measurement of β happened at a time when the sky-projection of the obliquity was low.

Photometric observations

CV Vel has been observed by the *Transiting Exoplanet Survey Satellite* (*TESS*[36]) mission in eight sectors so far, with a range of cadences. Sectors 8 and 9 were observed at 1800-s cadence; 35, 36, 89, and 90 at 600-s cadence; and 62 and 63 at 200-s cadence. We used the LIGHTKURVE package[37] to download the light-curves for all sectors from the *Mikulski Archive for Space Telescopes* (*MAST*†). Light-curves from the *TESS* Science Processing Center (SPOC[38]) are available for sectors 62 and 63, whereas only QUICK LOOK PIPELINE (QLP[39]) data are available for the other sectors.

We converted the light-curves from flux into differential magnitudes, specified the 'hard' option to reject data of lower quality, and subtracted the median magnitude from each sector. The results are plotted in Fig. 1, where eclipses and pulsations are both visible. We based most of our analysis on sectors 62 and 63 because of the higher time resolution of the data.

CV Vel is close to the Galactic plane so is in a relatively rich star field. A query of the *Gaia* DR3 database‡ returns a total of 405 sources within 2 arcmin of CV Vel and thus potential contaminants of the *TESS* light-curve. The brightest of those in the *Gaia* G_{RP} band, a red passband tolerably well matched to the *TESS* response function, is fainter by 4·46 mag. The fainter stars are relatively evenly spread so will be removed by the sky-subtraction step in the reduction of the *TESS* data. We therefore expect the amount of contaminating light in the *TESS* light-curve of CV Vel to be small but not zero.

Light-curve analysis

We concentrated our analysis on the light-curve formed by combining *TESS* sectors 62 and 63, totalling 21 746 data points, which have a higher time resolution than the rest of the data. The two stars are well-detached so are suitable for analysis with the JKTEBOP§ code[40,41], for which we used version 45. We fitted for the orbital period (P), a reference time of primary minimum (T_0; when star A is eclipsed by star B) close to the midpoint of the data, the sum ($r_A + r_B$) and ratio ($k = r_B/r_A$) of the fractional radii, the central-surface-brightness ratio (J), third light (L_3), and orbital inclination (i).

We included limb darkening (LD) using the power-2 law[42–44], using the same coefficients for both stars due to their extreme similarity. The linear coefficient (c) was fitted and the nonlinear coefficient (α) was fixed at a theoretical value[45,46]. We tested for the presence

*Note that Yakut *et al.*[32] switched the identities of the two stars[33]. Their results quoted in the current work have been updated to account for that.

†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

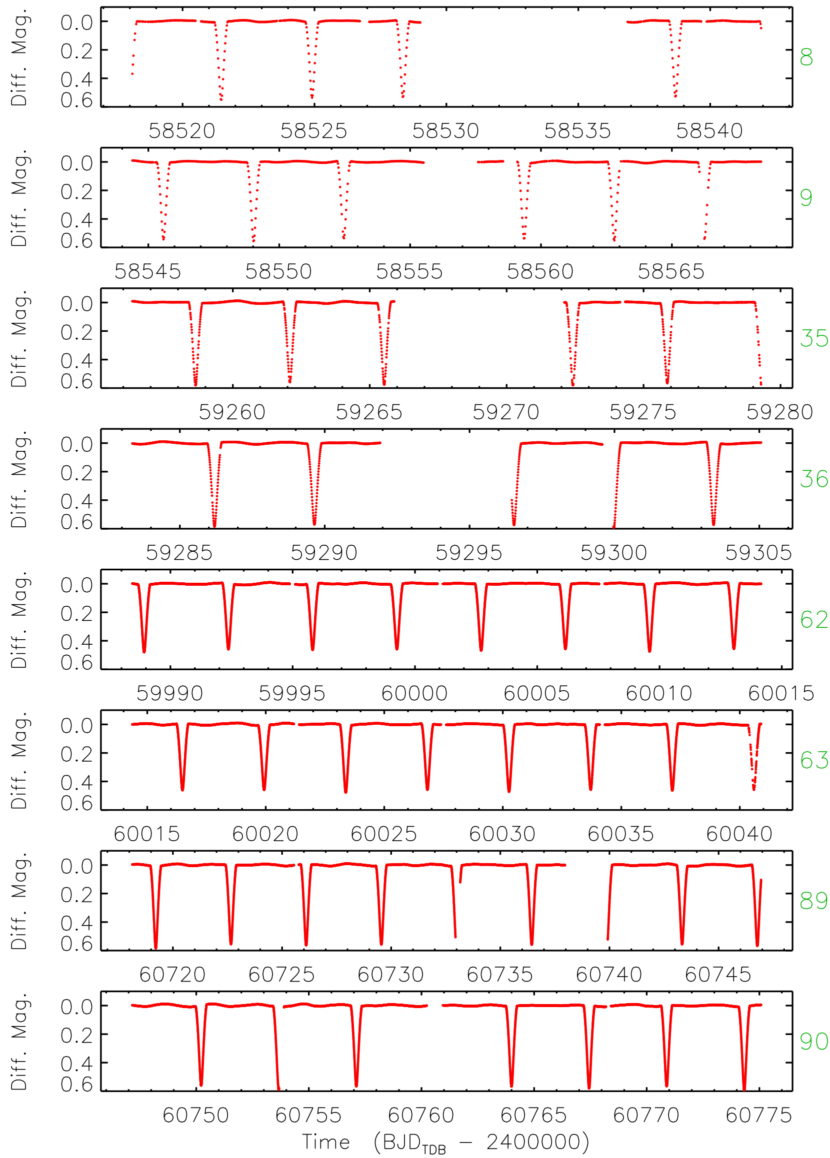

FIG. 1

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

of orbital eccentricity and found no substantive evidence, so assumed a circular orbit. The pulsations in the light-curve are of much greater amplitude than caused by effects such as which LD law to use and whether to include eccentricity, so our ability to tease out those

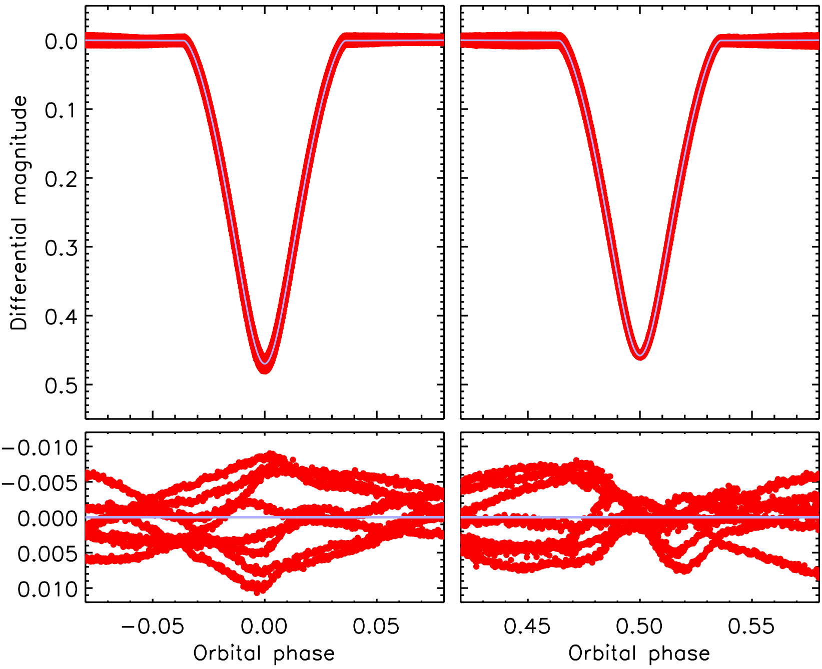

Fig. 2

JKTEBOP best fit to the light-curves of CV Vel from *TESS* sectors 62 and 63 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, and are dominated by the pulsations.

subtleties from the data is limited.

The best fit to the light-curve is insensitive to k, as previously noted for this system[29]. We followed Clausen & Grønbech in specifying a light ratio of 0·90 ± 0·02 measured by Andersen from two spectra of the system at quadrature. That light ratio was obtained at blue wavelengths but was applied directly in our JKTEBOP model of the much redder *TESS* data because the two stars have almost identical temperatures. We found that that light ratio gives a significant improvement in the determinacy of our light-curve model. For illustration, in Table II we give the best-fitting parameters with and without the inclusion of that light ratio. The amount of third light is small and consistent with zero, as expected.

We were able to obtain a good fit to the eclipses (Fig. 2). The residuals are dominated by the pulsations, which are at a maximum at the midpoint of primary eclipse and a minimum at the midpoint of secondary eclipse. As star A dominates the light of the system during secondary eclipse and is mostly obscured during primary eclipse, we deduce that the dominant pulsations in the light-curve arise from star B. That agrees with previous observations of stronger line-profile variability in star B than star A[32,33].

We determined the uncertainties in the fitted parameters using the residual-permutation algorithm implemented as Task 9 in JKTEBOP[47], thus treating the pulsations as correlated noise. There was no point conducting our usual Monte Carlo simulations as that algorithm assumes the data contain only the eclipse model and white noise. The best-fitting parameters and uncertainties are given in Table II. The uncertainties we find are driven by the pulsations, and are larger than those in recent publications[32,33]. Our orbital-inclination measurement agrees well with that from Clausen & Grønbech[29], so there is no evidence for changes in that parameter as might be caused by precession of the rotational axes[33].

We considered adding the *TESS* data from sectors 35, 36, 89, and 90 to this analysis, to average out the effect of the pulsations and potentially allow more-precise measurements of the properties in Table II. However, those data show much deeper eclipses (0·59 mag) than those from sectors 62 and 63 (0·48 mag) so it is not straightforward to combine them. Previous light-curves of CV Vel show eclipse depths in agreement with those from sectors 62 and 63, so we conclude that the different data-reduction procedures for QLP *versus* SPOC give an incorrect light-curve scaling. We have seen that before for other dEBs.

We then attempted to lower the error bars in Table II by removing the majority of the pulsational effects from the light-curve. We used PERIOD04 (see below) to fit and subtract 11 frequencies which plausibly exist, then refitted the light-curve with JKTEBOP. That gave a much improved fit but only a small change in some of the fitted light-curve parameters. The solution prefers a higher light ratio than that measured by Andersen, giving a ratio of the radii that is closer to unity and less consistent with expectations from stellar evolutionary theory. That new fit is also given in Table II for reference, but we did not use its results in the remainder of our analysis.

Orbital ephemeris

We calculated an improved orbital ephemeris based only on the *TESS* data. We fitted each pair of adjacent *TESS* sectors with JKTEBOP to obtain one effective time of primary eclipse per pair of sectors. Those are given in Table III. A straight-line fit to those data returns the following linear ephemeris:

$$\text{Min I} = \text{BJD}_{\text{TDB}}\ 2460009{\cdot}59629(6) + 6{\cdot}8894985(4)E \qquad (1)$$

where E is the number of cycles since the reference time of minimum and the bracketed quantities indicate the uncertainty in the final digit of the previous number. The scatter around the best fit is slightly larger than the error bars suggest, with a reduced χ^2 of $\chi^2_\nu = 1{\cdot}2$, so the uncertainties in the ephemeris have been multiplied by $\sqrt{\chi^2_\nu}$ to account for that. There is no evidence for a change in the orbital period based on those data, albeit over a small time interval. Further historical times of minimum exist, as do more recent survey data, which could be used for a more extensive search for orbital period changes.

Physical properties and distance to CV Vel

We determined the physical properties of CV Vel using our results from the light-curve analysis above (r_A, r_B, i, and P from Table II) and the JKTABSDIM code[48]. To those we added the velocity amplitudes of $K_A = 126{\cdot}69 \pm 0{\cdot}11$ km s^{-1} and $K_B = 129{\cdot}15 \pm 0{\cdot}11$ km s^{-1} from Albrecht *et al.*[33], adding the quoted statistical and systematic errors in quadrature to give a single error bar for each quantity. The temperatures of the stars were taken from Torres *et al.*[2], which are representative of most values quoted in the literature. The results are given in Table IV.

To measure the distance to the system we used the parameters above, the *BV* magnitudes from *Tycho*[18] and JHK_s magnitudes from 2MASS[19] given in Table I, and bolometric corrections from Girardi *et al.*[50]. A reddening of $E(B-V) = 0{\cdot}06 \pm 0{\cdot}02$ mag brought the distances in the *BV* passband into alignment with those in JHK_s. That led to a final distance measurement in the K_s band (which is least affected by reddening) of 568 ± 10 pc, in excellent agreement with the distance of 567 ± 11 pc from inversion of the *Gaia* DR3 parallax.

The age of the system was estimated by comparing the measured masses, radii, and temperatures to theoretical predictions from the PARSEC 1.2 evolutionary models[51]. We

TABLE II

Photometric parameters measured using JKTEBOP from the light-curve of CV Vel from TESS sectors 62+63. The error bars are 1-σ and are calculated from residual-permutation simulations. The adopted solution is the first one.

Parameter	ℓ_B/ℓ_A *constrained*	ℓ_B/ℓ_A *not constrained*	*With 11 frequencies removed*
Fitted parameters:			
Orbital period (d)	6·889466 ± 0·000056	6·889466 ± 0·000056	6·889488 ± 0·000027
Time of primary eclipse (BJD_{TDB})	2460009·59623 ± 0·00011	2460009·59623 ± 0·00011	2460009·59618 ± 0·00011
Orbital inclination (°)	86·652 ± 0·012	86·636 ± 0·051	86·645 ± 0·017
Sum of the fractional radii	0·2313 ± 0·0009	0·2315 ± 0·0008	0·2319 ± 0·0008
Ratio of the radii	0·971 ± 0·024	1·016 ± 0·091	1·009 ± 0·018
Central-surface-brightness ratio	0·9793 ± 0·0048	0·9792 ± 0·0048	0·9791 ± 0·0014
Third light	−0·0023 ± 0·0073	0·0000 ± 0·0065	0·0036 ± 0·0065
LD coefficient c	0·46 ± 0·11	0·49 ± 0·07	0·53 ± 0·08
LD coefficient α	0·3591 (fixed)	0·3591 (fixed)	0·3591 (fixed)
Derived parameters:			
Fractional radius of star A	0·1173 ± 0·0016	0·1148 ± 0·0072	0·1154 ± 0·0012
Fractional radius of star B	0·1140 ± 0·0014	0·1167 ± 0·0051	0·1164 ± 0·0012
Light ratio ℓ_B/ℓ_A	0·924 ± 0·042	1·01 ± 0·17	0·996 ± 0·035

TABLE III

Times of mid-eclipse for CV Vel and their residuals versus the fitted ephemeris.

Orbital cycle	*Eclipse time (BJD_{TDB})*	*Uncertainty (d)*	*Residual (d)*	*TESS sectors*
−212·0	2458549·02243	0·00013	−0·00018	08, 09
−105·0	2459286·19909	0·00009	0·00015	35, 36
0·0	2460009·59623	0·00011	−0·00006	62, 63
107·0	2460746·77262	0·00006	−0·00001	89, 90

TABLE IV

Physical properties of CV Vel defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 49).

Parameter	*Star A*	*Star B*
Mass ratio $M_{\rm B}/M_{\rm A}$	0·9810 ± 0·0014	
Semimajor axis of relative orbit ($\mathcal{R}^{\rm N}_{\odot}$)	34·899 ± 0·025	
Mass ($\mathcal{M}^{\rm N}_{\odot}$)	6·065 ± 0·015	5·950 ± 0·012
Radius ($\mathcal{R}^{\rm N}_{\odot}$)	4·094 ± 0·056	3·978 ± 0·049
Surface gravity (log[cgs])	3·997 ± 0·012	4·013 ± 0·012
Density ($\rho_{\odot}$)	0·0884 ± 0·0036	0·0945 ± 0·0035
Synchronous rotational velocity (km s^{-1})	30·06 ± 0·41	29·22 ± 0·36
Effective temperature (K)	18100 ± 500	17900 ± 500
Luminosity $\log(L/\mathcal{L}^{\rm N}_{\odot})$	3·210 ± 0·049	3·166 ± 0·049
$M_{\rm bol}$ (mag)	−3·28 ± 0·12	−3·17 ± 0·13
Interstellar reddening $E(B-V)$ (mag)	0·06 ± 0·02	
Distance (pc)	568·4 ± 9·5	

found an essentially perfect fit for an age of 40 ± 1 Myr assuming a solar metal abundance fraction by mass of $Z = 0{\cdot}017$. A lower metal abundance of $Z = 0{\cdot}014$ gives a slightly worse fit (but still well within the error bars) for an age older by 3 Myr. Similarly, a higher metal abundance of $Z = 0{\cdot}020$ leads to a preference for an age younger by only 1 Myr.

Pulsation analysis

The *TESS* light-curve of CV Vel shows clear evidence for multi-periodic pulsations (see Fig. 3), as expected from the prior detections of line-profile variations in both stars[32,33]. We combined the eight *TESS* sectors into four pairs, fitted and subtracted a JKTEBOP model, then calculated frequency spectra for each pair of sectors using version 1.2.0 of the PERIOD04 code[52]. Those are shown in Fig. 4.

All four pairs of sectors show the strong detection of an oscillation with a frequency of $f_1 = 0{\cdot}4886$ d^{-1}, an amplitude of 3·8 mmag, and a signal-to-noise ratio* (S/N) of 9·5. In the current paragraph we quote results from the data from sectors 62 and 63 as it has the lowest noise of the four pairs of sectors. A second frequency at $f_2 = 0{\cdot}3695$ d^{-1} and amplitude 1·6 mmag is detected with a S/N of only 3·6, lower than needed for confirmed signals[53], but its presence in all four sector pairs supports its reality. Two further candidate frequencies, $f_3 = 0{\cdot}7468$ d^{-1} (amplitude 0·9 mmag) and $f_4 = 0{\cdot}7048$ d^{-1} (amplitude 0·7 mmag) are detected with S/N values of 2·9 and 2·7, respectively. f_3 and f_4 are each visible in three of the four sector pairs so are likely real but not confirmable with the currently available data.

*The S/N is the ratio of the height of the peak to the mean signal within an interval of 2 d^{-1} centred on the peak.

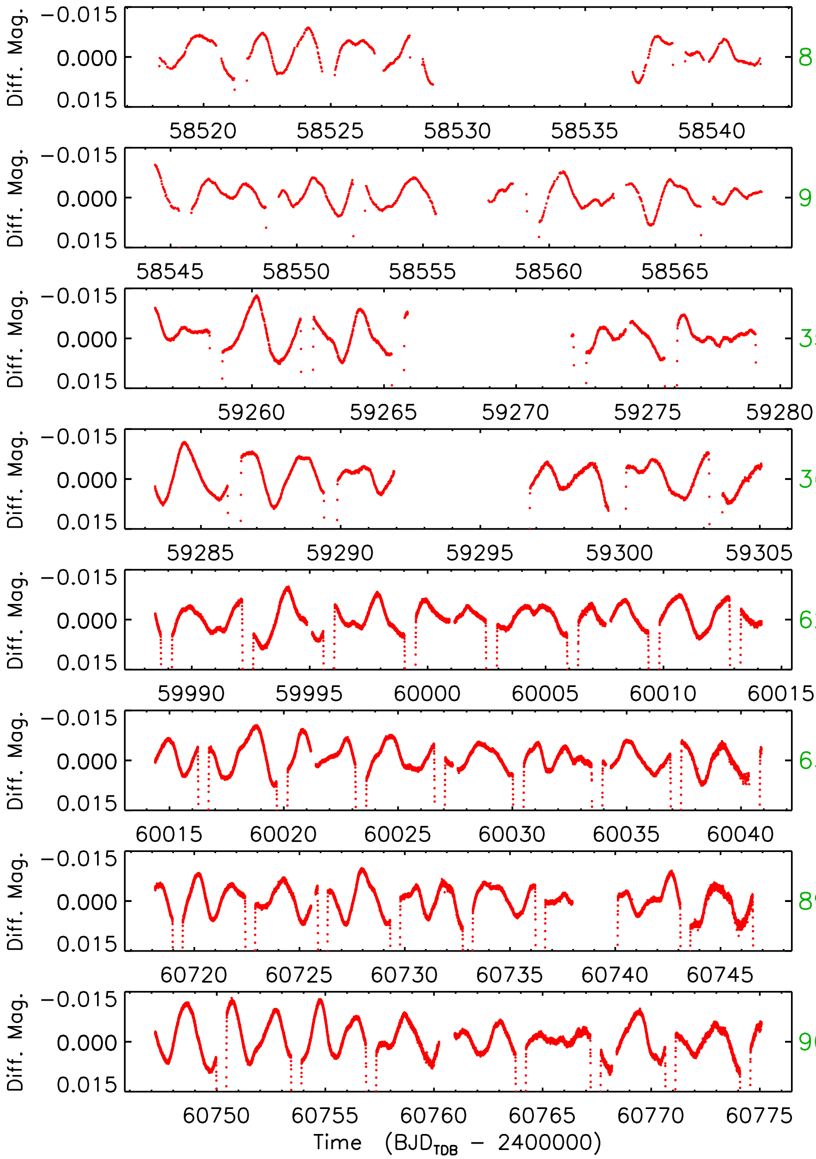

FIG. 3
Same as Fig. 1 but with the ordinate axis enlarged to make the pulsations clearer.

We did not see any peaks in the frequency spectrum near multiples of the orbital frequency. We also checked and found no significant frequencies from $1{\cdot}1\,d^{-1}$ out to the Nyquist limit of $215\,d^{-1}$.

The confirmed and tentative frequency detections all lie at low frequencies, in a range

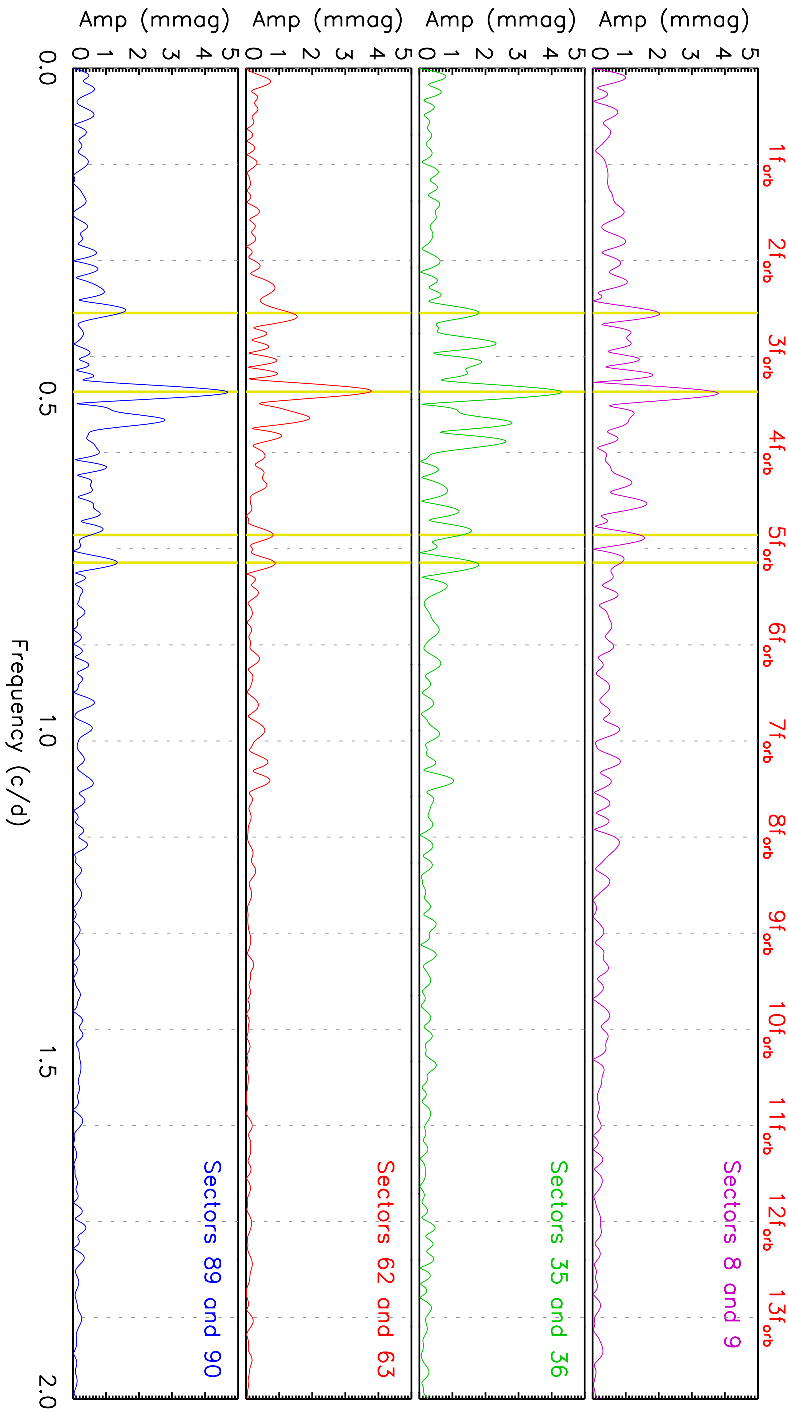

Fig. 4

Frequency spectra of CV Vel from the four pairs of *TESS* sectors (labelled in the top-right of each panel). The frequency spectra are plotted with coloured lines. Multiples of the orbital frequency are plotted with grey dashed lines and annotated at the top of the plot. The four frequencies discussed in the text are indicated with thick yellow lines.

characteristic of the SPB pulsators[8,14]. The properties of both stars are also inside and close to the hotter boundary for which SPB pulsations are expected[9]. As both stars show line-profile variations, we conclude that they are both SPB pulsators. We defer a detailed frequency analysis until light-curves of much longer duration are available in future.

Summary and conclusions

CV Vel is a dEB containing two almost-identical B2·5 V stars in a circular orbit of period 6·889 d. We have determined the masses and radii of the stars based on published spectroscopic studies and an analysis of light-curves from the *TESS* mission. The pulsations in the light-curve prevented us from determining the radii of the stars to high precision. We found a distance in good agreement with the parallax from *Gaia* DR3, and an age of 40 Myr from comparison with theoretical models. The rotational axes of both stars are misaligned with the orbital axis, and are precessing with periods of centuries. Due to that, the projected rotational velocities of the stars change over time.

Both stars are known to show line-profile variations indicative of pulsations of the SPB type. We have presented the first photometric detection of SPB pulsations and measured two certain and two tentative frequencies in the range 0·37 d^{-1} to 0·75 d^{-1}. Additional variability is visible in the frequency spectrum but no further frequencies are reliably detected in the available data. CV Vel is in the southern field (LOPS2[54,55]) of the *PLATO* mission[17], which is scheduled for launch in early 2027 and will observe that field for (at least) the first two years of its mission. Observations of CV Vel from *PLATO* will allow a much more detailed analysis of the radii and pulsation frequencies of the star, and we will be proposing it as a high-priority target in the *PLATO* Guest Observer programme[*].

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YOURFS: A READ-ONLY FILE SYSTEM FOR NON-LANDING DATA SCENARIOS ON ASTRONOMICAL SCIENCE PLATFORMS

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With astronomy entering an era of petabyte-to-exabyte-scale data from next-generation telescopes and surveys, existing cloud platforms face critical data-management challenges. Traditional approaches of mounting entire datasets or copying filtered subsets create trade-offs between access efficiency and storage costs, while conventional storage engines lack flexible permission control. To address that, this paper presents a POSIX-compliant read-only file system designed for non-landing data scenarios. The system integrates the FUSE (File system in USEr space) for POSIX interface implementation, libnfs for server-side data retrieval, and a database-driven metadata layer that enables file-level access isolation through sql-defined policies. This software aims to provide a curated and user-customized virtual view of massive datasets. It is suitable for data-filtering and small-file reading scenarios and can fully meet user requirements in those scenarios. The results demonstrate that YourFS effectively balances the accessibility and cost-efficiency of massive datasets, offering a viable technical paradigm for server-side data management in cloud-based science platforms.

Introduction

Astronomy has entered an era of big data due to the development of numerous ground-based and space-based photometric, spectroscopic, and digital sky surveys. For the projects constructed in the past few years, the data volume of sky surveys such as the Sloan Digital Sky Survey, *Large Sky Area Multi-Object Fiber Spectroscopic Telescope* (*LAMOST*), *Gaia*, and the *Transiting Exoplanet Survey Satellite* are still in the range of hundreds of terabytes [1,2]. In recent years, several next-generation large telescopes and surveys around the world, *e.g.*, the *Square Kilometre Array*, the *Five-Hundred-Meter Aperture Spherical Radio Telescope*, and the *Vera C. Rubin Telescope*, have been constructed, resulting in a sharp increase in data volume, and the data volume has already begun to reach the scale of petabytes (PB) or even exabytes (EB) [3–5].

Making data open is a tradition in astronomy, and the problems of data-storage and computing have been initially solved through large data centres. Cyber-infrastructure is becoming a crucial part of daily scientific research in astronomy, as the data sets are too large for astronomers to download and analyse using their own computers. Several pioneers also have designed many on-line services and tools to make data easily discoverable, such as SkyServer and CasJobs to provide browser and sql interfaces [6], and *Simbad* and *VizieR* to allow astronomers to query, explore, and analyse data on-line [7,8]. Modern science's reliance on enormous data sets, particularly evident in astronomy, has precipitated a critical demand for server-side analytical infrastructures, and usually a cloud scientific platform is provided for astronomers to work [9,10].

Science platforms offer a range of working environments yet exhibit shortcomings in data management. In terms of data management, different science platforms have proposed distinct solutions, which are technically divided into two categories. One category involves creating datasets based on scientific requirements and mounting them *via* links to provide data support for users' working environments[11–14]. The other category offers users access to interfaces through an application-programming interface (API) approach[15,16]. Given that the vast majority of astronomical software performs data processing by directly reading files through the POSIX protocol, the first method is more universally applicable. While the second method offers greater flexibility, it is not supported by most astronomical software and is thus more suitable for some newly developed astronomical software applications. The volume of astronomy data is immense, with individual datasets containing millions or even tens of millions of files. For instance, each sky-survey campaign of *LAMOST* yields an extensive set of spectral files*, and different scientists have varying research focusses and require distinct subsets of data[17]. To facilitate data access for scientific users, platforms often mount entire datasets or copy filtered results to users. However, researchers typically need only to examine a small fraction of the data. While the mounting approach reduces data-migration costs, it diminishes users' efficiency in locating specific data. Conversely, the copying method improves usability for researchers but dramatically increases data-storage costs. For common storage engines such as Ceph, BeeGFS, and GlusterFS, access permissions are typically controlled through ACLs (Access Control Lists). However, those implementations are often tied to hardware configurations, resulting in significant usability limitations and practical inconveniences.

For scientific users, data requirements are not static, and accessible scopes dynamically expand as data-protection periods expire or data-retrieval scopes change. Considering that the vast majority of current users prefer POSIX-compliant file systems and the widely adopted NFS (Network File System), this paper proposes a read-only file system with file-isolation capabilities, which implements essential POSIX interfaces. It enables users to mount remotely NFS shares transparently on local systems through an interface while defining file access scopes *via* a database, thereby achieving seamless cross-platform data sharing. In the technical-architecture section, this paper details the technical architecture and design of the file system, followed by a section which introduces the software-usage methods and application scenarios in astronomical science platforms. The last section presents system-test results and performance evaluation across usage scenarios.

The technical architecture

This file system is designed to be user-centric and fully customized, delivering a 'what you envision is what you obtain' experience, thus designated as YourFS. The software is developed in the c programming language, with its release version (v1.0) published and open-sourced on GitHub†. To achieve POSIX compliance, server-side data access, and data-isolation capabilities, the system employs FUSE (Filesystem in Userspace)‡ to implement the POSIX interface design. It dynamically invokes libnfs§ for data-loading operations and utilizes a database to define file-accessibility scopes, thereby establishing file-level access-isolation mechanisms through metadata-based permission constraints. That architecture ensures both protocol compatibility and granular security control in multi-user environments. The technical architecture is shown in Fig. 1.

Fuse and NFS

FUSE establishes a dual-layer architecture for user-space file-system development, con-

*https://www.lamost.org/lmusers/

†https://github.com/techwander/yourfs

‡https://github.com/libfuse/libfuse

§https://github.com/sahlberg/libnfs

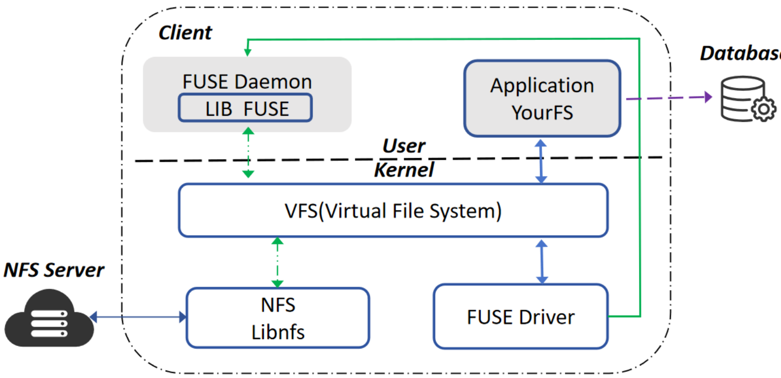

Fig. 1

The technical architecture of YourFS. The proposed system ensures POSIX compliance through FUSE implementation, facilitates server-side data retrieval *via* libnfs integration, and implements access-scope definitions through database-driven metadata constraints, achieving both protocol standardization and security enforcement.

sisting of a kernel-resident module and the libfuse user-space library. The kernel module mediates VFS [virtual file system] interactions *via* the `/dev/fuse` interface, while libfuse provides standardized programming abstractions for implementing file-system logic in user space, effectively bridging application-level operations with kernel-level file-system services. It demonstrates cross-version compatibility across Linux distributions, and that compatibility framework has made FUSE the *de facto* solution for implementing POSIX interfaces in modern distributed file systems.

NFS is designed to achieve cross-network file sharing and transparent access. Its core design philosophy enables client systems to access remote-server storage resources with the same operational semantics as local file manipulation, while maintaining cross-platform compatibility. As one of the most prevalent distributed file systems, NFS employs libnfs as its critical protocol-implementation library, which a supports cross-platform development interface, the NFSv3/v4 protocol, Kerberos authentication, and Access Control List (ACL) permission models.

Database

The database subsystem implements a metadata-driven authorization mechanism, where NFS-accessible paths are explicitly defined through sql-based policy configurations. That design ensures end-to-end access control validation before any file operation reaches the libnfs protocol layer. The database table implements a hierarchical storage model through three essential columns: parent, name, and realpath. Parent is the parent path of the file, name is the name of the file, and realpath is the absolute file path of the file in the NFS server mount point. This system implements conditional access control through database-driven authorization. When granting file access to a specific user, the corresponding lists are inserted into the designated database table. Conversely, those records remain unpopulated if access permission is not granted. The database tables can be configured for multi-user shared access with identical data-accessibility scopes, or alternatively, user-specific schemas may be independently defined to establish distinct access boundaries through metadata-based isolation mechanisms.

Runtime

The following describes the runtime logic when a user lists files in a directory in the YourFS file system. When a user process (*e.g.*, the `ls` command) is executed, the system calls `readdir()` to request directory contents. It is intercepted by the VFS layer and forwards it to the FUSE driver. The driver encapsulates the request into a FUSE protocol message and writes it to the `/dev/fuse` character device. The FUSE Daemon monitors the device *via* libfuse, which decodes the protocol message and triggers the `readdir()` callback function registered in YourFS. Then YourFS executes its custom logic to retrieve the directory in the database and queries metadata from a backend source *via* libnfs. The metadata is returned to libfuse and written to `/dev/fuse` *via* libfuse. The driver extracts the entries, passes them to the VFS, and the VFS populates the user process's buffer. The ls command receives the entries and displays them on the terminal.

Usage and application

In this section, we will detail the software's specific usage guidelines, including directory-organization methodology and database schema, along with its application to astronomical science platforms.

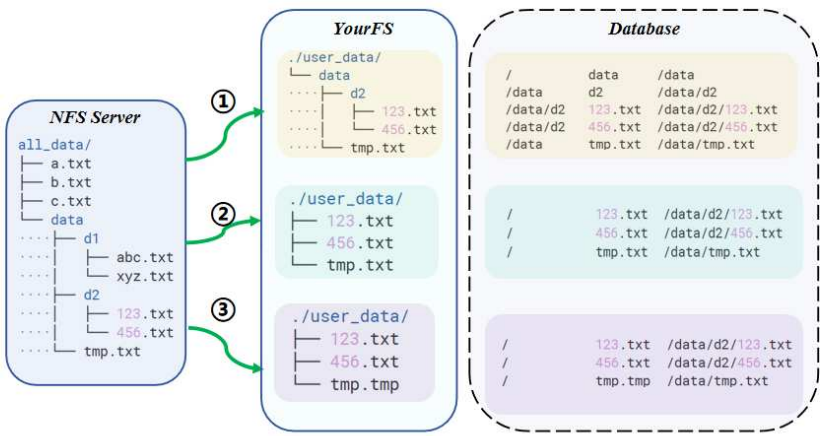

Fig. 2

This figure illustrates three examples of directory-listing customization. The left panel shows the file list in the NFS Server, the middle panel displays the mounted YourFS view (Partial File Display, Restructured Directory Hierarchy, Alias Creation for Specific Files), and the right panel presents the raw content stored in the database table.

Usage

The implementation of this file system primarily involves two phases: database construction and mounting operations. The database stores metadata defining accessible files, and the system dynamically generates a virtual directory structure based on the schema of the database tables, exposing only the authorized data to users. The NFS server hosts an enormous volume of directories and files, often reaching tens of millions of files in astronomical fields. In practical usage, however, users may require only a small subset of the data or even just a handful of files out of that vast repository.

To enhance clarity, three use-case scenarios have been designed to demonstrate the workflow and benefits of the file-system architecture. Fig. 2 illustrates three examples of directory-listing customization. The first example is used to display partial files, and it is usually used in partial-data-release scenarios. One needs only to write the file information involved to the data table. In astronomical applications, after cross-matching datasets, users often need to access only a handful of files, which are typically scattered across deeply nested directory hierarchies. That fragmented storage structure creates significant usability challenges. Example 2 demonstrates a directory restructuring example where modifying the parent-directory hierarchy consolidates those files into a unified view, achieving a flat, user-friendly structure for data access. Example 3 demonstrates how users can tag special files by creating aliases. That allows files to appear under modified names or paths in the virtual file system without altering their physical storage locations on the NFS server.

The YOURFS file system supports both SQLite3* and PostgreSQL† databases currently. Users can maintain backups of filtered data, enabling direct loading during subsequent usage without requiring redundant cross-referencing or retrieval operations.

Application to astronomical science platforms

In our science platform, there exists a vast amount of observational data; for instance, the *LAMOST* telescope has accumulated tens of millions of spectral-data records. In our previous solution, to facilitate user access to those data, we developed a data-retrieval system. That system allows users to obtain lists of desired data. Based on those lists, the system packages the corresponding files and generates download links. Users then utilize those links to download the data onto their data-processing virtual machines. To minimize data-download requirements and storage usage, we have integrated the platform with the YOURFS system to design an automated data-retrieval and -loading system. The system framework is illustrated in Fig. 3.

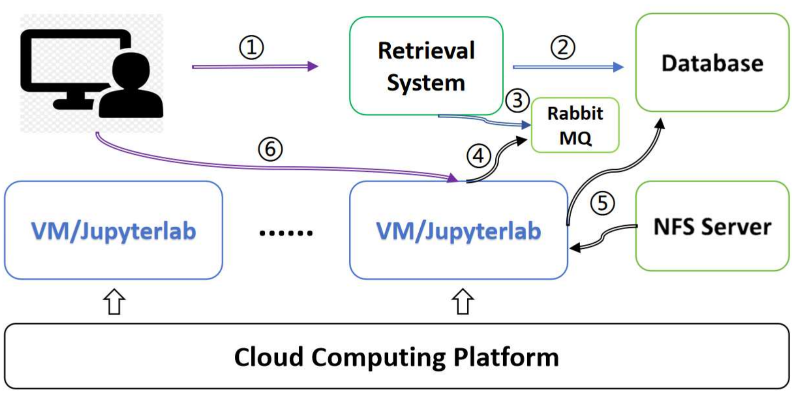

FIG. 3

This diagram depicts a typical application scenario of the YOURFS file system. Integration and testing have been completed on the NADC science platform. The YOURFS software is deployed on VM/JUPYTERLAB environments to provide users with data access services.

*https://www.sqlite.org

†https://www.postgresql.org

The user first accesses the data retrieval system through a web page. Upon retrieving the required samples, the backend of the retrieval system automatically creates a data table in the metadata-management database and writes the access information to the RabbitMQ message queue, including account, mount point, database, and so on. When the user's virtual machine detects information belonging to it in the queue, the VM automatically executes the relevant scripts. Those scripts simultaneously connect to the metadata database and mount the data directory from the NFS server. Consequently, when the user accesses the virtual machine, they can immediately view the required data with minimal latency. Since only partial metadata operations are involved, that process completes exceptionally quickly — typically within 3 seconds (<10 000 files) — enabling users to gain near-real-time access to the required data.

Performance test and comparison

Performance test

User experience is a critical metric for assessing storage-system functionalities. To enable objective evaluation, this test scope covers common user operations, including listing files and reading files. We designed a testing environment where the NFS and client reside within the same local-area network (LAN). The SQLite3 and PostgreSQL databases are deployed on the client and another server within the LAN, respectively. We tested the time required to list files in a single directory as the number of files increases from 1000 to 10 000. The test result is listed in Fig. 4.

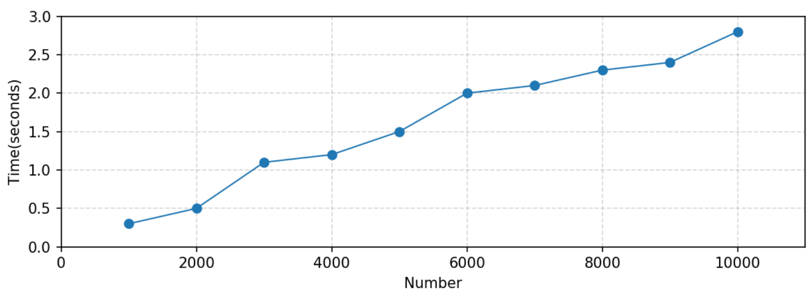

Fig. 4

This figure lists the time required (in seconds) as the number of files increases from 1000 to 10 000. Postgres is used as the database.

The tested values represent the average of 100 consecutive test iterations. The results indicate favourable response times. During testing, due to the caching mechanism, response times tended to decrease in subsequent test iterations. Notably, during the 5000-files test, the maximum response time reached over 2 seconds. In such scenarios, the user experience becomes noticeably degraded. Therefore, to ensure better performance, it is recommended to keep the number of files per directory below 5000. In the test using PostgreSQL as the database, the response times were similar to those of SQLite3.

In a gigabit local-area-network (LAN) environment, the random-file read speed can reach approximately 50 megabytes per second (MB/s) for a 1 GB file, which is around 70% of the performance of native NFS. Although significant performance gaps exist compared to the native NFS service, the solution delivers adequate user experience in most scenarios since retrieved datasets typically involve minimal data volumes. That is primarily due to the FUSE-based file system, where frequent context switches between user space and kernel space become the dominant source of latency. The software was originally designed to provide a curated, user-customized virtual view of massive datasets for numerous fragmented small files, and its read performance fully meets the demand for instant access to small files.

Comparison with other storage engines

In the field of computer science, a diverse array of storage engines has been developed to cater to different requirements, including mainly file storage, object storage, and block storage. Those storage engines serve as the underpinning of data-storage systems, with high performance and security as their core attributes, yet they lack flexibility in terms of file-level access-permission control. Although file-permission control is achievable through the ACL mechanism, it is inherently bound to individual users. Furthermore, it does not offer the directory-structure customization approach referred to in the usage section.

The file system proposed in this paper is a secondary encapsulation architecture based on file storage. That file system can build a virtual file system on any NFS-protocol-supported file system. It is non-exclusive of other file systems, which are adopted as its underlying storage substrate. By incorporating a database layer, it introduces file-level access-control capabilities. Although its performance is slightly inferior to that of traditional storage engines, it excels in flexibility and is thus more suitable for rapidly building customized small and even medium-sized datasets, while also delivering user-acceptable performance in practical applications.

Conclusions

YourFS presents an innovative solution to critical challenges in astronomical big-data management. By integrating FUSE's POSIX compatibility with NFS's distributed-access capabilities, coupled with a database-driven dynamic permission mechanism, the system provides a method for data accessibility and storage efficiency. Performance evaluations demonstrate the system's robust capabilities in operational scenarios. To ensure optimal responsiveness, maintaining fewer than 5000 files per directory is strongly recommended.

YourFS is designed for trusted multi-user environments (*e.g.*, internal scientific platforms), where users are granted read-only access to the entire shared file system by default. Its core value lies in providing a curated, user-customized virtual view of massive datasets, rather than enforcing strict isolation for proprietary or confidential data. That design choice aligns with the open-data tradition in astronomy and the requirements of non-landing data scenarios in trusted cloud platforms. For the performance, compared with native distributed file systems, the user-space FUSE layer introduces context-switch overhead, and the NFS backend cannot fully exploit the throughput of distributed storage architectures. YourFS is optimized for lightweight, on-demand data access in cloud scientific platforms, focussing on reducing data migration and storage costs instead of pursuing peak I/O throughput for ultra-large datasets. That positioning matches the typical usage patterns of astronomers who only require small subsets of massive survey data. The software has been successfully deployed on the cloud-computing platform and public dataset-sharing applications of the Chinese National Astronomical Data Center. It delivers outstanding practical performance, especially in data filtering and small-file reading, and can fully meet user requirements.

The upcoming release version 2.0 will implement advanced caching optimizations to boost software performance and significantly increase data-query efficiency, and the source code will also be open-sourced on GitHub.

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REVIEWS

Conjuring the Void: The Art of Black Holes, by Lynn Gamwell (MIT Press), 2025. Pp. 208, 22·9 × 30·5 cm. Price $44·95 (about £33) (hardbound; ISBN 978 0 262 04996 2).

Gamwell is a non-fiction author and art curator, her books concentrating on the relationship between science, its history, and art. When encountering 'black holes' and 'art' in the same phrase, I usually think of Peter Galison (director of the Black Hole Initiative, philosopher, professor of the history of science and physics at Harvard, author, and film-maker), and indeed he is the first person thanked in the extensive acknowledgements. After a foreword by Neil deGrasse Tyson and an Introduction, there are three chapters of vastly different lengths: 'Black Hole Basics' (24 pages), 'Historical and Philosophical Background to Imaging Black Holes' (18), and 'Artistic and Scientific Images of Invisible Objects' (126), followed by a one-page 'Conclusion'. Each chapter has several sections (three, four, and ten, respectively) which more or less alternate between science and art (or, in either case, its history). Thus, we have the sequence (at the end of the third chapter) 'Supermassive Black Holes', 'Black Holes as a Metaphor for Nothing, Silence, and Blackness', 'Gravitational Waves Caused by Merging Black Holes', 'Immersive Art About Black Holes', and 'Direct Observation of Black Holes by the Event Horizon Telescope'.

The science sections are at the level of a *good* popular-science book, probably better than all summaries of similar length I've read; they are correct but understandable and concentrate on the important features. Good is that Wheeler is *not* credited with coining the term 'black hole' (though he did much to popularize it), and a case is made (probably correctly) that the term is due to Dicke. We get a good overview of the history of the black-hole idea and of the most important concepts. Many of the figures related to science are from technical papers, and there is a spectrum from those, through scientific 'artist impressions', through cartoons and sketches, through quasi-realistic art, to abstract art. While many readers are probably familiar with Jean-Pierre Luminet's classic black-hole image, we are shown other examples from around the same time. I was pleased to find out that Luminet is also an artist; one of his drawings is reminiscent of the work of M. C. Escher (and the front cover of the album 'Inside the Triangle' by 1970s band Thee Image — the back cover features a band photo which will probably be too much for those who didn't live through those times). Whether Luminet's image or those from (simulations of) the *Event Horizon Telescope*, we get not just the pretty pictures but also the explanation of how they were made and what they actually show.

I know more about science than about visual arts. As in the sections about the former, in those about the latter we get summary texts and illustrations, though understandably the image-to-text ratio is higher in the latter case. Most of the art is modern and most art I like is not modern, but all the same I found both the text and image portions of the art sections interesting. There are also tie-ins between the modern science of black holes and related ideas in other times and cultures, but fortunately what is emphasized are interesting parallels, not *Tao of Physics*[1]-style woo.

This is a beautiful book. The dust jacket contains a hole, revealing a circle of black velvet (or something similar) in the centre of the front cover. I refrained from my usual penciled-in notes in the margins, putting them on a blank page at the end instead. However, very few were necessary, as there are almost no typos nor other things I often complain about in reviews. Somewhat unusual are headers and page numbers at the bottom of the page (and only on pages which are not solely devoted to figures and captions — there are many pages which are). All of the images are in colour except the few which are originally black and white, and the large format and slick paper make for an enjoyable reading experience; considering the high production standard, the price is more than reasonable. Five pages of endnotes are mostly references, but one is a very long list of 30 popular-science books in English about black holes published since 2020. (I've reviewed four of those in these pages[2–9], and several others I've reviewed from the same time also touch on black holes; there is no shortage of literature.) The page of 'Photo and Diagram Credits' contains only those which are not in the corresponding captions; since there are illustrations on nearly every page and many pages devoted solely to illustrations and their captions, there are many of the latter. An index corresponding to a bit more than three full pages ends the book.

There is also no other book like it. Whether for the combination of science and art or for a good overview of either, this is a good introduction to black holes and their role in our thinking. — PHILLIP HELBIG.

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The Arrow of Time: From Local Systems to the Whole Universe, edited by Cristian López & Olimpia Lombardi (Cambridge University Press), 2025. Pp. 315, 17 × 26 cm. Price £130 (hardbound; ISBN 978 1 00958 157 8).

There are many arrows of time (as "time's arrow" a term coined by Eddington): cosmological, thermodynamic, electromagnetic, quantum-mechanical, causal, weak-interaction, *etc*. When I was a student at the Hamburg Observatory, in the excellent library I found and read a book on *The Nature of Time*[1], the proceedings of a meeting held at Cornell in 1963, convened by Hermann Bondi and Thomas Gold, which is particularly interesting as it includes extensive discussion as well as the papers presented. (One participant is identified only as 'Mr. X'; the consensus is that he was Feynman. The fact that even Feynman didn't want his name to be associated with such discussions perhaps reflects the fact that many perceive them to be fringe or at least only marginally related to 'real science'.) Much modern discussion parallels that in that book; on the other hand, there has been progress, at least with respect to defining terms and making various points of view more clear, though there is still much disagreement about the nature of time, particularly time's arrow. This book is also the proceedings of a workshop (which took place in 2023 in Buenos Aires). The 16 authors of the 13 chapters (three have two authors) are primarily philosophers of science (though some work in physics as well). Many of the usual suspects are here, either as authors or cited in the references. (In most books on the philosophy of physics I have read, I came across various subsets of about thirty names; it is a relatively small field in terms of people actively working in it, though not in terms of scope.) The older book contains many authors known for their work in cosmology, astrophysics, astronomy, or General Relativity (GR), reflecting the fact that there was less specialization back then (and, of course, much less to know). These days, there are several full-time philosophers of physics, though many have a background in physics and most are very knowledgeable about physics, not just the philosophy thereof.

There is little actual astronomy in the book, even in the last, fourth part 'The Whole Universe'. On the other hand, most or all of the arrows of time are relevant for astrophysics, and the contributions provide a good overview of current thinking on the various arrows of time and the relationships among them. I was pleased to see two old papers (co-)authored by Tolman cited — not one of his many papers on entropy in cosmology (though his book on that topic[2] is) — but rather on thermal equilibrium in General Relativity[3,4]. I found useful the discussions on the distinction between time-reversal invariance, reversibility, and the arrow of time (Chapter 11) and on various ideas on how an arrow of time can arise even if the underlying physical laws are time-reversal invariant. An important role is played by the 'past hypothesis', a term coined by David Albert referring to the assumption that the Universe started in a low-entropy state* (and as such is a boundary condition rather than a law of Nature); most of the chapters cite his influential book on the topic[6]. There are, however, other ideas concerning the origin of various arrows of time, some of which I find intriguing and some of which seem to me to be rather desperate. Some of the contributions discuss the concept of free will and its relation to the arrows of time; there is certainly no consensus regarding free will†, though I hope that most readers agree with me that the idea of free will being able to change the *past* as well as the future is going too far.

The writing and editing are good, especially considering that the editors and many of the authors are not native speakers of English, and there are fewer typos and so on than in most

*Penrose[5] discussed the idea of a 'special' state of the beginning of the Universe in a somewhat different context.

†I don't think that I could believe in it even if I wanted to.

books I've reviewed in these pages (though Kip Thorne is transformed into Kip Throne). There are just a handful of black-and-white figures; notes are footnotes and each chapter has its own reference list (as is often the case in the philosophical literature, titles of articles are included, which I find useful in general and prefer unless space is at a premium); a two-page small-print index ends the book. This is a good introduction to and overview of the topic, and the extensive references are a good starting point for those wanting to explore the philosophical literature not just on the arrow of time but on physics and cosmology in general. — Phillip Helbig.

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The Universe: A Guide to Everything, by Helge Kragh (Reaktion Books), 2026. Pp. 188, 22 × 15 cm. Price £17·95 (hardbound; ISBN 978 1 83639 179 1).

I've read most of Helge Kragh's books and reviewed[1] one[2] in these pages. Kragh is a well-known historian of science and has written many books on the history of cosmology. In the preface, he clearly lays out his plan for the book: "Rather than aiming to describe what the universe *is*, the focus is on how people have conceived the universe, from the ancient Greeks to the present. It is a partial and inevitably selective history of cosmology, the science of the cosmos. The modern universe is in many respects entirely different from that of the past, but it does have a connection to the thoughts about the universe that emerged more than two thousand years ago." [Emphasis and capitalization as in the original.] His book is a marvellous success, in terms of both content and presentation — the book is extremely well written, better than most of those by native speakers of English. Although of course it can't contain everything, Kragh's selection of topics, all of which are clearly explained[*], are all good choices, and despite the necessary brevity he manages to mention some aspects which aren't usually mentioned. He does, though, spend the short first chapter briefly describing what the Universe *is*. Subsequent chapters cover the time up to Newton, stars and galaxies, and the expanding Universe (which includes not only standard relativistic cosmology which led to the current standard model, but also various alternative models, whether or not based on General Relativity). So far, so standard, but very well done. There is a thirty-page chapter on the Steady State model (only one page less than the longest chapter, the previous one on the expanding Universe). It was of course scientifically a dead end, but very important in the history of cosmology. (In contrast, Kragh notes that much of the work which now comprises standard references in the field received very little attention at the time: (some of) the works of Friedmann; Lemaître; Zwicky; and Gamow, Alpher, and Herman.) The penultimate chapter, 'New Horizons', covers such current topics as dark energy, the Hubble tension, and the standard or concordance model of cosmology. It is certain that those topics will remain not only a part of the history of cosmology but of cosmology itself. The final chapter, 'Beyond the Standard Model', discusses some for which the former is trivially true but perhaps not the latter: pre-big-bang cosmology, the far future and fate of the Universe[†]

[*] Kragh avoids common misconceptions involving the Hubble(–Lemaître) law (Kragh also suggests "Lemaître–Hubble"), cosmological horizons, cosmological expansion, the date of publication of the first paper on relativistic cosmology[3], the fact that Lemaître was *not* a Jesuit, *etc*.

[†] Although the laws of physics lend themselves just as easily to extrapolation to the future as to the past, the latter is much more popular than the former.

(citing a paper from this *Magazine*[4]), and the multiverse. The first and last of those topics are admittedly more speculative; my guess is that at least the last will become a standard part of cosmology and not just of its history. (For the long history of the multiverse idea, see an excellent book[5] reviewed[6] in these pages.)

So, is there nothing to complain about? I do have a few small quibbles. Some references (which refer to endnotes) are "quoted in Kragh. . . ". While 'quoted in. . . ' is actually preferable to a direct citation if the information comes solely from the cited source rather than the original, that is obviously not the case if the cited source is one of Kragh's own works. Although one can refer to the Hubble constant as the Hubble parameter, the fact that, in general, it is not constant in time is not a reason to do so. There are eight pages of colour plates at the centre of the book; some of the black-and-white figures scattered throughout the book could also benefit from colour reproduction. While the description of Olbers's paradox is correct, it might not be clear to readers less familiar with it that most of the proposed solutions — in particular, two which are mentioned — don't actually work. The de Sitter universe (empty of matter but with a cosmological constant; expanding exponentially) is described as static and spatially closed. That was indeed the way it was seen at the time, though the description is coordinate-dependent; today, it is usually described as spatially flat, of infinite extent, and of course expanding. That is difficult to make clear in such a book; for details see ref. 7.*

Both the reference list and the 26 items in the 'Select Bibliography' (I've read exactly half and reviewed five in these pages) are excellent jumping-off points for those interested in more details — often entire books correspond to just a few paragraphs in this book. (Although I appreciate the full-information references, somewhat strangely all journal volumes are in roman numerals, although the journals themselves in most cases use arabic.) A five-page index ends the book.

Everyone with even a slight interest in the history of cosmology should read this book, and even those who have devoted their careers to the topic will benefit. — Phillip Helbig.

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Astronomical Hazards for Life on Earth, edited by Gonzalo Tancredi (Cambridge University Press), 2025. Pp. 105, 25 × 18 cm. Price £98 (hardbound; ISBN 978 1 009 35308 3).

This slim volume, the proceedings of IAU Symposium No. 374, held in Busan (Republic of Korea) 2022 August 9–11, presents a partial summary of what was — or had the potential to be — a fascinating interdisciplinary symposium. According to the preface, the meeting included discussions of diverse astronomical risks and potential threats to life on Earth,

*Readers of German might want to consult a doctoral thesis by the same author[8] for more background on that as well as de Sitter's role in the early days of relativity and relativistic cosmology in general. The bulk of ref. 7 is also in German, but contains a foreword in English of more than 11 pages by David E. Rowe.

including those associated with solar variability and its long-term evolution, the effects of a supernova or gamma-ray burst close to the Solar System, a rare stellar passage through the Oort cloud, and even the ultimate fate of the Universe. Life's end poses questions as deep as those of its origin, and it would have been interesting to have seen a summary of key points arising from the contributions missing from these proceedings and the round-table discussions.

The book, conceived before the COVID health emergency but occurring (perhaps ironically) during health restrictions associated with the pandemic, unfortunately does not achieve its promise. Instead, most sections focus on different aspects of the near-Earth asteroid (NEA) impact hazard. While that might be a significant long-term threat to life on Earth (the threat to humanity is much greater), it is only one of many possible astronomical influences facing the evolution of life, whether on Earth or elsewhere.

Still, there are interesting papers. The editor's introduction gives a useful summary of various astronomical hazards that might occasionally affect life on Earth; several contributions show how different aspects of the impact hazard are now part of the corpus of 'normal' astronomical research, demonstrating how far the modern subject has advanced from its origin forty years ago in the weeds of the 'giggle' factor. There is a nice discussion of lunar impact events, and of possible fireballs that might be linked to the *c.* 370-m-diameter Apophis, which will pass within an astronomical whisker of Earth on 2029 April 13. Other papers discuss the relatively short (several Myr) time-scale for overturn of the observed NEA population, and how all-sky observational surveys will soon revolutionize our knowledge especially of small members of the population, presumably fragments of larger bodies.

In summary, this book will appeal to NEA specialists but probably not to the wider community of researchers suggested by its broad title. The cost, at nearly a pound a page, is disappointing. — Mark E. Bailey.

Astronomy and Satellite Constellations: Pathways Forward (IAUS 385), edited by Peter Grimley, John Barentine, David Galadi-Enriquez & Constance Walker (Cambridge University Press), 2026. Pp. 264, 25 × 18 cm. Price £98 (hardbound; ISBN 978 1 009 39922 7).

This is a review of the printed proceedings of IAU Symposium 385 (IAUS 385) held on 2023 October 2 in La Palma, Canary Islands, Spain.

This is only the second IAU symposium I've attended in-person; the first was IAUS 90[1*]. Curiously, CUP's on-line portal, Cambridge **Core**, has an information panel showing a date of 2024 December but published on 2026 January 19.

Given the rapidly moving subject of satellite launches and megaconstellations, the publication delay relegates the excellent papers published here to being an historical collection rather than a timely, useful work feeding promptly back into the community[†] — a point equally bemoaned by Helbig in his review[2] of the proceedings of IAUS 368.

The symposium was organized by the IAU Centre for the Protection of the Dark and Quiet Sky (IAU CPS) and partitioned according to the four 'hubs' within CPS: Community Engagement Hub, SatHub, Policy Hub, and Industry & Technology Hub. The total of forty-five papers in these proceedings are organized mostly in the order of the presentations in the programme, with about ten of those being separately contributed and poster-related papers following the others.

[*] For context, there was no 'on-line version' in 1979 as the internet really didn't take off until about four years later and the world wide web came about six years after that!

[†] The rapid growth of satellite megaconstellations is an *existential* problem for terrestrial astronomical observations and a growing challenge for orbiting observatories; astronomical research is under threat from fast-moving, politically unconstrained commercial interests and academic publication timescales are too slow!

Unfortunately there are about 35 presentations not present in the proceedings and no detailed report on the public session with UN Delegates & Observers held on the last day. Also, unlike the IAUS 90 proceedings, there is no inclusion of any Q&A discussion following each presentation though I certainly recall many such discussions. As such, these proceedings are not a complete representation of the symposium; perhaps there should have been more incentive for symposium contributors to submit papers for publication in the proceedings?

I agree with Helbig[2]: I find the paper used to be too thin with some text and dark/shaded diagrams showing through the paper.

There is a list of symposium participants but it doesn't distinguish between those who attended in-person and those who were on-line. Perhaps either an additional column for that list denoting in-person/on-line attendance or simply italicizing the names of those who were on-line would have made it clear. Also, it would have been a useful courtesy to include a key to the faces shown in the group photographs as was done for IAUS 90[1].

There is no use of colour in the book at all, maintaining a grey-scale for all of the figures. However, the on-line version uses colour for all submitted papers that included colour (including the symposium group photographs). Both Helbig[2] and Phillipps[3] mentioned the lack of colour in their respective reviews of IAU symposium proceedings (both published by CUP) with Helbig commenting that the printed version is more likely to be purchased by libraries and Phillipps suggesting that the lack of colour may be unimportant since the on-line version is likely to be more accessible to researchers (depending on the type of access).

That may also be true for other submitted papers but, comparing the source material of my own submission to these proceedings (p. 113) with what has been published, I noticed that the pie-chart figures have been significantly re-organized to optimize the use of space. Unfortunately, the associated pie-chart legends, kept with the relevant text, often became overly separated from their pie charts, necessitating a lot of page-flipping to match the legends to the pie slices.

In summary: for the price I would have expected a more complete record of the symposium, better-quality paper, and more use of colour. This is, however, a fair collection of papers covering a reasonably wide range of topics but, sadly, with about half of the presentations not appearing as papers and no post-presentation Q&A discussions included. For a topic of such importance to astronomy and its practitioners, the delay between the symposium and the publication is unhelpful. — Paul A. Daniels.

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Grubb Dublin and Grubb Parsons, by Ian S. Glass (Centre for Astronomical Heritage), 2026. Pp. 340, 29·7 × 21 cm. Price £0 (open acess) (on-line PDF file; ISBN 0 7503 0454 5 (previous edition)).

[This book is an expanded and updated edition of *Victorian Telescope Makers: The Lives and Letters of Thomas and Howard Grubb* (Institute of Physics Publishing Ltd), 1997, original ISBN 0 7503 0454 5. The copyright was ceded to the author in 2008. With many photos, traditional paper publication would be prohibitively expensive. It is freely available as a PDF file (formatted like a traditional book, and with both a fancy on-screen-reading interface and a link to the plain PDF file) at https://cfah.org.za/resources/grubb-glass and, with the permission of the author and in the interest of long-term availability, also at https://www.obsmag.org/issues/published/2026/08/grubb_dublin_and_grubb_parsons.pdf (plain PDF file) — Ed.]

This account by Dr. Glass of the successful evolution of the telescopes that formed and defined astronomy's own capabilities illustrates how parallel developments in industry, matched with home-made inventions and refinements, enabled the construction of large machinery that could be harnessed to achieve pointings on the sky of delicate precision and images of sub-arcsecond purity. To be sure, timing was everything; the founder (Thomas Grubb) was an exceptionally skilled engineer in many of the facets which telescope making required, and sufficiently supplied with the tools, facilities, money, and time that he could devote as long as it took to test, refine, and perfect instruments that all worked to spec. Glass has presented us with a masterful account of the achievements of this adventurous, industrious, and successful team, introducing numerous correspondence with like-minded astronomers and technicians in Europe and beyond, and sprinkling it with touches of family life and enough humour to render the book eminently readable from beginning to end. The result is a product of commendable scholarship, and deserves a place in every library that caters to general science, engineering, and the history of science, as well as astronomy.

The successes which the Grubb team could chalk up seemed to be due to the ability to stay ahead of the game. All the various stages of building, whether in driving heavy machinery yet maintaining delicate positional accuracy, annealing glass blanks to form acceptable bases for large mirrors, fabricating achromatic lenses, or grinding and (particularly) figuring and polishing the mirrors themselves, their techniques and materials could benefit from the abundant R&D which their processes engaged. As Glass relates, their heyday was the mid-to-late Victorian decades, and if their later merging with the (also Irish) Parsons Company could be regarded as an inevitable product of the rigours of two world wars, a number of the Grubb or Grubb–Parsons instruments are still in active service today. This book is well illustrated by images of both people and equipment, and concludes with lists of products from the original Dublin and the later Newcastle (UK) companies, furnishing a fine sense of the substantial and significant output which owes its roots to the foresight and persistence of Thomas Grubb's efforts on his first creations.

Scotland (through James Watt) gave us the steam engine, Wales (in the person of Philip Vaughan) the ball bearing, England (by one John Harrison) the chronometer, and Ireland (through the Grubbb family) the telescope. As Glass shows, it wasn't a question of being academic, but of knowing one's materials, the best tools to work on them, and (also) of achieving therewith a near monopoly for several decades in this specific field of observational astronomy. — Elizabeth Griffin.

The Impossible Man: Roger Penrose and the Cost of Genius, by Patchen Barss (Atlantic Books), 2024. Pp. 247, 24 × 16 cm. Price £33·35 (hardbound; ISBN 978 1 83895 932 6).

Roger Penrose needs no introduction. Patchen Barss does, at least to me. He is a Toronto-based science journalist with the usual credentials but also author of *The Erotic Engine: How Pornography Has Powered Mass Communication, from Gutenberg to Google*. At first glance, that might seem rather removed from Penrose, but a (to me) surprisingly large part of the book being reviewed is concerned with Penrose's (real and hoped-for) sex lives. As the author notes, Penrose cooperated intensively and extensively with the author, but the book is not an authorized biography in that Penrose didn't approve (or reject) any of the contents.

The prologue introduces us to the current Penrose, before a capsule history of the Universe brings us up to his birth and a very brief description of his life. The next few chapters are what one might expect: parents, siblings, childhood, undergraduate studies, his interest in Dutch artist M. C. Escher, doctorate, marriage. Those chapters give an idea of some of the influences which shaped Penrose, but to me they don't seem as special as the author makes them out to be. We then follow Penrose (on a NATO fellowship) to the United States (where he worked at Princeton, Syracuse, and Cornell), learn about his stillborn daughter, and meet some of his friends and colleagues, such as Wolfgang Rindler, Ted Newman, John Wheeler, Ivor Robinson, Andrzej Trautmann, and Engelbert Schücking, but I would have liked to learn more about them. Penrose's first wife Joan was from Detroit, and his father offered the newlyweds a cottage he owned across the border in Canada, Blink Bonnie, which became something of a North American base for Penrose. The conference in Jablonna (Poland) was one of the legendary conferences on General Relativity, and we are reminded about how much more adventurous travel was in those days.

Oil money attracted many relativists to Texas in the 1960s, including Penrose, who, however, quickly became disenchanted with Austin and the States in general (around the time of and partly because of the Kennedy assassination). Before setting off for Texas, they had visited Escher in the Netherlands, accepting a print as a gift, and son Christopher was born. In Austin, Penrose was in the company of of Schücking, Roy Kerr, and Ray Sachs, and just a few hours away in Dallas were Rindler, Robinson, Alfred Schild, and Istvan Ozsváth. Scientifically, he was the right person in the right place at the right time, but of course Texas is very different from the northeastern United States, and the Kennedy assassination was a real shock. He was killed while many of Penrose's colleagues in Dallas were waiting for him to arrive and address them.

Back in England in 1964, Penrose became a reader at Birkbeck College, and 22 months after Christopher, son Toby was born. At that point, the book shifts the emphasis somewhat from travel to Penrose's work, and we learn about Penrose diagrams, the singularity theorems (Penrose quoted as believing that Hawking got too much credit for their joint work), and his work on spinors. Around 1970, domestic life had become predictable, but Penrose was convinced that his most important work lay in the future, and he began to advertise himself *via* popular-science articles and so on. His sister Shirley mentioned that her childhood friend Judith Daniels was now studying maths. Penrose fell in love with Daniels, and the book quotes extensively from their correspondence; the letters had been made available to the author by Penrose. She comes across as something like Einstein's first wife, with whom he discussed his early work, but with time Daniels could no longer follow Penrose's increasingly complex forays into twistor theory. Penrose saw her as a muse, but also wanted more, which she made clear would not happen, at a meeting in Trieste. Despite the lack of a sexual relationship, their 'affair' ultimately led to the end of his marriage to Joan, and a professorship at Oxford was a welcome opportunity to leave the family (now including third son Eric) behind in London. (Before the Rouse Ball Professorship at Oxford became available, Penrose had considered applying for the Plumian Professorship at Cambridge, as Fred Hoyle had resigned — in part because he knew that Joan didn't like Cambridge and hoped that that might facilitate a break-up without him having to take the initiative. The Plumian Chair went to Martin Rees.)

That was the time of Penrose's work on aperiodic tiling. In general, things were looking up: a prestigious position at Oxford, his widowed mother happily remarried, separated from Joan, and still in contact with Judith. In the 1970s and 1980s, while still based in Oxford, Penrose was a frequent visitor to Dallas, Austin, and Houston. Here he met Salley Vickers, who had followed her husband (a former student of Dennis Sciama) to Austin. After a failed marriage with children, she and Penrose found common ground, eventually living together in California after Penrose had accepted a sort of adjunct associate professorship at Berkeley. Though she knew less about maths and physics than Judith, Penrose saw her in a similar role. However, in this case, Penrose realized that it wouldn't work out, and ended the relationship (which is also what Vickers wanted) after returning to England.

In 1987, another student of the ubiquitous Dennis Sciama, David Deutsch, became a postdoc with Penrose (who had helped him publish a paper on quantum computing a couple of years before). Although Deutsch had only one meeting with Penrose's relativity group, they often discussed quantum computing, consciousness, and so on. We learn about Penrose's disagreeement with Hawking regarding the black-hole information paradox, and the — at best — mixed reception to his books expounding his ideas on consciousness[1,2]. Around the same time, Penrose married his doctoral student Vanessa Thomas, who is 34 years younger. Although an obvious conflict of interest might have been avoided by switching to some other supervisor, it would be interesting to know why "she had no choice but to leave her DPhil unfinished when they married". They had a son, Max, in 2000, and remained together for another twenty years or so. The prologue introduces Penrose shortly after their separation, living alone, brewing coffee every Friday, and microwaving cups of it as needed throughout the week. During the corona pandemic, he made his own muesli every two weeks, and used one of two baths for banana storage, keeping them under water *via* a glass plaque he had received in return for delivering a talk in Texas.

While controversial, Penrose's later books[*] had become successful, and he described his work in physics in a massive tome[5] (the first edition of which probably contains more typos than any other book I have read). Later books presented his unorthodox views on cosmology[6] and his general disenchantment with current trends in physics[7]. The last proper chapter ends on a sad note, with an abortive attempt to set up a Penrose Institute and Penrose once again seeing a woman as his muse who didn't want to be seen as such, this time Ivette Fuentes(-Schuller), now a professor of quantum physics at Southampton. She did save Penrose from future embarrassment, though, by rejecting funding from Jeffrey Epstein. By selling the family home, Woodlands, Penrose purchased a house for himself, one for Vanessa Thomas, and a flat for himself within walking distance of his office. The final chapter returns to the scene of the prologue and details how Barss and Penrose began the many interviews which played an important role in the book, with Penrose insisting that Barss read the correspondence with Judith, which her sister had found after Judith's death in 2005 and had returned, unopened, to Penrose. Many people close to him had recently died: Hawking in 2018, Rindler and Joan in 2019, Newman and Penrose's younger brother Jonathan (a chess grandmaster) in 2021.

A long author's note and acknowledgements section explain how the book came about, and who was involved. All is well documented. At the same time, the author is aware that memories might not be accurate. There are a handful of black-and-white figures throughout the book. There are no footnotes but 14 pages of endnotes (mostly citations to sources). A thirteen-page small-print index ends the book.

Of course, biographies of scientists often include a description of not just their scientific work, but also their 'life and times', including aspects of their personal lives, and it varies from scientist to scientist how important one aspect is for the other, and from reader to reader how interesting the various aspects are. A biography of Richard Feynman which ignored his personal life would not only be less interesting but also a misrepresentation, as his personal life is something which he himself often publicized. With Penrose, the situation is somewhat different, as he didn't publicize his private life. While that in itself might not be a reason to ignore it, or at least to devote less space to it, my impression is that Barss makes two mistakes: he paints Penrose's personal life as somewhat unusual, whereas as far as I can tell it was par for the course for a man of his generation, family, social class, *etc*., and one gets the impression that the 'mistakes' in his personal life were somehow the price he had to pay in order to excel academically. One might think that Penrose, who is old, somewhat blind, and lives alone, didn't realize what direction the biography would take. On the other hand, he often complained that the establishment (though, as detailed in the book, at one point it was pointed out to him that he himself had become the establishment) didn't appreciate his work enough, and on other occasions at least seemed to take the view that any publicity is good publicity. As the scientific and personal aspects are intertwined in the narrative (rather

[*]While earlier, more technical, books, such as the two volumes co-authored with Rindler[3,4] were not controversial as such, neither did they attain the popularity and influence for which Penrose had hoped.

than being separated by chapters or sections, say), readers not interested in the latter (I can't think of any who would be interested in the latter but not the former) can't easily read around them.

I learned much about Penrose which I didn't know before. How much I needed to learn (and about what) is another question, and I would have liked more in-depth descriptions of various aspects of his work, such as the singularity theorems, spinors, non-periodic tiling, *etc.*— but at a level less demanding than in his rather technical *magnum opus*[5]. (Other aspects of his work, such as his recent ideas on cosmology and his somewhat older ideas on consciousness, don't interest me as much, and also Penrose has documented them well at the desired level in other books[1,2,6].) As there is not much concrete description of science (Penrose's or others'), there was little opportunity to notice mistakes. However, an expanding Universe does not necessarily imply that it must have a beginning. A newborn certainly has more than two trillion atoms. I also doubt that Hawking had to pursue mainstream success because he needed money to cover medical and physical care.*

In summary, I didn't feel that reading the book, which is written well, was a waste of time, but I think that a shift of emphasis would have made that time more valuable. — PHILLIP HELBIG.

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Starwatchers: Our Journey of Discovery in the Night Sky, by Joanne Baker (Bloomsbury), 2026 (first published 2025). Pp. 271, 20 × 13 cm. Price £10·99 (paperback; ISBN 978 1 5266 0801 7).

I remember Joanne Baker from cosmology conferences in the second half of the 1990s. After a good career start in academia (doctorate from the University of Sydney, NASA Hubble Fellow at Berkeley, Royal Society University Research Fellow at Oxford), she moved into writing (books) and editing (for *Nature* and *Science*). This book has three (long) chapters (divided into sections) on the Moon, the Solar System, and the rest (stars, galaxies, the Universe). Like a few other books[1–4] I've recently reviewed[5–8] in these pages, it is not about just astronomy but also the relationship between humanity and the heavens. The emphasis on the latter is strongest in the first chapter and weakest (but still present) in the third. I particularly enjoyed the first part, perhaps because I learned the most from it. While many expected topics are explored, we also get details on James Nasmyth and his lunar models, 'Moon madness', and non-Western cultures. The second chapter is the longest. It is not a systematic survey of the Solar System, but a mixture of planetary science, the history thereof, and the role the planets have played in human history. Like the rest of the book, the aim is to explore selected topics in a bit more detail, rather than give a superficial survey of many more. The third chapter covers astrometry, stellar distances, the Milky Way, spiral galaxies,

*Hawking has stated that he was happy with NHS care. Much later, after his tracheotomy in 1985, the NHS would have paid for nursing-home care or less than round-the-clock care at home, but as his wife wanted him to remain at home with round-the-clock care; the bill was footed by the MacArthur Foundation.

and the 1920 'Great Debate' between Shapley and Curtis*, before shifting gears somewhat to discusss the influence of modern physics on astronomy, radio astronomy, extraterrestrial life, radio astronomy, black holes, the dark sector, philosophical aspects of cosmology, and the possible fates of the Universe. The epilogue, like the introduction, provides details of Baker's own quest to connect with the Universe.

As usual, I have a few complaints about the discussion of cosmology. While some of them concern what are probably just careless typos or bad editing (on the whole, though, the book is written and edited well), the claim that "there was no need for a repulsive force to counter gravity, or to fling bodies apart" in Einstein's original cosmological model, and thus astronomers struggled to explain the expansion of the Universe, is essentially backwards: *without* such a force (a positive cosmological constant), Einstein noticed that he could not have the static model he wanted, so introduced such a repulsive force, though to keep the universe from collapsing, rather than causing it to expand. (It was later realized that there are non-static cosmological models both with and without a cosmological constant.) Perhaps the confusion stems from the wrong idea (which I've noted in some other reviews) that the cosmological constant (or dark energy) somehow causes the expansion of the Universe (not just its acceleration). Later on, she writes "Back in the 1910s, Einstein set [the value of the cosmological constant] to zero and it was effectively dropped: there was no need for it, and it made no difference to the calculations." Again, essentially backwards. (Later on, Einstein did drop the cosmological constant once he realized that the Universe is expanding, and of course it can make a profound difference to the calculations.) Another blunder is lumping different sorts of Multiverse into the same category; Tegmark[9,10] spells things out clearly. However, that is made up for by alerting me, in the suggestions for further reading, to a book on the Multiverse I hadn't yet heard of[11].

The book is written well and there are fewer typos and questionable style choices than in most books I've reviewed in these pages. There are 16 pages of high-resolution colour plates at the middle of the book, a useful addition. There are neither footnotes nor endnotes. The main text is followed by two pages of acknowledgements, four of suggestions for further reading grouped by chapter (about 20 suggestions, mostly books, for each), a particularly thorough ten-page small-print index, and a page of picture credits. I've read several of the books suggested for the topics in the third chapter, and reviewed some of them here.

This book should be added to a list of books to read on the history of the relationship between humanity and the heavens. While modern astronomy gives us more data than ever before, even many astronomers, not to mention non-astronomers, don't have the emotional connection to the sky which was common in the past. While observations improve almost automatically due to better technology, the emotional bond, in the past part of the culture, is something for which today one has to take the time to form on one's own. The rewards might not be conventional ones, but nevertheless worth pursuing. — PHILLIP HELBIG.

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*Baker describes Curtis as "working just up the road" from Shapley. At the time of the debate, Shapley was at Mount Wilson and Curtis at Lick (moving to the Allegheny Observatory later in the year). After his move to Harvard the following year, Shapley perhaps became more famous, but at the time Curtis, more than 13 years older, was the senior figure.

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Weird Universe: Everything We Don't Know About Space (and Why It's Important), by Erika Hamden (Mango), 2025. Pp. 189, 20·5 × 13 cm. Price £15·99 (paperback; ISBN 978 1 68481 728 3).

Erika Hamden is professor of astrophysics at the University of Arizona, where she is also director of the Space Institute. In 16 chapters (plus introduction and conclusion), this is an 'interesting facts' book, in that respect similar to a few[1–3] I've reviewed[4–6] in these pages, though the chapters here are longer. One could group them into 'General Relativity and Cosmology', 'Stars', 'Planets' — moving in — before moving out to the early Universe, the future of the Universe, and the dark sector, concluding with a couple of summary chapters. The topics are perhaps 'weird' in the sense that they differ from our day-to-day experience, but are thoroughly mainstream science. (Of course, the book doesn't really include *everything* we don't know.) By choosing only a few topics, somewhat more depth is possible than with typical popular-science-level introductions to astronomy.

Sometimes good things come from mistakes. In this case, her clear statement (p. 90) that 'revolution' in the political (or similar sense) is due to Copernicus's 'revolutions' (the *revolutionibus* in the title of his famous book) having a similar effect on science caused me to investigate the etymology. Both stem from the Latin term for 'turn around', but both meanings arose independently. (In fact, in the political sense the original meaning was more that of a cycle or return to the 'good old days' than the violent overthrow of an *Ancien Régime*, the latter becoming common only after the French Revolution.) Thus, 'Copernican revolution' is a pun or loaded metaphor. But sometimes they don't. As is often the case, some common cosmological misconceptions are repeated, such as the ideas that dark energy is responsible for the expansion of the Universe (p. 158). A very charitable reading could make a case for a confusing passage (p. 165) being correct, but most readers will probably take from it that a 'coasting universe' "in which the expansion continues forever, but at an unchanging rate" would be substantially younger than our Universe. Actually, by what appears to be coincidence, the age of our Universe is almost exactly the same as that of such a 'coasting universe'[7,8]. It's not the first time I've wondered why an author is so confident (p. 165) that our Universe is spatially infinite (though of course the observable Universe is not). Observationally, we don't know, since it is very close to being spatially flat, which is the border between finite and infinite. Theoretically, there are various arguments favouring a finite Universe. Similarly, I've often read that it is possible to measure the recession velocity of a galaxy (p. 167); it can be calculated *via* $v = H_0 D$ (the Hubble constant relates the expansion rate to the proper distance, independently of the cosmological model — but if we already know the distance, we don't need the velocity to do cosmology.*) A somewhat rarer claim (p. 168) is that "the most distant galaxies . . . were moving away from us *faster* than they should have been if the expansion of the universe were constant" [emphasis in the original]. Actually, it is the other way around, as the present expansion rate is fixed by H_0; acceleration thus implies that distant galaxies were moving *more slowly* when the light we detect today was emitted. (The current expansion rate is of course given by $v = H_0 D$.) On p. 176: "Dark matter was first discovered and observed by the American astronomer Dr. Vera Rubin in the 1960s." The concept of dark matter and observational evidence for it goes back much further (*e.g.*, ref. 10 and references therein). (Also, "in the 1960s" is stretching it a bit; presumably the first flat-rotation-curve paper co-authored by Rubin[11] described some work which might

*See the more detailed discussion in another review[9] in these pages.

have been done in the late 1960s, but that paper did not claim evidence for dark matter.*) Equating fine-tuning with the Anthropic Principle (p. 183) is at best misleading. (To be fair, much confusion exists around those topics (*e.g.*, ref. 12 and references therein).) The claim that the early Universe was dense enough to be a black hole (p. 180) is at best misleading. On the other hand, she doesn't make the common mistake of claiming that Wheeler coined the term 'black hole' (p. 28). My guess is that, as in most popular-astronomy books, most of the mistakes concern cosmology, but I noticed some in other areas as well. Especially because of its historical importance in the discovery of asteroids (which *is* discussed), I missed a mention of the Titius–Bode rule for planetary distances; "every planet is about twice as far from the Sun as the planet before" is a much worse approximation (slightly more accurate only for the distances of Saturn and Uranus). I also wondered why "we don't have a deeper understanding of why" the conservation of angular momentum exists; surely Noether's theorem and the isotropy of space are sufficient.

A few other errors I put down to carelessness or bad editing. On the whole, though, the book is well-written and I have only about my average number of complaints concerning style and so on. I did find it rather distracting, though, that the text is in a sans-serif font with relatively large interline spacing (similarly to another book recently reviewed[13] in this *Magazine*). There are only a handful each of black-and-white photos and footnotes; there are neither references/bibliography/further reading nor an index nor any acknowledgements, but a short biography of the author.

Despite my qualms (which refer to only a minority of the subjects discussed), in particular my standard complaints about cosmological misconceptions, this is an interesting book which provides a good overview of many interesting topics in astronomy. — PHILLIP HELBIG.

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Here and There

MAKES THE BLOOD BOIL

And this being June, when the sun is closer by, as it makes its presence felt the mercury will rise quickly. —*The Sunday Telegraph, 2026 June 14, p. 32*

*In that paper, Rubin and Ford also mention earlier work by others; the claim that Vera Rubin discovered dark matter is certainly not due to her claiming that, as she acknowledged previous work.

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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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