THE
OBSERVATORY

A REVIEW OF ASTRONOMY

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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2024 November 8 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. Questions may be asked at the end of the lecture so please put them in the Q and A session and Dr. Pam Rowell will put them to the meeting.

We have finally signed a 999-year lease on the property [applause]. I'd like to thank, on behalf of the Societies, Dr. Andrew McDonald of the Society of Antiquaries who did a lot of the spade work, and I'd also like to thank the courtyard Presidents, Treasurers, and CEOs both present and past. I also wish to thank Mike Edmunds and James Hammond, who, along with me, signed all the documents, and Richard who applied the stamp. I personally wish to thank Phil Diamond who stayed calm whilst I was panicking. They all deserve another round of applause [applause].

The first talk is by Professor Pilar Ruiz-Lapuente, presently a Research Professor at the Instituto de Física Fundamental in Madrid and a Visiting Professor at the Instituto de Ciéncies del Cosmos at the University of Barcelona. She did her graduate work at Garching and ESO and has held postdoctoral positions at the Institute of Astrophysics in Paris and at the Harvard Smithsonian Center for Astrophysics. Her first tenured position was Associate Professor at the University of Barcelona and she participated in the Supernova Cosmology Project (SCP) which resulted in the discovery of the expansion of the Universe, for which she shared the Gruber Cosmology Prize in 2007 and the Breakthrough Prize in Fundamental Physics in 2015. Previously she was awarded the Distinction for Research from the government of Catalonia in 2002. She has edited two books on type-Ia supernovae and dark energy and is the author of three popular books on the expansion of the Universe, and philosophical questions relating to physics and chemistry. At present, with the SCP she has found indications that the dark energy responsible for the accelerating expansion of the Universe is likely not to be the cosmological constant; she is also working on the Hubble tension. Please welcome Professor Ruiz-Lapuente to talk about 'What type-Ia supernovae are telling us about the Universe'.

Professor Pilar Ruiz-Lapuente. If we have to give an account of how the expansion of the Universe was discovered, there are certain achievements that we usually mention. First, in 1915, Vesto Slipher had seen that most galaxies (then called nebulae) seemed to move apart from us. This was derived from the shifts towards the red wavelengths of the characteristic spectral lines of such nebulae. The distance determination to those galaxies by Hubble provided a first value of the Hubble constant H_0 which was of 500 km $s^{-1}Mpc^{-1}$. Lemaître had also used Slipher's velocities and available distances to derive a larger value, 575 km $s^{-1}Mpc^{-1}$. The available predictions of cosmological models based on General Relativity developed by Friedmann and Lemaître allowed us to interpret the distance–recession-velocity diagram as that of an expanding Universe. The fact is that both Hubble and Lemaître aimed at obtaining the rate of the expansion of the Universe at about the same time. Nowadays, we know the result that the galaxies are moving away with velocities proportional to their distance as the Hubble–Lemaître law. The evolution in time of this law, which corresponds to the evolution of the rate of expansion of the Universe is the Hubble–Lemaître parameter $H(t)$. The value of H_0, the present value of $H(t)$, has gone down since the earliest determinations placed the galaxies too close, due to an inadequacy of the methods used. In the 1990s, there were several approaches proposed to obtain H_0 and discrepant values were in the range 50 to 100 km $s^{-1}Mpc^{-1}$. *The Hubble Space Telescope* Key Project in 2001 determined H_0 to be 72 ± 8 km $s^{-1}Mpc^{-1}$. However, later on, the value of H_0 measured from the fluctuations in the power spectrum of the CMB in 2018 gave $H_0 = 67{\cdot}4 \pm 0{\cdot}5$ km $s^{-1}Mpc^{-1}$. In contrast, H_0 is found to be between 69 and 74 km $s^{-1}Mpc^{-1}$ from various methods working on the distance ladder. In particular, the use of Cepheids by Riess and co-workers in their SH0ES programme gives $H_0 = 73{\cdot}3 \pm 0{\cdot}9$ km $s^{-1}Mpc^{-1}$, a discrepancy at the $5{\cdot}7\sigma$ level with the CMB value. Such a difference is nowadays referred to as the Hubble Tension. It seriously questions the ΛCDM model and some authors claim the need for new physics in the early Universe to make the *Planck* value compatible with that derived by methods involving low-z astrophysical distance indicators such as Cepheids. This year there have been some other issues questioning the ΛCDM model. In 2024, we had indications that dark energy might not be the cosmological constant, but a component whose equation of state varies with time. That would make dark energy different from vacuum energy. The Union3 SNe-Ia sample determined that the equation of state is at $1{\cdot}7$–$2{\cdot}6\sigma$ tension with vacuum energy. The DESy5 SN results also found tension at a similar significance level $\sim 2\sigma$. Those data together with the DESI BAO acoustic oscillations do not favour $w_0 = -1$, $w_1 = 0$ either (the parameters corresponding to a cosmological constant). The final significance level is around $3{\cdot}9\sigma$. Another important cosmological question is the isotropy of the Universe. The value of the Hubble–Lemaître parameter along redshift in different directions of the sky can tell us whether the cosmological principle holds. The cosmological samples of SNe Ia can give us very useful tests. In this summarized account, we will expand preferably on the key question of whether the Hubble tension exists. We will do it by reviewing our new method to go straight to the Hubble flow to test H_0, avoiding the three steps required if one wants to calibrate with Cepheids in a middle range of distance of 40 Mpc. The middle step requires the elaboration of a non-linear relation of the absolute magnitude of a fiducial SN Ia, M_{B0}, with rate of decline of the light-curve, *i.e.*, luminosity for a SN Ia of stretch 1, colour $B-V$ at maximum 0, and reference mass of the host galaxy. One can simplify the procedure and go straight to the Hubble flow by using SNe Ia twins. Fakhouri *et al.* in 2015 found that by using SN-Ia pairs with closely matching spectra

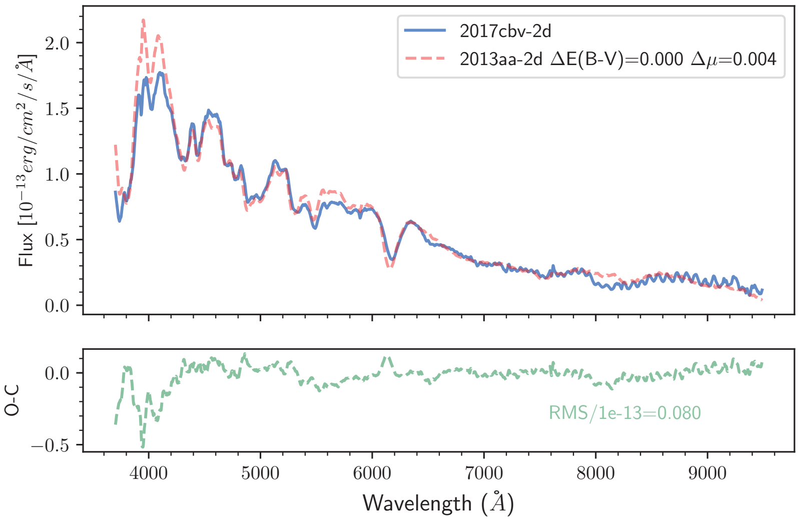

Fig. 1a

Comparison of early-time spectra of SN 2013aa and SN 2017cbv at 2 days before maximum light.

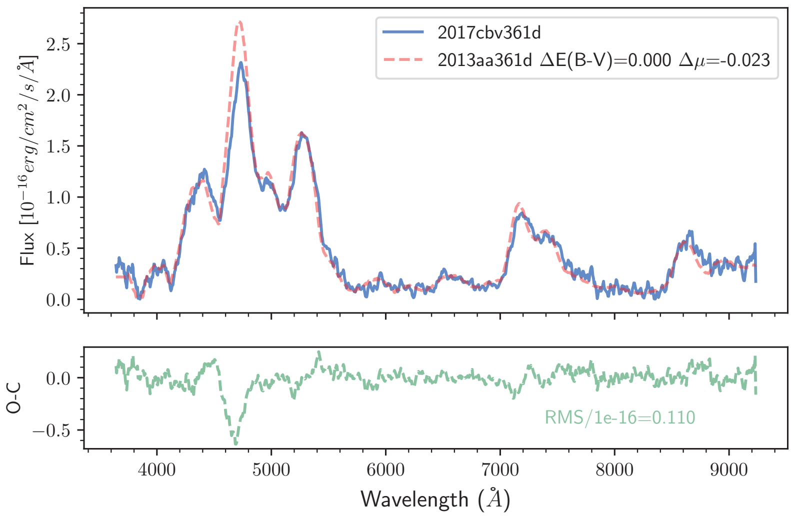

Fig. 1b

Comparison of late-time spectra of SN 2013aa and SN 2017cbv at 361 days past maximum light.

from the SN Factory sample, they achieved a reduced dispersion in brightness. They were able to standardize SNe Ia in the redshift range z between 0·03 and 0·08 to within 0·06–0·07 mag. Their aim was to determine with more precision the nature of dark energy. In our case, we want to use the similarity of SNe Ia not only in the light-curve but also in spectra along the evolution of the SNe Ia to measure its distance better. We called it the 'twins for life' approach and it provides a direct measurement of distance, intrinsic colour, and reddening caused by Galactic and extragalactic dust by the use of the whole spectrum of the SN Ia. It allows the consistent pairing of SNe Ia through all phases. The selection of twins is made of SNe Ia with a similar stretch, being then of similar luminosities, but in addition the 'twinness factor' can make more precise the distance estimate, with a modulus error of 0·04 mag in all filters, as we showed. This is 2% in relative distances. So, all this makes a very useful tool to obtain the right distance ladder. To the relative distance error of 2% one has to add the error of the anchor, of another 2%. Those anchors to serve as reference distances are chosen from nearby galaxies for which a consensus in the distance from various methods has been reached with the latest *JWST* measurements (NGC 5643, M101).

It has been proven that comparison of twin SNe Ia can provide a robust way to establish the extragalactic distance ladder. Here in Figs. 1 and 2 we show how we apply the method. The method has been applied to the twins in the galaxy NGC 5643: SN 2013aa and SN 2017cbv. The comparison using spectra before maximum and at the nebular phase shows that the error in the distance determination is of $\Delta\mu \sim 0{\cdot}000 \pm 0{\cdot}005$ mag.

We have already applied the method to galaxies in the Hubble flow, using SNe Ia from the Carnegie Supernova Project I. The SNe-Ia light-curves nearby and in the Hubble flow have the same rate of decline. They are also of the same spectral subtype and they are perfect twins. In Fig. 3, we show SN 2013aa compared with SN 2008bf in two phases (other phases give the same perfect match). The distance derived from this comparison is $76{\cdot}92 \pm 1$ Mpc. The perfect match of the spectra makes the blue and red lines almost indistinguishable. This has been applied to several galaxies in the Hubble flow and a value of H_0 has been obtained. From this work, it is clear that the Hubble tension is real. This is an important corroboration, since the method is very straight forward. The method goes from nearby galaxies to the Hubble flow with $d > 65$ Mpc without stopping in the middle. With the advent of very large samples (> 1000) of SNe Ia, it has been possible to determine in a better way the equation of state of dark energy. The latest suggestions are that dark energy might not be vacuum energy or the cosmological constant. The hints come mainly from two collaborations: the DESy5 SN with ~ 1500 SNe Ia in the redshift range $0{\cdot}10 < z < 1{\cdot}13$ and the Union3 (Rubin *et al.* 2023) sample of 2000 SNe Ia with z from 0·01 to 1·7. Whereas the discovery of dark energy involved 42 high-z SNe Ia by Perlmutter *et al.* in 1999, and ten high-z by Riess *et al.* in 1998, these new samples of thousands and the new ones to come are testing the present value of the equation of state w_0 and its evolution w_a. Both data samples do not favour anymore the cosmological constant (which has $w_0 = -1$ and $w_a = 0$). The results obtained from these samples favour $w_0 > -1$ and $w_a < -1$. Thus, dark energy is evolving in time and there are new proposed candidates discussed in the literature. More data are coming in 2025 and will bring us more information. With the large SNe-Ia samples, tests on the isotropy

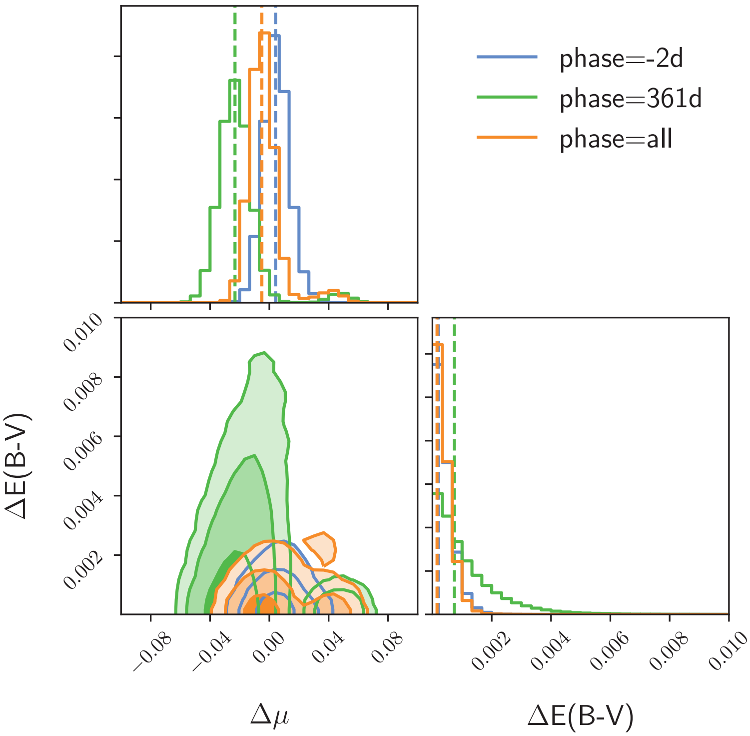

FIG. 2

The results for SN 2013aa and SN 2017cbv showing the corner plots with the 1σ, 2σ, and 3σ confidence regions favoured by each phase and those from the joint computation.

of the expansion of the Universe can be done. Samples such as the DESy5 SN and Pantheon+ have been analysed by various groups to see whether H_0 is the same along different directions in the sky. There is debate about it. Our present analysis points to an anisotropy at around ~ 2σ level in Pantheon+, but to isotropy in other samples. So, the question deserves further examination. Along these lines, we have reported work on SNe Ia using cosmological samples that are setting a new frame for our cosmological model. We first have presented our view on whether there is Hubble tension or not, from a new method developed by us that is able to achieve high accuracy in distance estimations. The purpose of this talk has been to give a brief account of what SNe Ia are telling us about our Universe. We have tested whether the ΛCDM model is well in accordance with what we learn from SNe Ia. In this respect, we think that there are reasons to suggest that some modifications are needed. Briefly: (*i*). The Hubble tension is real. We have seen with our use of 'SNe Ia twins for life' that a value such as the one provided by the CMB of $H_0 = 67{\cdot}4 \pm 0{\cdot}5$ km s^{-1}Mpc^{-1} is far from the H_0 indicated by our direct twin-to-twin distance ladder. Though the

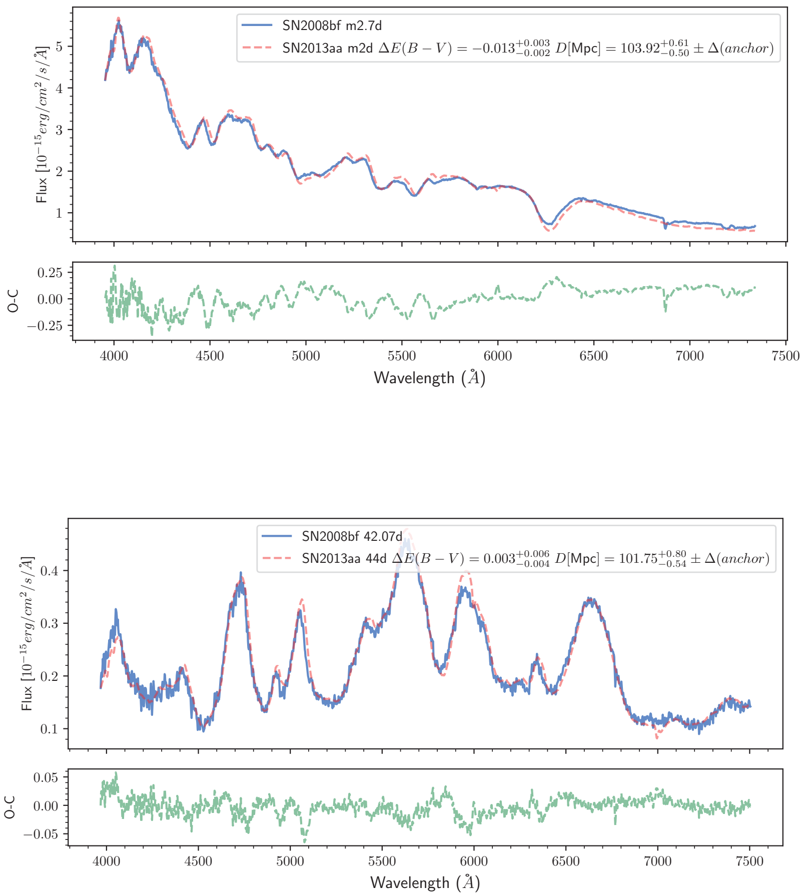

FIG. 3

(Top) Comparison of early time spectra of SN 2013aa and SN 2008bf at 2 days before maximum light. (Bottom) Comparison of the spectra of SN 2013aa and SN 2008bf at 42 days past maximum light.

sample needs to be enlarged, we find that our distances bring H_0 to the range 71 km s^{-1} Mpc^{-1}, with the error in process of evaluation. In fact, 67 km s^{-1} Mpc^{-1} can only be reached from highly significantly erroneous distances to SNe Ia and their galaxies in the Hubble flow. Some early dark energy might be needed to be added to our cosmological model. (*ii*). There is evidence that dark energy is not the cosmological constant, but it varies with time, though more SNe Ia are needed to see whether this still holds at a higher significance level. (*iii*). There is a lot of activity on testing the isotropy of the Hubble expansion along different directions in the sky. Contradicting results are found at this point by various authors, and further research is needed. The coming years will shed some light on the cosmological model of our Universe. We look forward to the new data to come and to theoretical ideas that will bring a better understanding of the Universe.

The President. Thank you very much. Are there any questions in the room?

Reverend Garth Barber. How robust is the assumption that SNe Ia are standard candles out to cosmological distances, say $z = 1$, given that you might have evolution of the fractional elements? And secondly we have heard that there are at least three models for supernova, including single degenerate, double degenerate, and core degenerate, and might the mix of the different types of supernova vary over cosmological time?

Professor Ruiz-Lapuente. We use a purely empirical relationship to calibrate the luminosities of supernovae independent from any model. Supernovae as old as those at high redshift are found nearby. Even if they are less luminous, their light-curves decay more rapidly and by the relation of maximum brightness to rate of decline we account for that.

The President. I have read quotes from Einstein saying that his biggest mistake was including the cosmological constant and also saying that his biggest mistake was taking it out again. Can you say which of these is correct?

Professor Ruiz-Lapuente. The first one was when talking with George Gamow. The second one never took place. At the time of Einstein's death nobody was advocating the return of the cosmological constant.

The President. Thank you very much again [applause].

The next speaker today is Dr. Or Graur, Associate Professor of Astrophysics at the University of Portsmouth's Institute of Cosmology and Gravitation, Research Associate at the American Museum of Natural History, and also an Honorary Research Professor at University College London. He conducts observations of supernovae and tidal-disruption events which are luminous flares caused by stars ripped apart by supermassive black holes, as well as cultural studies of the myths of the Milky Way. His popular science books include *Supernova* and *Galaxies*, both published by MIT. He is going to talk to us about 'Old Dogs, New Tricks: Late-time observations of type-Ia supernovae with the *Hubble Space Telescope*'.

Dr. Or Graur. Supernovae are the superheroes of the Universe, as recognized even by DC Comics, creators of superheroes such as Superman, Batman, Wonder Woman, and even a superhero called Supernova. Unlike this superhero, who can only fly and emit bright flashes of light, real supernovae play many important roles in the Universe. As the explosions of stars, they are the endpoint of stellar evolution for all stars more massive than eight times the mass of the Sun, as well as many white dwarfs. Core-collapse supernovae leave behind stellar remnants in the form of neutron stars and stellar-mass black holes. The explosions create many of the heavy elements in the Universe and disperse them into interstellar space, where they are recycled into the next generation of stars. The expanding explosion fronts, called supernova remnants, gouge holes in the inert gas of the interstellar medium (such as the Local Bubble through which the Sun is currently travelling) and accelerate cosmic rays to relativistic velocities. Finally, and perhaps most famously, certain supernovae, called type-Ia supernovae, are used as standard candles to measure extragalactic distances and constrain cosmology.

I want now to focus solely on type-Ia supernovae. Ever since my PhD, I have tried different methods to constrain the nature of the progenitors of these supernovae. While it is widely agreed that the exploding star is a carbon–oxygen white dwarf, it is still unclear how to blow up such an inherently stable star. Leading theories place the white dwarf in a binary system where it either steals gas from a non-degenerate companion (such as a red giant) or merges with a second white dwarf. There are several ways to constrain these progenitor scenarios, including searching for the companions in pre-explosion images or measuring the rates at which type-Ia supernovae occur in various types of galaxies. All of these methods span time-scales of hundreds of thousands of years before the explosion to thousands of years afterwards. One time-scale, however, remained unaddressed for many years: the behaviour of type-Ia supernova light-curves several years after explosion.

The light-curves of type-Ia supernovae are powered by the radioactive decay of iron-group elements created during the explosion. With a half-life of ~ 6 days, the decay of ^{56}Ni to ^{56}Co dominates the first days of the explosion. The light-curve then proceeds to be dominated by the decay of ^{56}Co to stable ^{56}Fe, which has a half-life of ~ 77 days. For most observers, this is where the story ends, as type-Ia supernovae are rarely followed for more than a few weeks, let alone a few months. However, in 2009, a team led by Ivo Seitenzahl suggested that, starting roughly 1000 days after the explosion, the fading of the supernovae would slow down as X-ray photons and electrons from the long-lived decay chains ^{57}Co → ^{57}Fe (half-life of ~ 272 days) and ^{55}Fe → ^{55}Mn (half-life of ~ 1000 days) would begin to dominate the energetics of the light-curve.

In 2016, I led a group that conducted *Hubble Space Telescope* observations of a nearby type-Ia supernova, SN 2012cg, out to 1055 days. We found that the light-curve did indeed slow down and was consistent with the combined radioactive decays of ^{56}Co → ^{56}Fe and ^{57}Co → ^{57}Fe (Fig. 4). These results were quickly corroborated by similar observations of SNe 2011fe and 2014J.

Theorists soon showed that the same light-curve, especially that of SN 2011fe, could be fit with other models that caused the light-curve to slow down: atomic 'freeze-out', a variable magnetic field in the supernova ejecta, or delayed deposition of energy into the ejecta. There are two ways to test the various models. First, where possible, continue to observe the same supernova out to > 2000 days, where a second kink due to the radioactive decay of ^{55}Fe → ^{55}Mn should become apparent. To date, only SN 2011fe has been followed that long, and observations purport to show the expected kink. The other tack is to study samples of supernovae and search for correlations between their light-curves and other intrinsic properties. There might be such a correlation between the rate at which the light-curves slow down and the intrinsic luminosity of the supernova, similar to the correlation used to standardize these supernovae for use in cosmology. However, at the moment, this claim rests on no more than five objects. A *Hubble Space Telescope* programme carried out by my postdoc Dr. Huei Sears is expected to triple this sample and either validate or reject this correlation.

From optical observations, I would like to move on to the near-infrared, where we have discovered a surprising plateau in the *J* and *H* bands from 150 to 500 days past maximum light (Fig. 5). A follow-up ground-based project carried out by Dr. Maxime Deckers doubled the number of objects on the plateau and showed conclusively that it was present in *J* and *H*, but not *K*. Dr. Deckers also showed that the onset of the plateau was due to a shift in the dominant ionization state of the supernova ejecta from doubly-ionized to singly-ionized

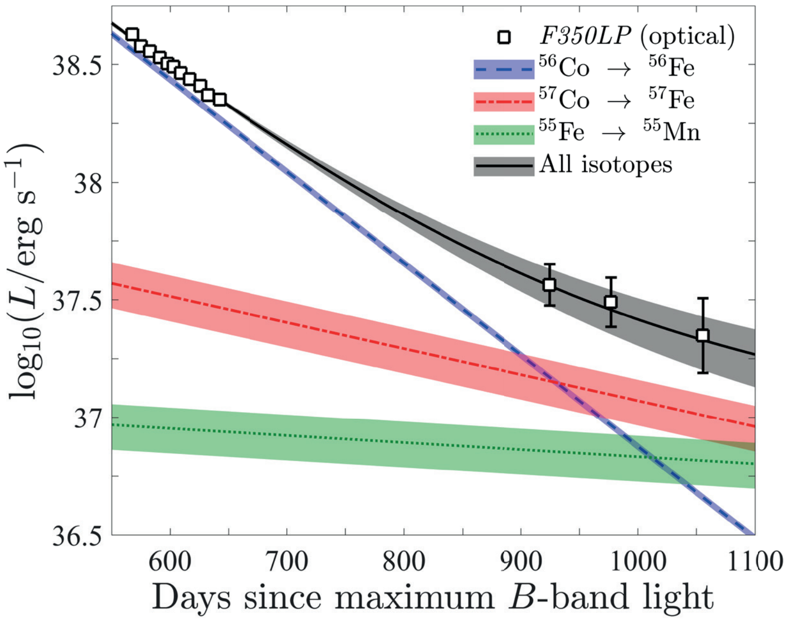

Fig. 4

Luminosity contributions in SN 2012cg from the decays of ^{56}Co (blue dashed), ^{57}Co (red dashed), and ^{55}Fe (green dotted). The total luminosity produced by these decay chains (black solid) fits the F350LP measurements with a χ^2 value of 2·1 for 12 degrees of freedom. (From Graur *et al.*, *ApJ*, **819**, 31, 2016.)

iron-group elements. As part of this process, ultraviolet photons are scattered to longer wavelengths, creating the plateaus in *J* and *H*.

Type-Ia supernovae come in several flavours. So-called 'normal' type-Ia supernovae are used in cosmology, but there are several other subtypes, from under-luminous 1991bg-like (Fig. 6) and Iax-like supernovae to over-luminous 1991T-like supernovae. Since all my previous *Hubble Space Telescope* observations had been of normal type-Ia supernovae, I set out to look for the near-infrared plateau in a 1991bg-like supernova called SN 2021qvv. I found no evidence of a plateau in that supernova, but noted that it was one of the dimmest of its kind ever observed. That leaves a window open for the plateau to appear in more luminous examples of this class.

Finally, I would like to discuss how my work on SN 2021qvv made me take a closer look at 1991bg-like supernovae, which I had mostly ignored in the past. To my surprise, I discovered that these supernovae were also standardizable, even though for decades it had been assumed that they were not. The trick was using the correct light-curve-shape parameter: the colour-stretch parameter s_{BV} instead of the more common s, x_1, or Δm_{15}. The fact that these supernovae were standardizable after all had been shown in the past by the Carnegie Supernova Project in a 2018 paper, but the wider community had failed to notice it.

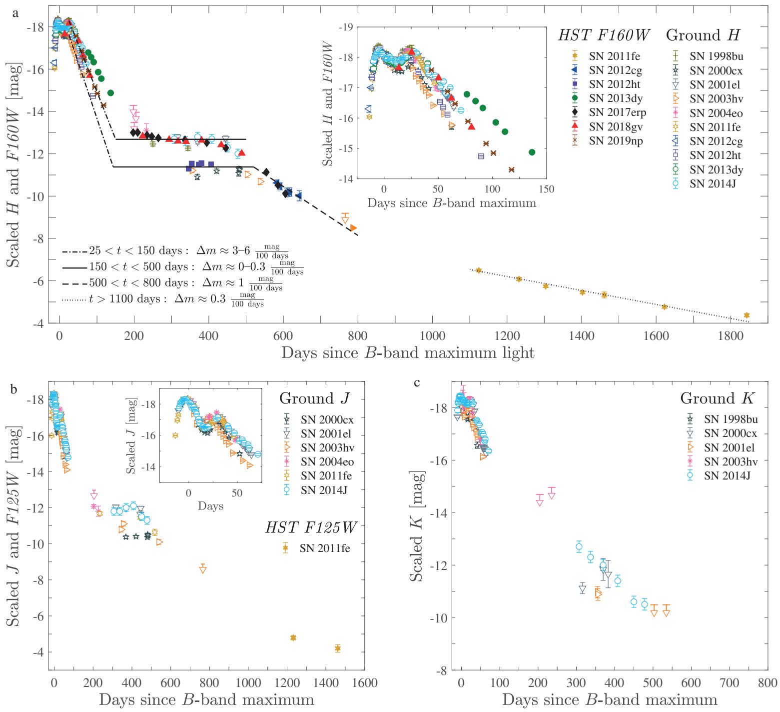

FIG. 5

SN Ia near-infrared light-curves. Although standard to ~ 0·1 mag at peak, the H-band light-curves (a) begin to branch out after the second peak, with decline rates in the range 3–6 mag/100 days. At ≈ 150 days, the light-curves settle into a plateau phase that lasts until ≈ 400–500 days, when they once again transition into a second decline phase with a rate of ≈ 1 mag/100 days. At the plateau phase, the SNe have a range of ~ 2 mag, where the brighter SNe had slower decline rates before entering the plateau. The measurements in this plot have been scaled to the light-curve of SN 2011fe. Using this scaling, the plateau phase is also apparent in the J band (b). Synthetic photometry of SN 2014J in the K band (c) show no hint of a plateau in this wavelength range. Black curves, meant to guide the eye, represent the distinct phases of the H-band light-curve. Representative decline rates along each phase are noted in the legend at the bottom of the upper panel. Error bars represent 1σ measurement uncertainties, while downward arrows indicate 3σ upper limits. (From Graur *et al.*, *Nature Astronomy*, **4**, 188, 2020.)

Now that two different groups have shown that 1991bg-like supernovae are standardizable, we can use them to construct a new cosmological distance ladder, one that would be independent from the ladder that uses Cepheids and normal type-Ia supernovae. A new ladder would then provide an independent measurement of H_0 and hopefully help settle the current Hubble Tension.

The President. Questions in the room?

Reverend Barber. With single-degenerate, double-degenerate, and core-degenerate types of supernovae, can you tell which is which from the spectrum and distance?

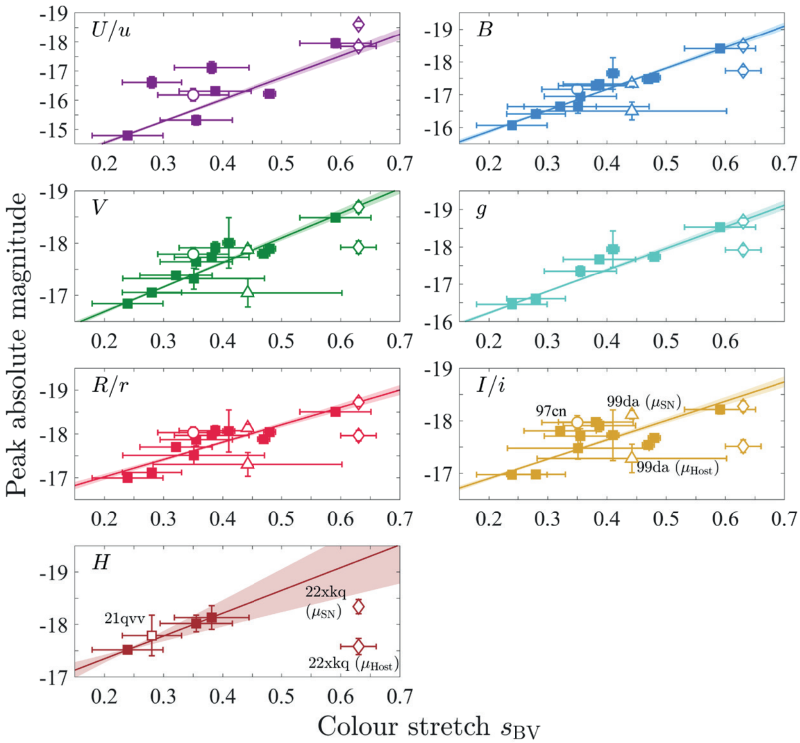

FIG. 6

Peak absolute magnitude *versus* colour stretch, s_{BV}. Magnitudes have been corrected for Galactic line-of-sight reddening. The shaded regions around the linear fits represent the 1σ uncertainties of the fits. The correlations, calculated using the calibration sample (filled squares), are statistically significant in all filters except U/u. SNe 1997cn, 1999da, and 2022xkq are shown as an open circle, triangle, and diamond, respectively. SNe 1999da and 2022xkq are shown twice, once when using a host-based distance modulus (μ_{Host}) and once when using a distance modulus derived by SN light-curve fitters (μ_{SN}). For clarity, the second measurements of SNe 1999da and 2022kxq are shown without their horizontal error bars. The *H*-band measurement of SN 2021qvv, shown as an open square, is not used in the fit. (From Graur *et al.*, *MNRAS*, **530**, 4950, 2024.)

Dr. Graur. One of the great hopes was that we would be able to tell between them using these late-time observations because each of the progenitor scenarios gives you a different composition for the white dwarf. You should get different amounts of these radioactive isotopes; I wasn't able to test this with my data, but Ben Shappee claims you can do this with 2011fe. That is why you have several lines on the plot. I'm not convinced by this yet, especially since we are not persuaded that you can explain this just by the radioactive decay change.

Reverend Barber. Is it a work in progress?

Dr. Graur. Yes.

The President. Any more questions? Just a semantic point. I don't think it is the supernovae that have the new tricks, I think it is the theorists!

Dr. Graur. Well, I'm an observer! [Laughter.]

The President. Thank you very much for your talk [applause].

Now we come to the George Darwin Lecture to be given by Professor Chiaki Kobayashi of the University of Hertfordshire. Professor Kobayashi is an internationally recognized leader in the field of the chemical evolution of galaxies and is a pioneer in the study of the origin of the elements, a subject which bridges nuclear physics and astrophysics. She was awarded a PhD from the University of Tokyo in 2002 and has worked in Germany and Austria as well as the UK. As well as running large-scale computer simulations of galaxies, she is also involved in a number of observational surveys with a particular focus on elemental abundances. She is well known for having created an astronomer's version of the periodic table. So I ask Professor Kobayashi to talk to us about 'The origins of elements in the Universe'.

Professor Chiaki Kobayashi. [When the Universe started with the Big Bang 13·8 billion years ago, only light elements such as hydrogen and helium were produced. Carbon and heavier elements that matter to human beings and modern technology were instead created inside stars. Computer simulations allow us to predict the complex history of the Universe starting from the formation of stars, the production of elements, and the evolution of the element distribution in galaxies. These theoretical predictions have been tested with detailed observations of stars in the Milky Way. Thanks to the *James Webb Space Telescope* it is now also possible to study elemental abundances in very early galaxies, which has brought a surprise, that might also be a clue to understanding the origin of elements in the early Universe.]

The President. Are there any questions?

Mr. Suryansh Saxena. Referring to the slide of supernovae and time-scale — what does this tell us about the elemental composition of the early Universe and how does it help in influencing the model we have for stellar and galactic structure now?

Professor Kobayashi. We know that massive stars produce more oxygen than iron. This figure shows how long this stage continues. The area between oxygen to iron is flat. From the earliest time to now, star formation takes place very quickly, and we can work out how many massive and low-mass stars can be formed. We can use this as a cosmic clock — how quickly star formation took place in each area of the galaxy — in the bulge, for instance. How much gas flows in from the outside to that area? As to the second question — how much gas is frozen into that area — how much outflow takes place? These things can be constrained by looking at other elements.

Mr. Howard Bromley. Do you have your periodic table for the isotopes as well?

Professor Kobayashi. I do!

Mr. Bromley. But not with you?

Professor Kobayashi. Not here. The nuclear physics is actually not that accurate for some isotopes so when I compare with observed isotope ratios in the metal lines, there is some mismatching still. The nuclear physics has to be exactly right. I'm still working with nuclear physicists to get the isotopic ratio of a similar table.

Professor Ian Crawford. In light of the neutron-star mergers and your more recent paper that you published since that periodic table, would you now revise the relative contribution of neutron-star mergers and type-II supernovae?

Professor Kobayashi. Core-collapse supernovae dominate at low metallicity but neutron-star mergers may dominate at high metallicity. I am now working with people on neutron-star mergers as the best prediction for how much of each element should be produced by each event. What is the mass ratio between the compact objects? The relative contribution between neutron-star mergers will be different with the new improvements from binary-star studies.

The President. In my undergraduate lectures I have always known that when it came to element abundances I would simplify and I have just learned by how much! [Laughter]. I used to make fun of Joni Mitchell — she sings in her song *Woodstock* "we are stardust" and then "we are golden". One of my students pointed out that gold is a very important component of our brains because of its electrical properties, so although we are not exactly golden it's an important part of us so it is interesting that it is still a mystery. One more round of applause for a wonderful lecture. [Applause.]

Finally, drinks will be back in our new house and the next monthly A and G Highlights meeting will be on Friday, December 13th. What can go wrong?

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2024 December 13 at $16^{h}\ 00^{m}$
in the Geological Society Lecture Theatre, Burlington House

Mike Lockwood, *President*
in the Chair

The President. Welcome to the meeting. This is a hybrid meeting. Questions can be put in the Q and A and they will be read out by Dr. Pam Rowell. As you will know we are losing Phil Diamond in about six months. He will be an extremely hard act to follow but we are in the process of finding a successor.

Our first talk is from Deborah Kent from the University of St. Andrews. She is a reader in history and mathematics at the School of Mathematics and Statistics and is an affiliate at the Institute of History at the University of St. Andrews. Her research focusses on mathematical sciences in the 19th and 20th Centuries with a recent emphasis on 19th-Century eclipse expeditions including personal experience from two 21st-Century total eclipses. She is a librarian of the London Mathematical Society, a Council Member of the British Society for the History of Mathematics, and a member of the RAS. Her talk is entitled 'To Burlington House and the Kerguelen Islands: The 150th anniversary of RAS movements near and far'.

Dr. Deborah Kent. I'm delighted to be here to speak about the 150th anniversary of RAS activity in two very different places in 1873: the well-known Burlington House and the less-familiar and less-hospitable Kerguelen Islands.

Beginning in 1820, the Society first met in various locations, including the rooms of the Geological Society, then in Covent Garden and later in rented rooms in Lincoln's Inn Fields. On receiving the original Royal Charter on 1831 March 7, the (then) Astronomical Society of London became the Royal Astronomical Society. In 1834, the government provided RAS accommodation in Somerset House, which housed other learned societies. Space soon became a concern. To address this, the British government bought Burlington House in 1854 for £140,000 (in 2023 this equates to £293·4 million) to put public offices on the site. By 1857, the Royal Society, the Linnean Society, and the Chemical Society had moved from Somerset House to Burlington House. The Royal Academy of Arts moved in 1867.

The RAS relocated in 1874. Across the courtyard that year, the RA began with a memorial exhibition of Sir Edwin Landseer who had died in 1873 October. The exhibit featured 532 of his works, including the iconic *Monarch of the Glen*. An RA sensation that year was *The Roll Call*, an oil painting by Elizabeth Southerden Thompson Butler that portrayed ordinary soldiers after battle. It made the artist a national celebrity and drew crowds that required police intervention. According to *The Times*, "this one of the pictures of the year least likely to be forgotten".

Elsewhere in Burlington House in 1874, the Linnean Society was busy enumerating lichens, algae, plants, and fungi from the *Challenger* expedition. The President of the Chemical Society was William Olding, noted for his involvement with the development of the Periodic Table. The Geological Society was discussing the skull of an extinct sea cow *Halitherium*. As for the RAS, they had two main concerns in 1874: the transit of Venus and their own relocation to Burlington House.

There were then (as now) both objections to spending public money in support of the learned societies and counterarguments reinforcing the national advantages of doing so. In the end, support prevailed. The Geological Society of London, the Society of Antiquaries, and the RAS would move. The RAS Council were then occupied with renovations: sorting out seating, meeting with architects, sourcing brass rods to hang pictures, and complaining about the costs of heating. (Current members of Council may relate!) The first meeting in Burlington House was held on 1874 November 13 at "8 o'clock precisely".

The Society has held regular meetings there for 150 years and, following a recent landmark 999-year lease agreement between the Government, the RAS, and its fellow learned societies, this will continue.

The year 1874 also brought a long-anticipated transit of Venus. Starting in 1857, Astronomer Royal George Biddell Airy had written articles in *MNRAS* to facilitate expedition planning. Already in 1716, Edmond Halley suggested that simultaneous observations of a transit of Venus from widely separated locations had the potential for improving the measurement of the mean Earth distance (now known as the Astronomical Unit). Airy hoped more accurately to determine this distance, and provided an overview of the upcoming 25 years of prospects.

By 1869, Airy was lobbying the Secretary of the Admiralty for support and funding. He sent estimated expenses, copies of related discussions, and a paper by Mr. De La Rue (celebrated for the first photo of the corona showing prominences) on the application of photography. The Admiralty granted support, and according to the initial parliamentary report on 1869 July 6, £5,000 (equivalent to about £10·5 million today) to cover actual expenditures, but not the costs of operating the naval ships used to transport the expeditions.

Preparations included assembling instruments and training observers. At Greenwich, they practised on a special machine designed to simulate the anticipated black-drop effect. Both the RAS council and individual members lent instruments for the expeditions.

Official British expeditions were sent to Hawaii, which was then a British possession known as the Sandwich Islands (observing stations were at Honolulu, Kailua, and Waimea), Egypt (Cairo and Suez), Rodriguez Island (Point Coton, Point Venus, and Hermitage Islet), Kerguelen Island (Observatory Bay, Supply

Bay, and Thumb Peak), and New Zealand (Burnham, near Christchurch). There were also German, Dutch, Australian, US, French, Russian, Austrian, and Italian expeditions to observe the transit of Venus. Agnes Clerke enumerated 62 parties observing the 1874 transit from nearly 80 separate locations. It may have been the largest ever international effort to observe a single astronomical event.

British observers made elaborate efforts to determine correct longitudes for each of the main observing sights. The party at Kerguelen stayed for several months, persevering through bad weather to take 100 double observations of lunar altitudes and 30 transits of the Moon across the meridian. They also made extensive geomagnetic measurements and laid a tidal gauge. In all locations, British observations of the black drop did not occur as expected from the model. Many observers missed the initial contact and some were entirely clouded out. Overall, it was not brilliant.

In early 1877, Parliament pressed for a report of results from all the effort and expenditure. Airy and Tupman rushed out a partial report, published in 1877 July. The world over, reduction of the observations proved a lengthy chore. For one example, the observations made in 1874 in New South Wales were not published until 1892. The final volume of Airy's expeditions appeared in 1881.

One notable outcome of the 1874 transit of Venus came from a private expedition mounted by Lord Lindsay. Together with David Gill, they sailed to Mauritius on Lindsay's yacht *Venus*. Their plans included using a state-of-the-art heliometer to test the method of diurnal rotation for determining parallax of minor planets. An article in the current issue of *A&G* details their work.

I would be remiss not to mention a beautiful pamphlet on the transit written by Chintamanny Ragoonatha Chary, who worked with Norman Pogson at Madras Observatory. The RAS archives have a beautiful copy of this document — originally written in Tamil, then translated into Sanskrit, Canarese, Malayalum, and that relates the transit of Venus phenomenon to traditional Hindu astronomy. There's more on this story in the 2022 February issue of *A&G*.

I would like to express my special thanks to Dr. Siân Prosser for assistance with RAS archives and her predecessor the late Peter Hingley for work on the transit of Venus expeditions.

The President. Thank you so much. I might be asking you for some references to Airy's creative accounting [laughter]. Were the guys with bowler hats theoretical cosmologists? [Laughter.] Given that the 1870s is the height of Empire, do you know why they chose to go to an island in the middle of the Indian Ocean, rather than India, Hong Kong, or Singapore which had telegraph facilities and commercial shipping?

Dr. Kent. Part of it was connected to where they needed to be in terms of latitude. That is part of the consideration. Kergulen was a French territory at the time and the French had also gone. The transit of Venus is a very interesting episode in scientific competition — they may have been discussing methods with each other; additionally there is a deep national competition going on. Perhaps it is still a matter of establishing British dominance.

Dr. Robert Massey. A couple of points. Firstly, there is the risk to contemporary projects if they don't work. Imagine what would we would be doing if *JWST* had failed to make it into space. The transit of Venus was recorded a century earlier by Lomonsov — you can see it by eye when the planet is on the edge of the Sun. I wondered how they would sell the event. It wasn't, strictly speaking, a discovery.

Dr. Kent. At this point in the 1870s, the state of photography and astronomy is a point of great debate particularly when it starts being used for solar eclipses and partly for other kinds of astronomical observation. A lot of total solar eclipses leading up to 1874 were viewed as practice for the transit of Venus. The fact of having an image is viewed as incontrovertible by some and by others is viewed as "well, you might have some dust on your slide". In brief, the debate is between the status of a photograph and a visual observation. The statement of the results is that that is due to capturing it on a photograph.

Dr. Simon Mitton. I caught your comment about them making a lot of magnetic observations and that is very significant since in the 1860s Victoria had launched a huge magnetic campaign which went throughout the Empire and that also may explain why they went to Kerguelen, because they would not have detailed material from that part of the world

Dr. Kent. There is something about there truly being nothing there and that would have been part of the appeal of taking measures from there.

The President. Thank you very much, that was really interesting.

Our next speaker is Professor Sugata Kaviraj from the University of Hertfordshire. He is a Professor of Astrophysics at Hertfordshire, and a Senior Research Fellow at Worcester College, Oxford. Before going to Hertfordshire he spent his postdoctoral period at Oxford where he was funded by a Leverhulme Early-Career Fellowship, then at UCL funded by a Research Fellowship from the 1851 Royal Commission, and at Imperial College London funded by an Imperial College Research Fellowship. He is a past recipient of the RAS Winton Capital Award and his talk is called 'Dwarf galaxies in deep-wide surveys: a new frontier in the study of galaxy evolution'.

Professor Sugata Kaviraj. Dwarf ($M < 10^{9.5}\ M_{\odot}$) galaxies dominate the galaxy number density, making them critical to a complete understanding of galaxy evolution. However, typical dwarfs are not bright enough to be detectable, outside the very local Universe, in past large surveys like the SDSS, because they are too shallow. The dwarfs that do exist in such surveys have extreme star-formation rates which boost the luminosities of the dwarfs above the detection limits of shallow surveys like the SDSS. However, this also makes them anomalously blue and unrepresentative of dwarfs in general.

New deep-wide surveys from the *Hyper Suprime-Cam* (*HSC*), *LSST*, and *Euclid* are poised to revolutionize our understanding of galaxy evolution, by offering unbiassed statistical samples of dwarfs for the first time, *e.g.*, down to $M \sim 10^{8}\ M_{\odot}$ out to at least $z \sim 0{\cdot}4$. These surveys will enable us to study key aspects of galaxy evolution in the dwarf regime which we were historically restricted to studying only in massive galaxies. While *LSST* and *Euclid* will offer footprints of several thousand degrees, the *HSC* surveys, albeit much smaller, offer a preview of the game-changing science that is rapidly becoming possible.

For example, the fraction of red/quenched dwarfs in the *HSC* ultra-deep survey is around 40%, a factor of eight higher than what is concluded using shallow surveys like the SDSS. Red dwarfs reside in higher-density environments and closer to nodes, large-scale filaments, and massive galaxies. However, the probability of dwarfs being red is most strongly correlated with the distance to the nearest massive galaxy, rather than the density of its local environment. Interestingly, many red dwarfs reside in regions of very low ambient density. Around 15% of the red-dwarf population resides both outside the virial radii of massive galaxies and in regions which represent the lower 50% in density percentile. A large fraction of red dwarfs must, therefore, be quenched by mechanisms unrelated to local environment, such as stellar and AGN feedback.

Dwarfs show three principal morphological types: early-type, late-type, and a featureless class which lacks both the central concentrations found in early-types or the spiral structure that typified late-types. The featureless class is particularly interesting because it lacks an obvious counterpart in the massive regime. Dwarf early-types, unlike their massive counterparts, do not show an abundance of tidal features (even in ultra-deep images which are capable of revealing them). Thus, dwarf early-types are more likely to be shaped by secular processes, not interactions.

Finally, spectral-energy-distribution fitting on deep-ultraviolet to mid-infrared broadband photometry suggests that around a third of dwarfs show signs of AGN activity, indicating that AGN could be important in this regime, as they are in massive galaxies. This is supported by new broadband variability studies which suggest that the incidence of AGN in dwarf galaxies may be similar to that in their massive counterparts.

In summary, dwarf galaxies represent a vast discovery space for new and future deep-wide surveys like *Euclid* and *LSST* which promise revolutionary new insights into how galaxies form and evolve over cosmic time.

The President. Thank you very much, Sugata. One thing I didn't understand — your completion lines, how are they calculated?

Professor Kaviraj. I asked the question "If I had a purely old stellar population at a given stellar mass, at what redshift would that stellar population fall below the detection limit of my survey?" I'm assuming that a purely old stellar population, *i.e.*, something that doesn't have any star formation whatsoever is like a faintest limiting case. If you believe that is a good approximation of the faintest limiting case, at what redshift does that faintest limiting case drop below the detection limit of the survey? I would say that completeness thresholds calculated in this manner are pretty pessimistic, because if you look at real populations, no galaxy in the local Universe has a truly old population.

The President. My question was really based on how model dependent they were because that could have implications further down the line.

Professor Kaviraj. In terms of population synthesis it is not model dependent at all; whatever model you use, you will get the same answer.

Professor Richard Ellis. Very interesting. How reliable do you think your identification of AGN is in this new deep survey, just in photometry? You are proposing a very high fraction and in the spectroscopic fraction in massive galaxies is only a few per cent so why should there be so many AGN in the faint population?

Professor Kaviraj. There are two parts to this answer. Firstly, if you try and work out the AGN fraction of dwarfs using BPT [a Baldwin, Phillips & Terlevich diagram] but if you do it in a spatially resolved manner (there is work by Mezcua *et al.* that came out this year) what you find is that the AGN fractions are very high in dwarf galaxies. They are higher than what you find in massive galaxies — up to 50% or so. In fact the BPT technique becomes less sensitive as you go into the dwarf regime because the accretion discs are becoming hotter and therefore the AGN fractions may actually be lower limits. I don't think it is an issue that the dwarf AGN fraction is larger than the massive AGN fraction. I think that is the trend that we see. Secondly, you are right that when I do SED fitting it is inherently uncertain at some level; what has been done so far has used data from the ultraviolet to the infrared, but it doesn't go beyond 15 microns. It is possible that the models are not quite right and I would agree that there is potentially a large error bar. For variability results that I mentioned, the *VST*-COSMOS survey has a one-square-degree footprint, but all the other characteristics are basically identical to the *LSST* survey. In that kind of survey it is very clear about what is variable. I would say that the variability results are pretty clear. If you look at the variability results the AGN fractions are high whether you do it by SED fitting or variability. I don't think it is surprising any more that the AGN fraction of the dwarfs may actually be higher. For example, you can trigger gas infall using a small perturbation in dwarf galaxies and perhaps trigger AGN formation in that way.

Mr. Suryansh Saxena. Due to their small size how long can they sustain star formation? What kind of of stars are actively formed in the blue dwarfs?

Professor Kaviraj. Star formation is the same in all galaxies. You have a young stellar population of hot, massive, main-sequence stars and the reason why a young stellar population is brighter is because these stars are brighter and they also die off quite quickly. Whilst these stars are alive the population is bright and blue and then it essentially fades away. How long they can sustain star formation depends on how long they can be supplied with gas. To answer your question I would have to repeat these experiments at different epochs so you can work out how long the star formation time-scales are. Clearly dwarfs are not all quenched so it is possible for dwarfs to have star formation. To work out what the time-scales are you would need a larger redshift baseline.

The President. Thank you so much.

The last talk is from Dr. Ryan Ogliore. He is an Associate Professor in Physics at Washington University in St Louis. He received his bachelor's degree in Physics and Mathematics from Claremont McKenna College and his PhD in Physics from California Institute of Technology. His graduate research was in cosmic-ray astrophysics and he uses various microanalytical techniques to study extraterrestrial samples from all over the Solar System. He has worked on several past, current, and future NASA planetary missions in physics and astrophysics and today he is going to tell us about 'Sample return missions: past, present and future'.

Dr. Ryan Ogliore. The study of Earth rocks by high-precision laboratory techniques has been critical to our understanding of the geological processes that have shaped our planet. To put Earth in its appropriate cosmo-geological context, we need to understand the formation and evolution of the Solar System with the same precision. Therefore, it is necessary to have actual samples of the moons, asteroids, comets, and planets of our Solar System in the lab.

Rocks from space that fall to Earth naturally are called meteorites. More than a hundred years of studying nearly 80 000 known meteorites have answered some fundamental questions about our origins: Exactly how old is the Solar System? (4567 million years). What heat source caused planets to differentiate into a crust, mantle, and core? (The radioactive decay of aluminium-26). Studies of the *Apollo* samples returned from the Moon told us about one of the most significant events in Earth's history: the Moon-forming impact between the Earth and a Mars-sized body named Theia.

The meteorite record is, perhaps, the most spectacular record of nature known to science, but it is highly biassed. This natural record of extraterrestrial samples is biassed towards small objects on Earth-crossing orbits. Large bodies are not represented in the meteorite record except for the HED meteorites (thought to be derived from asteroid 4 Vesta), the SNC meteorites (originating from ancient Mars), and meteorites from our own Moon. The giant-planet region, from the asteroid belt to Neptune, is unsampled and therefore a geochemical unknown. A small body that likely originated in the outer Solar System, beyond Neptune, was sampled by a daring NASA space mission called *Stardust*.

Comet Wild 2 was in an outer Solar System orbit until 1974, when a close encounter with Jupiter sent it closer to the orbit of Mars. The *Stardust* mission collected many thousands of tiny dust grains, totalling only a milligram, in a novel low-density silica-glass foam called aerogel. The *Stardust* samples returned to Earth in 2006 and were distributed to scientists all over the world for analysis. After 18 years of study by scientists using the best laboratory instruments on Earth, a remarkable story emerged. The mission was called 'Stardust' because it was expected to return stardust leftover from the origin of the Solar System, 4567 million years ago. However, the rocky component of Comet Wild 2 contained very little stardust. Instead, most of the dust was igneous in nature, formed in unknown high-temperature events in the young Solar System.

Meteorites derived from asteroids contain igneous rocks with similar mineralogy, but detailed analyses of the Comet Wild 2 samples showed another surprise. Asteroids accrete 'local' materials with similar characteristics, all formed in a relatively confined area of space (and then altered on the asteroid). Comet Wild 2 accreted an enormous variety of materials from all over the Solar System which remained unaltered on the comet. The lack of excess magnesium-26, a decay product of aluminium-26, showed that the comet accreted material that formed relatively late (more than 3 Myr after the Solar System's birth). At this time, the Solar System can be thought of as a 'debris disc', containing very little gas but lots of leftover dust from impacts and other energetic events. This material migrated to the outer Solar System where it was slowly accreted into Comet Wild 2, along with abundant ices that formed beyond the orbit of Neptune.

The Sun contains the overwhelming majority of the mass in the Solar System and is obviously bright enough to be studied from Earth with spectroscopy. But to understand the formation of the Sun and planets from the primordial solar nebula, it was necessary to collect and return an actual sample of the Sun in the form of the solar wind. The *Genesis* mission, despite crash-landing on its return home, allowed scientists to compare the precise isotopic composition of the Sun with the rest of the sampled Solar System. The results were shocking. Oxygen, very common in both rocks and gases, was highly enriched in the light isotope compared to the planets (as sampled by the Earth, Mars, and asteroids). By studying tiny objects inside primitive meteorites, scientists now think that this Sun–planets dichotomy was established by irradiation of the forming Solar System by nearby massive O- and B-type stars in the Sun's birth cluster.

In addition to the large Sun–planets dichotomy revealed by *Genesis*, there is a smaller but well-resolved dichotomy within the sampled planetary bodies. Very precise analyses of meteorites show that these bodies can be divided into two groups that seem to reflect differences in the abundance of nuclei that formed by the rapid- and slow-neutron-capture processes. A forming Jupiter, which opened a gap in the Sun's protoplanetary disc, may have kept these two reservoirs separate. The Earth, Moon, and Mars are grouped with those bodies enriched in slow-neutron-capture nuclei, and thought to have formed in the inner Solar System.

However, many mysteries remain because the Earth and Moon lie at an extreme end of the inner Solar System bodies that have been measured so far for isotopes. Therefore the Earth could not have been built from known meteorites. There was a component, enriched in nuclei formed by the slow-neutron-capture process and lost from the meteorite record, that was incorporated into the forming Earth, and likely also Venus and Mercury. Returned samples from Mercury and Venus could help us understand the Earth's building blocks.

The gravitational tug-of-war between the giant planets and some of their moons creates heat, transforming some satellites into ocean worlds that may support life, and in one case, a volcanic wonderland. Jupiter's innermost Galilean moon, Io, has enormous lava lakes, 300-km active lava flows, and volcanoes thousands of times more powerful than our own. Plumes erupt a hundred miles off Io's surface into the hard vacuum of space, entraining volcanic ash. A daring space mission flying through one of those plumes (Fig. 1) can collect hundreds of milligrams of ash that contains a record of Io's formation and evolution and can test the hypothesis that Jupiter kept the chemical reservoirs of the inner and outer Solar System separate.

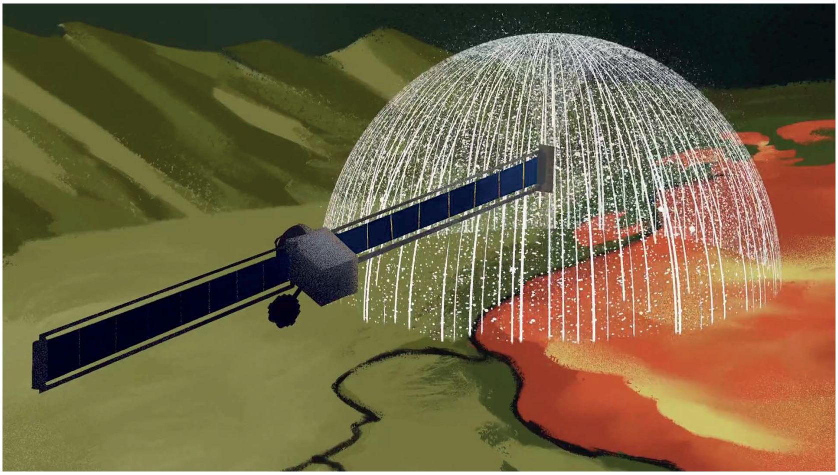

FIG. 1

Artist's rendition of a spacecraft approaching a plume on Io, ready for sample collection. (Image credit: Sofia Shen, NASA–JPL.)

Emerging nuclear-rocket technologies may radically change what is possible for future planetary-science space missions. It may be possible (within reasonable cost and time constraints) to sample the surfaces of Mercury, the moons of the gas giants, Uranus and Neptune, Pluto, and Kuiper-Belt objects. The science return from such missions would revolutionize our understanding of the processes that create the strange and habitable worlds we see in our own Solar System and operate in other planetary systems across the Universe.

The President. Thank you very much, Ryan. How do you know the difference between extrasolar material and Solar System material because you said that *Stardust* did not return?

Dr. Ogliore. We have grains that formed around other stars that pre-dated the Sun's birth and they all have very large isotopic anomalies. For rocks that formed in the Solar System, the differences are usually no more than a part per thousand. For grains that formed around other stars, the differences could be a factor of 2! It could not be more obvious. Some interstellar grains may have been sputtered and then re-condensed in the local interstellar medium. Then they would have the same isotopic composition as the Solar System and it is a trickier problem to identify those grains.

The President. Is that about processing and transport of the material?

Dr. Ogliore. Yes. It's processing somewhere, so if you sputter and re-condense a heterogeneous reservoir it eventually samples the bulk average and so that is the kind of thing that may have happened with interstellar grains that are harder to identify.

Mr. Horace Regnart. I hope I haven't read too much H. G. Wells and Ray Bradbury but am I right in my understanding that it will establish that what I would call called diploids from the Moon and Mars have arrived here? Is that an adequate guarantee that sample returns won't bring back something nasty?

Dr. Ogliore. Indeed this is worth thinking about. I was part of a group that was thinking about Mars sample return, including how to sterilize those samples before they are sent out to various labs. A huge amount of radiation would do it! However, Martian material can be found on the Earth right now. Martian meteorites are something that you can buy on eBay. Those meteorites have spent a long time in space and have been sufficiently sterilized. We don't have to worry about planetary protection for Io because it is a very inhospitable place for life as we know it. There are rules in place for planetary protection (both protecting a planet from Earth contamination, and *vice versa*). A sample directly from an asteroid or the Moon is of no concern. I think the probability is very, very, small that there is anything alive in the samples cached by the *Perserverance* rover. Nonetheless we have to do due diligence and sterilize the samples before we analyse them.

Ms. Frances Chapman. Would it help you if we all went out at night and took selfies? Do you have instruments in place?

Dr. Ogliore. Totally. There have been many meteorites detected on doorbell cameras, so we have a lot of footage and we can tell where that strewn field is. People also look at Doppler-radar detections of falling meteorites. We find more meteorites now because we have more video recordings and weather-radar data. You can report fireballs on-line at fireball.amsmeteors.org.

The President. I was struck by how many were spotted on car dashcams — in Russia in particular.

Professor Sara Russell. I was interested in what you were saying about cryogenic curation. Is that mission-critical for the Io sample return? We had a return mission from a comet that was not cryogenically stored, and also how difficult is it to keep it cryogenically stored in transit from the body back to Earth?

Dr. Ogliore. It's not critical at all for Io because we will be bringing back volcanic glass. If we were bringing back water or ice samples from Europa that would be necessary, but then there would be planetary-protection concerns. In the future we will want to return rock and ice from a comet — for example, a thin section where we can see CO_2 ice next to some igneous rock. We want that geological context with ice too, all the way through analysis. Johnson Space Center in Houston, Texas, is looking at a low level for cryogenic sample return for *Artemis* samples from the Moon. I think we are a long way from cryogenic return from these outer Solar System bodies because we need to keep these things undisturbed all the way from collection throughout analysis, which is really hard.

Dr. Paul Daniels. In the UK there is *UKMON* which is the UK monitoring network for meteors. It is a fairly dense camera network and quite often the cameras will capture more than one image of a meteor which will give a 3-D track of the meteor. For the brighter ones quite often you can get a fairly good idea of where you might find the debris in the case of meteorites.

Dr. Ogliore. This is fantastic! We have 70 000 meteorites but many fewer 'fresh' meteorites from witnessed falls. The more we collect the higher the chance we're going to get something that is really amazing, like something on a hyperbolic orbit or from the Kuiper Belt.

The President. I often wonder about doing spectroscopic analysis on those. It won't tell you about isotopes but it will give you chemistry. I think we should thank all three speakers [applause]. You are all invited, as usual, for drinks across the road in our new premises and the next meeting will be Friday, January 10th.

REDISCUSSION OF ECLIPSING BINARIES. PAPER 24: THE δ SCUTI PULSATOR V596 PUP (FORMERLY KNOWN AS VV PYX)

By John Southworth

Astrophysics Group, Keele University

V596 Pup is a detached eclipsing binary containing two A1V stars in a 4·596-d-period orbit with a small eccentricity and apsidal motion, previously designated as VV Pyxidis. We use new light-curves from the *Transiting Exoplanet Survey Satellite* (*TESS*) and published radial velocities to determine the physical properties of the component stars. We find masses of 2·098 ± 0·021 $M_{\odot}$ and 2·091 ± 0·018 $M_{\odot}$, and radii of 2·179 ± 0·008 $R_{\odot}$ and 2·139 ± 0·007 $R_{\odot}$. The measured distance to the system is affected by the light from a nearby companion star; we obtain 178·4 ± 2·5 pc. The properties of the system are best matched by theoretical predictions for a subsolar metallicity of $Z = 0{\cdot}010$ and an age of 570 Myr. We measure seven significant pulsation frequencies from the light-curve, six of which are consistent with δ Scuti pulsations and one of which is likely of slowly-pulsating B-star type.

Introduction

Eclipsing binary systems contain the only stars for which a direct measurement of their mass and radius is possible. Detached eclipsing binaries (dEBs) are an important class of these objects because their components have evolved as single stars. Their measured properties can be compared to the predictions of theoretical models of stellar evolution to check the reliability of the predictions and help calibrate the physical ingredients of the models[1–3].

Another approach to improving the theoretical descriptions of stars is that of asteroseismology[4]. The measured stellar oscillation frequencies can be compared to theoretical predictions to infer their densities, ages, rotational profiles, and the strength of chemical mixing[5–8].

Some dEBs show the signs of pulsations in one or both components, and thus might provide more exacting constraints on stellar theory. The pulsational types so far found in dEBs include δ Scuti[9–12], γ Doradus[13,14], slowly-pulsating B-type (SPB)[15,16], and *β* Cephei[17–19]. Several of these have been studied in previous papers in the current series: the hybrid δ Sct/γ Dor systems RR Lyn[20] and GK Dra[21], and the high-mass pulsators V1388 Ori[22] and V1765 Cyg[23].

In this work we present an analysis of V596 Puppis (Table I) based on published spectroscopy and new space-based photometry. We include an independent discovery of δ Scuti pulsations in this object.

V596 Puppis

The variability of V596 Pup was discovered from photographic patrol plates by Strohmeier, Knigge & Ott[32] without further comment. Andersen & Nordström[33] found it to exhibit double lines which were sharp and underwent large-radial velocity (RV) variations. Olsen[34] obtained 67 photoelectric brightness measurements which showed it to have two sets of eclipses with approximately equal depth. The secondary eclipse occurred at phase 0·48, indicating an eccentric orbit. It was given the name VV Pyx in the *65th Name-list of variable stars*[35].

The only detailed analysis of V596 Pup is by Andersen, Clausen & Nordström[31] (hereafter ACN84), who obtained complete light-curves (1495 points[36] in each of the *uvby* passbands) using the Strömgren photometer[37] on the Copenhagen 50-cm telescope at ESO La Silla, Chile, and photographic spectroscopy (28 high-dispersion photographic plates, each yielding an RV measurement for both stars). They confirmed the orbital eccentricity, detected apsidal motion, measured a spectral-line-strength ratio of 1·00 ± 0·03 between the stars, and found projected rotational velocities of $v \sin i = 23 \pm 3$ km s^{-1} for both stars. Due to the similarity of the two stars, ACN84 assumed they were identical and presented the physical properties of the mean component of the system. A *V*-band light-curve has since been presented by Shobbrook[38].

Samus *et al.*[39] performed a comprehensive revision of the sky positions of objects included in the *General Catalogue of Variable Stars* (*GCVS**). In 38 cases the variables were found to be in a different constellation than that adopted for their original *GCVS* designation, either due to changes in constellation boundaries, proper motion, or improved measurement of their right ascension and declination. Kazarovets *et al.*[40] specified new names for these 38 variable stars, at which point our object of interest became V596 Pup instead of VV Pyx.

V596 Pup has a close visual companion which is moderately fainter. The *Index Catalogue of Visual Double Stars*[41] gives a separation of 0·3 arcsec and a brightness difference of 1·1 mag. Jens Viggo Clausen obtained a visual estimate of the magnitude difference of 2 mag on a night of good seeing, which is in good agreement with spectroscopic measurements from two deep photographic plates (ACN84). ACN84 further suggested that the companion shows RV variability so could itself be a binary system. McAlister *et al.*[42,43] found angular separations of 0·397 arcsec and 0·417 arcsec, respectively, *via* speckle interferometry; further measurements were made by this group but are not itemized here. The *Gaia* DR3 entry of V596 Pup (Table I) gives an unusually imprecise parallax (4·31 ± 0·17 mas) and a large RUWE (renormalized unit-weight error) of 4·8, suggesting the positional measurements were compromised by the nearby companion. The RUWE should be approximately 1·0, and a value above 1·4 is

* http://www.sai.msu.su/gcvs/gcvs/

TABLE I

Basic information on V596 Puppis. The BV magnitudes are each the mean of 87 individual measurements[24] distributed approximately randomly in orbital phase. The JHK$_s$ magnitudes are from 2MASS[25] and were obtained at orbital phase 0·673.

Property	*Value*	*Reference*
Right ascension (J2000)	$08^h27^m33^s{\cdot}275$	26
Declination (J2000)	$-20°50'38''{\cdot}25$	26
Bright Star Catalogue	HR 3335	27
Henry Draper designation	HD 71581	28
Gaia DR3 designation	5706279565053294848	29
Gaia DR3 parallax	4·3083 ± 0·1673 mas	29
TESS Input Catalog designation	TIC 144085463	30
B magnitude	6·63 ± 0·01	24
V magnitude	6·59 ± 0·01	24
J magnitude	6·403 ± 0·018	25
H magnitude	6·410 ± 0·024	25
K_s magnitude	6·374 ± 0·024	25
Spectral type	A1 V + A1 V	31

indicative of a poor astrometric solution[29]; lower boundaries of 1·2 to 1·3 have been given by other authors[44,45].

ACN84 found an apsidal period of $U = 3200^{+1400}_{-800}$ yr. The relativistic contribution to this is significant, and it was identified by Giménez[46] as a candidate for the detection of this phenomenon. The apsidal motion of the system has subsequently been discussed by many authors[47–50]. The most recent work, by Claret *et al.*[51], found a significantly shorter apsidal period of 758 ± 29 yr.

Finally, Kahraman Aliçavuş *et al.*[52] included V596 Pup in a list of 42 eclipsing systems which show pulsations. A set of peaks in the frequency spectrum of the system in the region of 35–40 d^{-1} were interpreted as resulting from δ Scuti pulsations.

Photometric observations

V596 Pup has been observed in three sectors by the NASA *Transiting Exoplanet Survey Satellite*[53] (*TESS*). The data from sector 8 were obtained at a cadence of 1800 s, and from sectors 34 and 61 at a cadence of 120 s. Our analysis below concentrates on the data at 120-s cadence to avoid the smearing effects of the longer cadence. A fourth set of *TESS* observations (sector 88) was obtained in 2025 January but was not available when our analysis began.

The data were downloaded from the NASA Mikulski Archive for Space Telescopes (MAST*) using the LIGHTKURVE package[54]. We specified the quality flag "hard" to reject low-quality data, and used the simple aperture photometry (SAP) light-curves from the SPOC data-reduction pipeline[55]. The data from sector 8 were only available in QLP (Quick-Look Pipeline) form[56] and were also obtained using LIGHTKURVE. We converted the data points into differential magnitudes and subtracted the median magnitude from each sector for normalization. The light-curves are shown in Fig. 1 and contain 747, 17373, and 17764 data points from sectors 8, 34, and 61, respectively.

Light-curve analysis

The eclipses in V596 Pup occupy 14% of each orbital period, and the remaining data hold little information about the properties of the system.

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

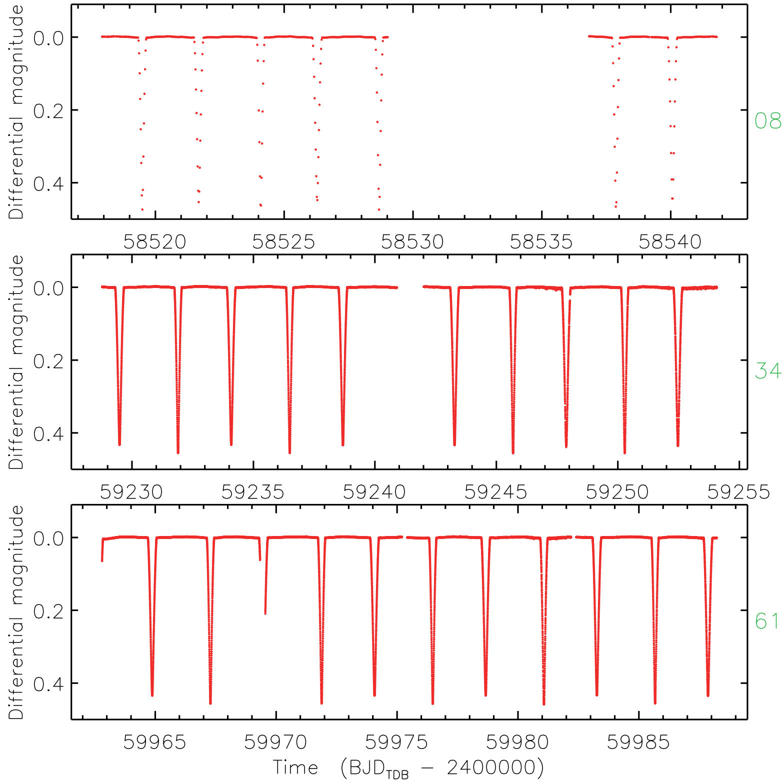

Fig. 1

TESS photometry of V596 Pup. The flux measurements have been converted to magnitude units then rectified to zero magnitude by subtraction of the median. The data from sector 8 are from the QLP pipeline, and from sectors 34 and 61 from the SPOC pipeline. The sector number is shown in green to the right of each panel.

We therefore extracted the data around each eclipse from the short-cadence light-curves by retaining only the data points within one full eclipse duration of the midpoint of a fully-observed eclipse. This left a total of 4826 data points from sector 34, and 4753 from sector 61. We define star A to be eclipsed at the deeper eclipse, and its companion to be star B.

We modelled the light-curves of the eclipses using version 43 of the JKTEBOP* code[57,58]. The fitted parameters were the fractional radii of the stars (r_A and r_B), expressed as their sum ($r_A + r_B$) and ratio ($k = r_B/r_A$), the central-surface-brightness ratio ($\mathcal{J}$), third light (L_3), orbital inclination (i), orbital period (P), the reference time of primary minimum (T_0), and the quantities $e \cos \omega$ and $e \sin \omega$ where e is the orbital eccentricity and ω is the argument of periastron. Limb darkening (LD) was accounted for using the power-2 law[59–61] with the same LD coefficients for both stars due to their similarity. The linear coefficient (c) was

*http://www.astro.keele.ac.uk/jkt/codes/jktebop.html

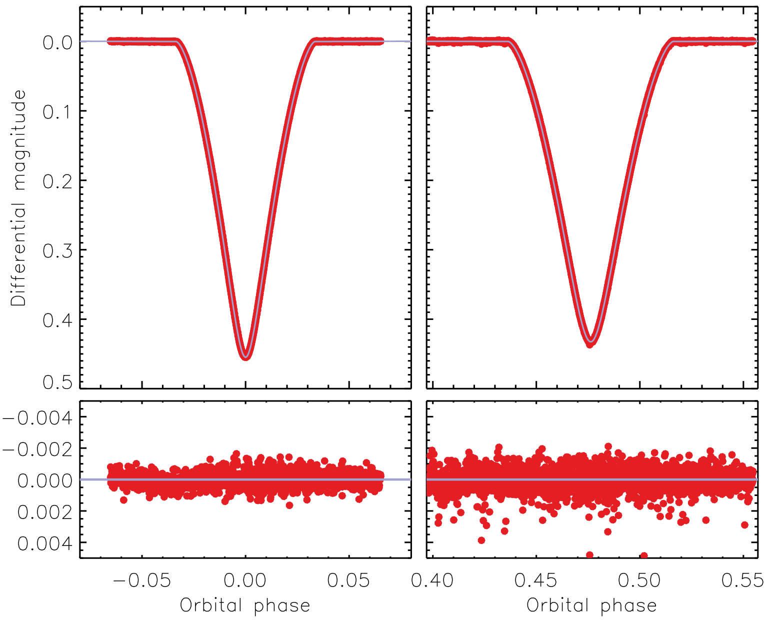

FIG. 2

JKTEBOP best fit to the light-curves of V596 Pup from *TESS* sector 34. 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 panel.

fitted and the non-linear coefficient (α) held fixed at a theoretical value[62,63]. Our initial fits to sectors 34 and 61 together led to a larger scatter than expected. We further constrained the ephemeris by measuring a time of primary eclipse from sector 8 and including it in the fit, finding that this made things worse (the best-fitting time of minimum from sector 8 was 29σ from the measured value). From this we deduce that the effects of apsidal motion are significant over the time interval of the *TESS* observations, and also that the amount of third light may differ between sectors due to the different orientations of the *TESS* cameras. A natural solution is to model the data from sectors 34 and 61 individually, and leave discussion of the apsidal motion to future work. This resulted in much better fits being obtained, which are shown in Figs. 2 and 3. The best-fitting parameter values are given in Table II. The residuals *versus* the best fits are larger in the secondary eclipse than in the primary eclipse, for both sectors. Inspection of the residuals *versus* time suggests that this is due to chance. We experimented with rejecting the eclipses with higher scatter but found that this had little effect on the results.

The parameter uncertainties were obtained using Monte-Carlo (MC) and residual-permutation (RP) simulations (JKTEBOP tasks 8 and 9). As part of this process the data errors from the *TESS* reduction pipeline were normalized to force a reduced χ^2 of unity. We were expecting the RP error bars to be larger than the MC ones due to the pulsational signatures in the light-curve, which were not included in the model and thus are effectively red noise, but for most

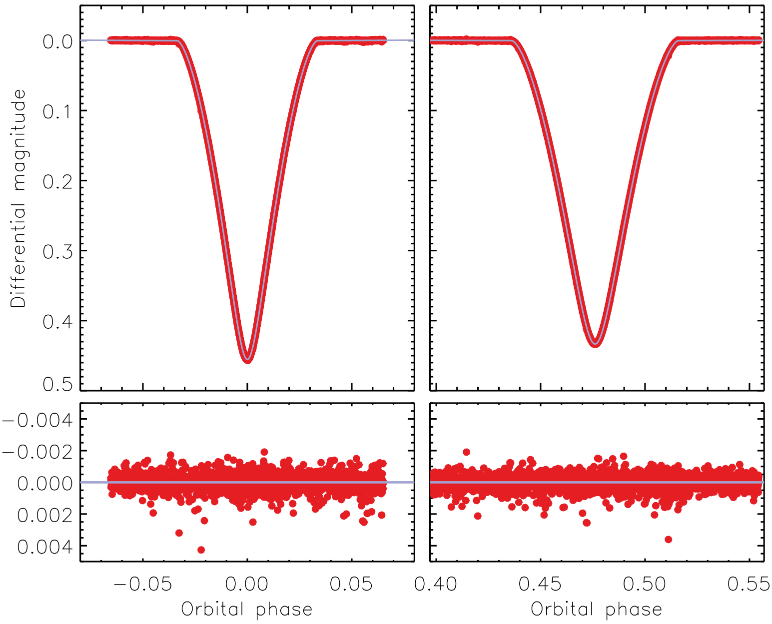

FIG. 3

JKTEBOP best fit to the light-curves of V596 Pup from *TESS* sector 61. Other comments are the same as for Fig. 2.

parameters the two were very similar. The main exception to this is $e \cos \omega$, from which we infer that the pulsations affect the measured phase difference between the eclipses.

Table II contains the measured parameters from the fits to sectors 34 and 61, plus the larger of the MC or RP error bar for each parameter. Given the similarity of the data and results for the two sectors we adopt the unweighted mean of those values in common. The uncertainties are extremely low so we take the largest of the four options for each parameter (Table II), thus forego the $\sqrt{2}$ boost from having two datasets fitted separately.

The analysis above provides measurements of the fractional radii of the stars to a precision of 0·15%. The surface-brightness ratio is almost unity: the difference in the depths of primary and secondary eclipse is driven primarily by different fractions of the stars eclipsed at these times due to the eccentricity of the orbit. Two orbital ephemerides are also obtained, but are not valid for other time periods as they don't account for the apsidal motion.

Radial-velocity analysis

Armed with a new high-precision measurement of the orbital eccentricity, it was reasonable to reanalyse the published RVs of the stars (ACN84) to see if they were consistent and allowed a more precise measurement of the velocity amplitudes, K_A and K_B. We manually digitized the RVs in table 2 of ACN84 then fitted spectroscopic orbits (see below). We found that the RVs for both

TABLE II

Photometric parameters of V596 Pup measured using JKTEBOP from the light-curves from TESS sectors 34 and 61. The error bars are 1σ and were obtained from a residual-permutation analysis.

Parameter	*Value (sector 34)*	*Value (sector 61)*	*Adopted value*
Fitted parameters:			
Orbital period (d)	4·5961598 ± 0·0000025	4·5961597 ± 0·0000023	
Reference time (BJD_{TDB})	2459236·4944615 ± 0·0000066	2459976·4770916 ± 0·0000049	
Orbital inclination (°)	88·1294 ± 0·0055	88·1387 ± 0·0038	88·1340 ± 0·0055
Sum of the fractional radii	0·23018 ± 0·00012	0·23027 ± 0·00011	0·23022 ± 0·00012
Ratio of the radii	0·9820 ± 0·0027	0·9815 ± 0·0021	0·9817 ± 0·0027
Central-surface-brightness ratio	0·99906 ± 0·00035	0·99944 ± 0·00027	0·99925 ± 0·00035
Third light	0·2026 ± 0·0010	0·1999 ± 0·0010	
LD coefficient c	0·554 ± 0·015	0·560 ± 0·011	0·557 ± 0·015
LD coefficient α	0·4574 (fixed)	0·4574 (fixed)	0·4574 (fixed)
$e \cos \omega$	−0·0370930 ± 0·0000089	−0·0374236 ± 0·0000064	
$e \sin \omega$	0·08941 ± 0·00021	0·08963 ± 0·00016	
Derived parameters:			
Fractional radius of star A	0·11614 ± 0·00017	0·11621 ± 0·00013	0·11617 ± 0·00017
Fractional radius of star B	0·11404 ± 0·00016	0·11406 ± 0·00013	0·11405 ± 0·00016
Light ratio ℓ_B/ℓ_A	0·9631 ± 0·0051	0·9626 ± 0·0040	0·9629 ± 0·0051
Orbital eccentricity	0·09680 ± 0·00019	0·09713 ± 0·00015	0·09696 ± 0·00019
Argument of periastron (°)	112·533 ± 0·048	112·663 ± 0·039	

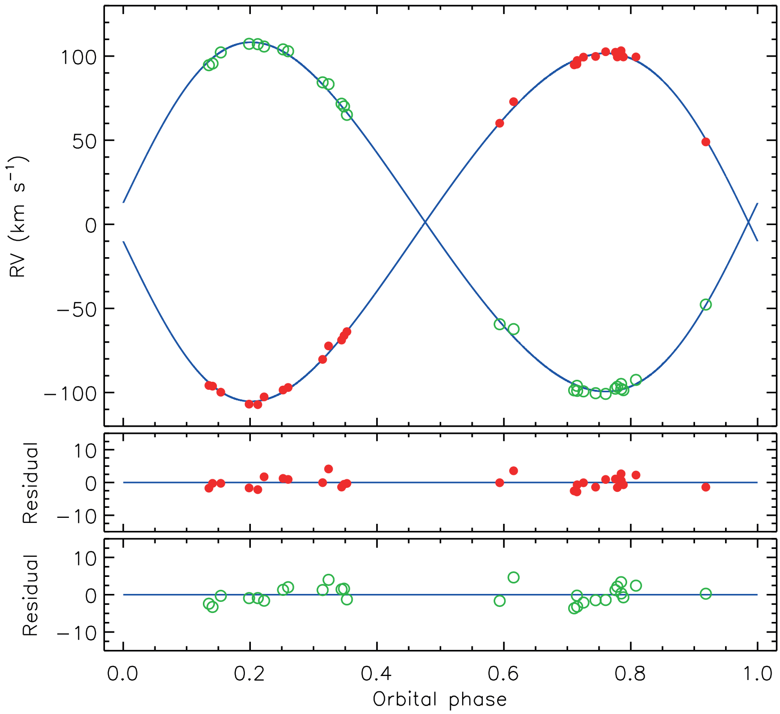

FIG. 4

RVs of V596 Pup from ACN84 compared to the best fit from JKTEBOP (solid blue lines). The RVs for star A are shown with red filled circles, and for star B with green open circles. The residuals are given in the lower panels separately for the two components.

stars at time HJD 2444348·5342 were highly discrepant, and that the time did not match the orbital phase in column 3 of the table. Changing the time to 2444384·5342 solved all three problems, and is more in line with the typical observing-run time allocations*.

We then fitted the RVs for the two stars using JKTEBOP. The only fitted parameters were K_A, K_B, ω, the systemic velocities of the stars, and a phase offset *versus* our orbital ephemeris from *TESS* sector 34. The phase offset is small (–0·011), so our star identifications match those of ACN84. The systemic velocities of the stars were very similar so we ran a final fit with a value common to both stars. Error bars were obtained from 1000 MC simulations[64]. The measured parameters are $K_A = 103{\cdot}47 \pm 0{\cdot}37$ km s^{-1}, $K_B = 103{\cdot}82 \pm 0{\cdot}49$ km s^{-1}, $\omega = 108{\cdot}0^\circ \pm 2{\cdot}0^\circ$ and a systemic velocity of $1{\cdot}31 \pm 0{\cdot}26$ km s^{-1} (where the error bar does not include uncertainty in the definition of the velocity scale). The fitted orbits are shown in Fig. 4. The values and uncertainties we find are in good agreement with those from ACN84.

*The times of the RVs are grouped into three discrete observing runs of 5–10 days each.

Physical properties and distance to V596 Pup

We calculated the physical properties of V596 Pup using the JKTABSDIM code[66] with the P, e, i, r_A, and r_B from our analysis of the *TESS* light-curves, and the K_A and K_B from our analysis of the ACN84 RVs. We adopted an effective temperature of $T_{eff} = 8500 \pm 200$ K from ACN84 for both stars, as their surface brightnesses are practically identical. A somewhat larger value of 9311 ± 195 K was given by Zorec & Royer[67].

Our mass and radius measurements (Table III) are consistent with those of ACN84, with the advantages that we have values for both stars rather than just the mean component, and that the radii are now measured to a precision of 0·3% *versus* 0·9%. The synchronous rotation velocities in Table III are consistent with the measured values (ACN84).

The distance to V596 Pup merits discussion. Inversion of the parallax from the *Hipparcos* and *Gaia* satellites give distances of 222^{+63}_{-40} pc and 232 ± 9 pc, respectively. However, the *Gaia* value is unusually uncertain for a celestial object this close to the Solar System, and is accompanied by a RUWE indicating a poor astrometric fit (see *Introduction*). ACN84 determined a distance of 195 ± 10 pc, somewhat shorter than both parallax-derived values (albeit that the *Hipparcos* distance is very uncertain).

We calculated a new distance estimate using the *BV* and JHK_s apparent magnitudes of the system (Table I), the calibrations of surface brightness *versus* T_{eff} presented by Kervella *et al.*[68], and the other quantities inputted to JKTABSDIM. The JHK_s magnitudes were converted to the Johnson system[69] but not corrected for the presence of the close companion. With an interstellar reddening of $E(B-V) = 0{\cdot}07 \pm 0{\cdot}02$ mag to equalize the distances at optical and infrared wavelengths, we obtained a much shorter distance of 162·8 ± 2·2 pc in the K_s band. An alternative approach using theoretical bolometric corrections from Girardi *et al.*[70] gives a consistent distance of 165·1 ± 2·3 pc.

The star within 0·4 arcsec of V596 Pup will contaminate the photometry of the system. Without a precise magnitude difference and T_{eff} of the star we cannot properly correct for its contamination in the *BV* and JHK_s magnitudes. Its light acts to make V596 Pup appear brighter and therefore closer to the observer. If we adopt a magnitude difference of 1·1 mag in all passbands[41] we find a distance of 190·1 pc instead of 162·8 pc; for a magnitude difference of 2 mag (ACN84) the distance becomes 175·3 pc. Our preferred option is instead

TABLE III

Physical properties of V596 Pup defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 65).

Parameter	*Star A*	*Star B*
Mass ratio M_B/M_A	0·9966 ± 0·0059	
Semi-major axis of relative orbit ($\mathcal{R}^N_\odot$)	12·109 ± 0·029	
Mass ($\mathcal{M}^N_\odot$)	2·098 ± 0·021	2·091 ± 0·018
Radius ($\mathcal{R}^N_\odot$)	2·1785 ± 0·0072	2·1387 ± 0·0070
Surface gravity (log[cgs])	4·0835 ± 0·0024	4·0981 ± 0·0020
Density ($\rho_\odot$)	0·2029 ± 0·0011	0·2137 ± 0·0011
Synchronous rotational velocity (km s^{-1})	23·98 ± 0·08	23·54 ± 0·08
Effective temperature (K)	9500 ± 200	9500 ± 200
Luminosity $\log(L/\mathcal{L}^N_\odot)$	1·542 ± 0·037	1·526 ± 0·037
M_{bol} (mag)	0·885 ± 0·092	0·925 ± 0·092
Interstellar reddening $E(B-V)$ (mag)	0·07 ± 0·02	
Distance (pc)	178·4 ± 2·5	

to interpret the third light in our solutions of the *TESS* light-curves as arising from the nearby star. In this case the amount of contamination is at least precisely determined, and we obtain a distance of 178·4 pc with a negligible additional uncertainty.

We cannot find a way to make our distance match that from *Gaia* DR3. Ignoring interstellar extinction changes the K_s-band distance by only +2.7 pc. Adding 1000 K to the T_{eff} values requires a larger $E(B-V)$ and only shifts the distance measurement by +2·4 pc. Such a small effect might seem surprising, but is explicable: our preferred distance estimates rely primarily on the K_s band, which is well into the Rayleigh-Jeans tail of the spectrum so is insensitive to temperature. The 2MASS JHK_s apparent magnitudes were taken at orbital phase 0·673 so are well away from eclipse — if they were in eclipse then this would make them fainter and bring the measured distance even closer. We conclude that the *Hipparcos* parallax is too uncertain to conflict with our results, that the *Gaia* DR3 parallax is unreliable due to the close companion, and that our own distance measurements are also imperfect as they incorporate assumptions about the brightness and T_{eff} of the close companion.

Comparison with theoretical models

The similarity of the components of V596 Pup means the system is not a particularly good test of theoretical models, but a comparison is still informative. We compared the measured properties of V596 Pup to the predictions of the PARSEC 1·2S theoretical stellar-evolutionary models[72], concentrating on the radii and T_{eff} values predicted for the known masses.

A metal abundance of $Z = 0{\cdot}017$ and an age of 540 Myr fits the radii well but underpredicts the T_{eff} values by 600 K. A lower metal abundance of $Z = 0{\cdot}014$ requires an age of 560 Myr to match the radii but still underpredicts the T_{eff} values, by 400 K. Moving to a Z of 0·010 and an age of 570 ± 20 Myr provides an excellent match to all three properties for both stars. This suggests that V596 Pup is moderately metal-poor, something that should be confirmed spectroscopically. A Hertzsprung–Russell diagram is shown in Fig. 5.

Pulsation analysis

The *TESS* light-curve of V596 Pup shows clear evidence for pulsations of relatively short period. The object has been previously identified as showing δ Scuti pulsations[52]. We calculated frequency spectra for sectors 34 and 61 using version 1.2.0 of the PERIOD04 code[73]. The sectors were treated individually to avoid problems with aliasing, and the JKTEBOP best fit was subtracted from the data prior to analysis. The frequency spectrum for sector 61 had a lower noise level so we used it to measure the significant frequencies in the light-curve.

We found seven significant frequencies in the spectrum for sector 61, where we take the minimum signal-to-noise ratio (S/N) to be 4 (refs. 74 and 75). All of these are also present in the spectrum for sector 34, confirming their existence. An additional frequency at 36·3 d^{-1} is present in sector 61 but not sector 34 so may not be of astrophysical origin. The frequencies and their amplitudes are given in Table IV, and the spectra are shown in Fig. 6.

Six of the frequencies are in the interval 30–50 d^{-1} so can be attributed to pulsations of the δ Scuti type. The T_{eff} and luminosity values of the stars put them slightly beyond the instability strip and in a region where the fraction of pulsators is approximately 0·1 (see Murphy *et al.*[76]). The remaining frequency is much lower, at 1·9 d^{-1}, and cannot be due to p-mode pulsations. It is instead

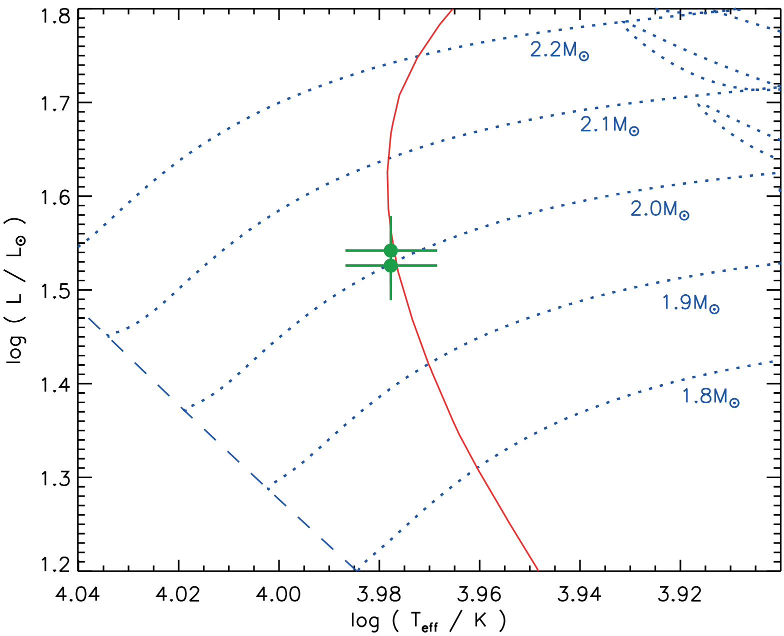

FIG. 5

Hertzsprung–Russell diagram for the components of V596 Pup (filled green circles) and the predictions of the PARSEC 1·2S models[71] for masses of 1·8, 1·9, 2·0, 2·1, and 2·2 $M_\odot$ (dotted blue lines with masses labelled) and the zero-age main sequence (dashed blue line), for a metal abundance of $Z = 0{\cdot}010$. The isochrone for an age of 570 Myr is shown with a solid red line.

borderline consistent with being of the SPB type[77], with the components of V596 Pup having $T_{\rm eff}$ values at the lower limit of this class[78].

The orbital frequency of V596 Pup is 0·2176 d^{-1}, and the Loumos & Deeming[79] frequency resolution is 0·10 d^{-1}. Frequencies f_3 and f_6 are close to being the 157th and 197th multiples of the orbital frequency, but this similarity is of low statistical significance given the frequency resolution of a single *TESS*

TABLE IV

Significant pulsation frequencies found in the TESS sector 61 light curve of V596 Pup after subtraction of the effects of binarity.

Label	*Frequency* (d^{-1})	*Amplitude* (*mmag*)	*S/N*
f_1	1·9060 ± 0·0010	0·126 ± 0·006	5·0
f_2	30·0686 ± 0·0049	0·027 ± 0·006	5·4
f_3	34·1693 ± 0·0019	0·070 ± 0·006	9·2
f_4	38·5870 ± 0·0011	0·125 ± 0·006	11·8
f_5	39·8933 ± 0·0013	0·102 ± 0·006	10·5
f_6	42·8533 ± 0·0027	0·049 ± 0·006	6·5
f_7	46·3927 ± 0·0040	0·033 ± 0·006	4·8

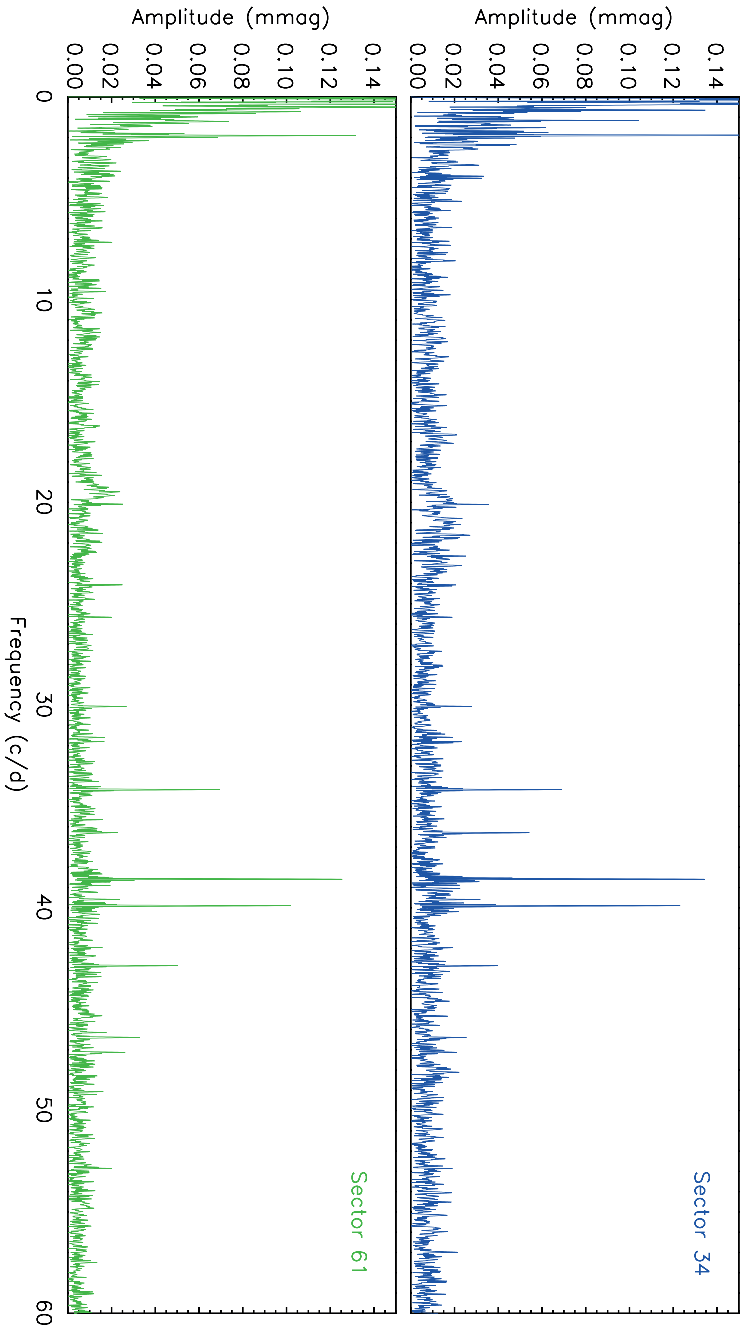

Fig. 6

Frequency spectra of V596 Pup from *TESS* sector 34 (upper panel, blue lines) and sector 61 (lower panel, green lines).

sector. We are not able to attribute any frequency to an individual star with the available data, and indeed cannot rule out that some or all of the pulsations arise from the close companion.

Summary and conclusions

V596 Pup is a dEB containing two A1V stars in an orbit of period 4·596 d which shows both eccentricity and apsidal motion. We have determined the physical properties of the component stars using two sectors of short-cadence data from *TESS* and published photographic RVs from ACN84. We measure the radii of the stars individually for the first time, rather than the radius of the mean component of the system. The radii are extremely well-determined by the *TESS* data, and are consistent with the spectroscopic light ratio from ACN84. The properties of the system are best matched by theoretical predictions for stars of a metal abundance of $Z = 0{\cdot}010$ and an age of 570 Myr.

V596 Pup has a companion at 0·4 arcsec which is fainter by 1·7 mag in the *TESS* passband, assuming it is the sole source of third light in the *TESS* data. This companion causes a poor fit to the astrometry in *Gaia* DR3, and thus an uncertain parallax. We instead measure a distance *via* the system's K_s-band apparent magnitude and calibrations of surface brightness *versus* $T_{\rm eff}$, obtaining $178{\cdot}4 \pm 2{\cdot}5$ pc after correcting for the light from the third star under the assumption that it has the same $T_{\rm eff}$ as the eclipsing stars.

Pulsations are visible in the light-curve of V596 Pup. We subtracted the effects of binarity and measured seven significant pulsation frequencies in the data. Six of these are consistent with p-mode pulsations (30–46 d^{-1}) and one with g-mode oscillations (1·9 d^{-1}). We assign the higher frequencies to δ Scuti pulsations and the lower frequency to SPB pulsations; the component stars are outside but close to the instability strips for both types of variability. There is a chance that some or all of the pulsations arise from the fainter companion to the binary system.

The current work significantly increases the precision of the radius measurements of the members of the V596 Pup system. Further improvements to the analysis could be obtained by better characterizing the fainter nearby star, obtaining spectroscopic chemical abundances to check our inference of a low metallicity of the system, and measuring its apsidal period precisely to constrain the internal-structure constants of the component stars

Acknowledgements

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[*]https://www.cosmos.esa.int/gaia

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

System; the *Simbad* database operated at CDS, Strasbourg, France; and the arχiv scientific-paper preprint service operated by Cornell University.

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CORRESPONDENCE

To the Editors of 'The Observatory'
Exquisite Precision

In a recent book review[1], in reference to one of the échelle spectrographs with a precision of 10 cm s^{-1} on the ESO *Very Large Telescope*, Tatum wondered "... whether astronomers can really make use of such exquisite precision". There are at least two fields of study where the answer is 'yes'. One involves the detection of exoplanets *via* the changing radial velocity of a parent star. The change in the radial velocity of the Sun due to the Earth is about 10 cm s^{-1}. Thus, even higher resolution would be needed in order to detect less massive and/or more distant planets around Sun-like stars, and even more if the system is not seen edge-on. The same goes for a more massive star, and moreover in such a case a planet in the habitable zone would be further away as well, reducing the change in radial velocity even more.

The other, at the other end of the astronomical scale, is cosmology. The cosmological redshift z is given by $R_0/R - 1$, where R_0 is the scale factor now and R the scale factor at the time of emission. One usually assumes that R_0 is constant, since time-scales directly familiar to humans are orders of magnitude shorter than the light-travel time from an object with a significant cosmological redshift. Looking at the back of an envelope, the age of the Universe of about 10^{10} years means that one might expect z to change by about 10^{-10} in a year. The speed of light is about 3×10^{10} cm s^{-1}, thus such a spectrograph could detect the change in cosmological redshift within a few years. The details depend on the cosmological model, and one can determine the cosmological model by measuring this so-called redshift drift as a function of redshift, which is particularly interesting since there is no possibility of confusion due to evolutionary effects.

The above discussion assumes two (or more) measurements at different times, each of which would correspond to a different time of emission. However, in a gravitational-lens system in which one sees more than one image of the same object, in general the light-travel time will be different. For a galaxy lens, that is on the order of months while for a cluster of galaxies the time delay could be a thousand years or so. In such a case, one could measure the redshift drift in a single night by taking spectra of each image. In the case of a cluster lens, due to the much longer time delay, the redshift drift could be greater than that which could be measured by observing the same single-image object over the lifetime of an astronomer. If the cosmological parameters are well known, one could effectively measure the time delay *via* measuring the difference in redshift between two images of the same object, which could constrain the mass distribution of the gravitational lens.

The idea of redshift drift is older than I am[2]*, but has received more attention recently due to the possibility of actually measuring it; there is an ESO Key Programme for the task[3]. More details, especially for redshift drift in the context of strong gravitational lensing, can be found in my latest paper in *MNRAS*[4].

Yours faithfully,
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* Sandage was both pessimistic about improvements in spectroscopy and optimistic about the future of humanity: "[A] precision redshift catalogue must be stored away for the order of 10^7 years ..." and "... data for extragalactic astronomy must be collected from ancient literature."

REVIEWS

The Universe in a Box: A New Cosmic History, by Andrew Pontzen (Vintage), 2024 (first published 2023). Pp. 251, 19·8 × 13·8 cm. Price £12·99 (paperback; ISBN 978 1 529 92200 4).

Andrew Pontzen, until recently a professor of cosmology at University College London, is now a professor at the University of Durham. While this is his first book, he has popularized science in magazines, on radio, and on television, and is well known in the field of cosmological simulations, the topic of this book. A good move is to start with discussing weather and climate, something people are familiar with; the distinction between the two (details at a particular place and time as opposed to long-term large-scale trends) carries over into cosmological simulations, where the goal is to understand the general behaviour, not to mimic a specific scenario in detail. There are many interesting historical details on weather forecasting, climate simulations, chaos, and so on. The second chapter has a similar discussion with respect to simulations of the large-scale structure of the Universe and the roles of dark matter and dark energy in producing structures such as the cosmic web. History is important here as well and I was happy to meet Erik Holmberg's fascinating optical analogue computer for galaxy simulations for the second time in a popular-science book (for the first, see refs. 1 & 2). Like the details of raindrops or even clouds in weather simulations, individual stars are much too small to be resolved in a cosmological simulation, leading to a discussion of sub-grid approximations, heuristic parameterizations designed to accommodate such small-scale phenomena into the simulation. An important application is the introduction of baryonic physics to refine more straightforward simulations containing only dark matter and dark energy. There is a balanced discussion between the critical claim that one gets out only what one puts in and the increased faith in such schemes when they successfully predict behaviour for which they were not designed. In that respect and others there is good discussion of how one uses simulations as a tool for understanding rather than to mimic reality. An important sub-grid phenomenon in galaxy simulations are black holes and their effects on star formation, worth an entire chapter.

Chapter 5 shifts gears somewhat by moving to quantum theory, but that is relevant due to the role played by quantum mechanics in the early Universe and its potential role in quantum computation. Computation is the subject of the sixth chapter on machine learning in general and its uses in astronomy. While rightly criticizing current exaggerated hype ("ChatGPT ... comes across as a bland know-it-all" with its output being "like a mediocre TV script: believable on the surface but with little substance" with aimlessly drifting conversations lacking any large-scale coherence and limited to "the restatement of existing ideas that it found who-knows-where on the Internet")*, Pontzen also considers it a realistic possibility that artificial intelligence could improve enormously and emulate or exceed human thinking in many respects. That leads to a discussion of the simulation hypothesis, the idea that if consciousness is easy enough to simulate, then a typical conscious being is more likely to be simulated than real[3]. The idea has prominent supporters — or at least some who don't think that it is patently absurd and not worth considering — (including the Astronomer Royal[4]), but also prominent detractors (such as George Ellis, who reminded

*On the other hand, a good friend of mine once described conversations between his fellow pupils at school as the mutual exchange of standard statements they had learned by heart; he is now a teacher.

the audience of his view on that topic at a recent philosophy-of-cosmology conference I attended in Milan). Pontzen speculates that such a simulation might employ sub-grid methods, as one would need the entire Universe to simulate the Universe in detail (though if our Universe is simulated, we don't know anything about the universe in which that simulation is running). (However, if simulating consciousness is a goal (and one could argue that simulated consciousness is also consciousness), I wonder why the much easier task of simulating a brain and its sensory inputs is not a more popular topic.) In the same, final, chapter is an over-arching discussion of 'Simulations, science and reality' which also serves as a summary of the book.

This is not a book about the details of simulations† but about their purpose, their role within science, even the human side of them, presenting a balanced view by an expert on the subject. Thirteen pages of small-print endnotes sometimes play the role of footnotes but are mostly references, usually to the scientific literature but also to various internet resources. An eleven-page small-print index ends the book. There are no figures. It is well written with a lower than average number of typos and so on. My only real complaint is a paragraph which, while also recognizing his contributions, is strongly critical of Feynman as a person; even if true, I don't see the relevance to the rest of the book nor any reason why Feynman is singled out for such criticism. Apart from that, I can warmly recommend the book. — Phillip Helbig.

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Steven Weinberg: A Life in Physics, by Steven Weinberg (Cambridge University Press), 2025. Pp. 253, 23·5 × 16 cm. Price £25/$29·95 (hardbound; ISBN 978 1 009 51347 0).

Steven Weinberg's (1933–2021) autobiography will become an invaluable source for future historians of physics and astronomy. His candid memoir of a scintillating life in physics opens with a child's memory of the key books that sparked his innate curiosity about the physical world. George Gamow's creation, Mr. Tompkins, introduced young Steven to the weird world of Special Relativity and quantum mechanics; science-fiction classics likewise stirred his imagination; and from Jeans' *The Mysterious Universe* he gleaned that he "would need special mathematics" to make sense of the universe. 'Making sense' became Weinberg's lifetime goal.

Weinberg was polishing his memoirs at the time of his death. Steven's wife, Louise, has organized and edited them to produce this engaging account of his life as a scientist and public intellectual. Many vignettes of his formative encounters with dozens of leading physicists in the mid-20th Century enrich the narrative. Weinberg's talent as a writer of popular science shines through brightly. He offers many good stories: on working styles, he liked to work on fundamental physics with the TV tuned to the History Channel, a trick that doubled his productivity — absorbing some old knowledge while striving to

†Those interested in that aspect might want to consult a book[5] reviewed last year in these pages[6].

make sense of new knowledge. Louise and Steven passionately shared their life experiences as academics in search of truth. Each had a study as a place for quiet work at home. Steven recounts (page 112) that he became habituated at working from his desk overlooking the garden. We are in the time of the Vietnam war, when Steven spent his time on informed interest in international affairs, trying to make sense of the new world order. Louise steered him away from the dismal company of disheartened older men and directed her young husband to get back to working on physics. Steven writes: "I do not exaggerate when I confess that she saved my life", a great life in physics no less. Weinberg's prose style is redolent of Émile Zola's novelistic realism, which blends rather well with the racy travelogue approach of Gamow's *My World Line* (Viking, 1970). Weinberg is instructive on how one should write history of science in a contemporary style, composed of social contexts, complex conundrums, and conflicting conclusions. Echoing Copernicus (1543), I recommend diligent readers "to buy, read, and enjoy this work." — Simon Mitton.

The Known Unknowns: The Unsolved Mysteries of the Cosmos, by Lawrence M. Krauss (Head of Zeus), 2024 (originally published in 2023). Pp. 373, 20 × 13 cm. Price £9·99 (paperback; ISBN 9781801100656).

Lawrence Krauss has worked at various US universities in several fields related to cosmology and particle physics (including strong gravitational lensing, so his papers on that topic crossed my desk back at the beginning of my career — yes, real papers and a proper antique desk back then) and has written around a dozen popular-science books (of which so far, apart from this book, I've read only his biography of Richard Feynman). The title refers to a famous quotation by former US Vice President Dick Cheney, which follows one by Feynman in which he notes that he isn't frightened by not knowing things.

Space, time, matter, life, and consciousness. Those are the topics explored in the corresponding five chapters. While the known unknowns are mentioned, most of the text is a presentation of what we do know. Of course, 36–60 pages per topic is not anywhere near enough to give a complete overview; rather, there is a very broad-brush summary and a few topics are discussed in somewhat more detail. Readers familiar with a topic will thus probably find little that is new, and even the known unknowns might be familiar. Each chapter begins with a list of a handful of questions, the answers to which are always 'We don't know.' One example from each chapter: 'Does time have a beginning?', 'Are there hidden dimensions?', 'Will matter end?', 'Is DNA life unique?', 'Can we create [consciousness]?' While those questions are discussed in the corresponding chapters, they are not a table of contents: the order isn't always the same, and they arise in the context of discussion of more specific topics.

There are some good discussions, such as the relationship between the geometry and destiny of the Universe and how that is affected by the presence of a cosmological constant or some more bizarre form of dark energy, a topic often presented wrongly. The book is well written and a good mixture of the current consensus on various topics and the author's own opinions. I learned a few things, such as the puzzle of conflicting measurements (depending on the method) of the half-life of the neutron. However, I'm struggling to find the target readership. Those familiar with the topics will already know the known unknowns. Those who aren't can't get an impression of how they relate to the rest of the corresponding field from the information provided here. (Having said that, discussion of a few topics in a bit more detail avoids repeating broader but shallower capsule summaries of entire fields.) They could also be led astray by statements such as that dark energy causes the Universe to expand, or an unfortunate typo (resulting in an essentially opposite statement) in the otherwise good discussion of why the net electric charge in a spatially closed universe must be zero. Most readers of this *Magazine* will probably be more familiar with the first three chapters than the last two and might very well learn more from them, but by the same token it would be difficult to appreciate Krauss's description of the known unknowns if they don't know the known knowns.

There are no figures and neither footnotes nor endnotes. The seventeen-page index is quite thorough for a book such as this one, though unusually not set in a smaller font than the main text. Despite my qualms, this is not a bad book by any means, but one of those which the potential reader should browse personally first (as indeed I had done before I bought it) in order to decide whether it is worth reading. — Phillip Helbig.

Amazing Worlds of Science Fiction and Science Fact, by Keith Cooper (Reaktion), 2025. Pp. 248, 21·5 × 14 cm. Price £15 (hardbound; ISBN 978 1 78914 994 4).

Planetary science and Science Fiction (SF) were always closely related. Well before *Sputnik* in 1957, some of SF's earliest writers (*e.g.*, Verne and Wells) and indeed hugely influential, 1950s-based ones (*e.g.*, Asimov, Clarke, and Heinlein) often looked up at the (mainly) night sky and postulated. Here, Keith Cooper (*Astronomy Now*'s editor) brings these two areas back into focus. Within SF, barren, dry Tatooine (*Star Wars*), spice-laden Arrakis (*Dune*), and icy Gethen (*Left Hand of Darkness*) are themselves spectacular but there are real, strange exoplanets out there (*e.g.*, the Trappist-1 system, Proxima b, Kepler 16b, and LHS 1140b).

Earlier SF lacked much of the data we now have but many current writers use up-to-date information in formulating their scenarios. This is not only due to the marvellous 2·4-m *Hubble* but also because of its more recent and powerful 6·5-m upstart — the *JWST* (both outside our protective atmosphere). The book's appendix lists a number of SF scribes consulted and also has a column (nice!) of major SF novels, films, and TV (all referenced therein).

The cover and book title 'nods' to *Amazing Stories* — a US-based 1950s 'pulp', comic-like paperback publication. Carrying many now classic SF short stories, it was often taken to the UK (as ship's ballast). Cooper also deals herein with the Earth Similarity Index — our own planet being of course 1·00. The nearest to us in said Index — Teegarden's Star — has 0·95, though that exoplanet is not at all like ours in many ways. And so far, we appear to be alone.

Cooper also deals with biosignatures (phosphine and dimethyl sulphide) — strong signatories of possible life elsewhere. And our own Solar System has prime candidates: not only Jupiter's Ganymede, Callisto, and (*vide* Clarke's *2010* novel/movie) Europa, but also Saturn's Enceladus. And all amino acids linked to life are left-handed whereas sugars are right-handed. The text here ranges over many other scientific items (including Roche limits, magnetic pulsars, extratrojans, ecumenpolises, and Dyson spheres).

Cooper's book contains a lot of data but no mathematical formulae. And it is nice when he uses such terms as 'astronomical unit' or 'parsec' and then defines them. This tome appears to be targeted at SF readers and those (non-professional astronomers) who enjoy popular science. However, many in the astronomy field will also enjoy this. I certainly did. Recommended. — David Lally.

The Life and Work of James Bradley: The New Foundations of 18th Century Astronomy, by John Fisher (Oxford University Press), 2023. Pp. 531, 24 × 16 cm. Price £ 83 (hardbound; ISBN 978 0 19 888420 0).

James Bradley was the third Astronomer Royal, following John Flamsteed and Edmond Halley but, despite his achievements — including discovery of aberration and nutation — and widespread recognition in his own life-time, is not as well known today. In comparison with his predecessors, he has been neglected by biographers, so this comprehensive biography by John Fisher is very welcome. His *Life and Work of James Bradley* is embedded in context: astronomical and social, especially networking and patronage. It was an exciting time for astronomy: Rømer had shown that the speed of light was finite, but annual parallaxes in confirmation of the heliocentric system had yet to be convincingly demonstrated. In Chapter 1, Fisher covers the work and tribulations of Flamsteed, as a comparison and contrast with Bradley. Bradley's own introduction to astronomy was *via* his maternal uncle, James Pound, who took him under his wing. Pound's influence on Bradley's career was so significant that Chapter 2 is devoted to his activities prior to taking on his nephew. Pound had entered the service of the English East India Company as a chaplain and had, over a few years, sailed between various company stations in the South China Sea. He was also a skilled astronomer and was provided with a quadrant by Flamsteed to make observations for him. At some time in 1702–03, Pound was posted to the island settlement of Pulo Condore, close to the mouth of the Mekong Delta. There he took up residence in a wooden dwelling situated about 400 yards outside the fortified settlement — which was fortuitous because this saved his life during the massacre which took place in the settlement on the night of 1705 March 3. According to Fisher, the best account of the massacre is that given by Pound in his letter to the Court of Managers of the Company. Along with 14 others, he escaped on a sloop and after a harrowing voyage reached Batavia. Pound returned to England in 1706 July and a year later was offered the lucrative living of Wanstead, near London.

In 1711, James Bradley took up residence with Pound and entered Oxford University in preparation for a career in the Church of England, as desired by his father. He also began assisting Pound in his astronomical observations. From examination of the Wanstead observing books, Fisher shows that Bradley's first recorded observation in 1715 indicated that he had by then become a very capable observer. Bradley's day-to-day observing record is included in the detailed, often day-by-day, chronology of his life and work presented in Appendix 1. This chronology includes a great deal more information, making it a valuable resource. Many of the observations were of the Galilean satellites of Jupiter on behalf of Halley, who had become his mentor. Bradley was eventually given the credit for the observations when they were published by Bevis in 1752, but we are not given a reference for this. Nor is a reference given for the tables for Jupiter's satellites published by Hodgson in 1749 which "studiously avoided all mention of Bradley" (p. 94). This is unfortunate. It would have been interesting to read — or find out using the references — how the observations compared. Fisher returns briefly to the satellites on pp. 150–151, reporting Bradley's recognition that the three inner satellites were interacting gravitationally with one another, effectively laying the ground for the Laplace Resonances. I would like to have read more about this. Halley had hoped to use timing of the Galilean satellite eclipses to solve the longitude problem but such observations were impractical from the deck of a ship at sea. On the other hand, Bradley was able to use them to determine the longitudes of Lisbon and the fort of New York relative to London.

For the first half of 1719, Bradley continued observing vigorously; but then he was ordained and received a living at Bridstow. Through the efforts of Samuel Montagu, private secretary to the Prince of Wales, he also received half a divided living in Pembrokeshire in 1720. Fisher reports that Pound laid out over £18 in fees in connection with the latter. As he took up his duties, Bradley's observing ceased — but not for long. In 1721 he was elected to the Savilian Chair of Astronomy at Oxford. It had been initially offered to Pound, who declined it because holders of the chair were not allowed to hold ecclesiastical benefice, with the consequence that he would have to give up his livings. Once Pound had declined, Bradley's candidature was supported by Lord Chancellor Thomas Parker, and Pound paid the costs of the election. Bradley's church sinecures were sufficiently modest that giving them up was an acceptable sacrifice.

Bradley's observations leading to his discovery of aberration and nutation began in a campaign led by Molyneux at his house at Kew, where he had installed a zenith sector built by George Graham. The aim was to repeat Hooke's experiment of 1669 from which he claimed to have measured the parallax of γ Draconis. Bradley's observations of this star showed movement, but not in the sense expected of annual parallax. Fisher brings out well the progress of the experiment, and the consideration of alternative explanations. To test the possibility that they were observing nutation, Bradley and Molyneux began observing another bright star separated by 12 hours in right ascension, whose movement soon enabled them to rule out that possibility. To increase the number of stars observable, Bradley commissioned from Graham a new zenith sector having a larger field of view. After Pound's death, Bradley no longer had access to the Wanstead parsonage but was able to continue observing from the nearby house belonging to Elizabeth Pound, his aunt. The new sector was installed there and Bradley was able to measure motions of stars having a range of right ascension. In April 1728, a pattern became apparent: the stars' motions ceased when they were observed at times when the Earth was moving directly towards or away from them. Later that year, he deduced the cause in terms of the Earth's motion in its orbit round the Sun and the finite velocity of the light from the stars — a new, unexpected phenomenon that confirmed the heliocentric view. Fisher sets out Bradley's argument in full. There are three versions of his report written in letters to Halley: Fisher identifies Bradley's 'final' version and presents this in Appendix 2, together with the differences between it and the version read by Halley to the Royal Society and published in the *Philosophical Transactions*.

In 1729, Bradley accepted the post of lecturer in experimental philosophy at Oxford for which he delivered two or three courses of 20 lectures a year for over 30 years. This lay outside the duties associated with the Savilian Chair and provided valuable additional income. His principle was that the laws of nature could be discovered only "by experiments and observation & examining the Phaenomena & finding from them by what laws their motions are ordered and regulated which is properly the Business and scope of Natural and Experimental Philosophy". Bradley's course notes are not available, but the author gives us (in Chapter 6) an account of the content from the note book of one of the students. In 1732, the increased demands on his time in Oxford prompted him to move from Wanstead to the Oxford dwelling that came with the Savilian chair. His aunt Elizabeth Pound accompanied him to Oxford, but he was able to continue observing with the zenith sector at her house in Wanstead. This he did until 1747, when he completed his investigation of the residuals from his observations of aberration suggesting the existence of another, distinct phenomenon. This was the nutation of the Earth's axis caused by the Moon. Bradley had suspected this early in his study but continued observing to cover a whole period, 18·6 y., of the precession of the Moon's orbital nodes — not only was he a meticulous observer, but also a very patient one, willing to continue a campaign long enough to make certain of a result. Besides these and many other observations (Appendix 1), and his teaching, he was active in other projects: studying the shape of the Earth from isochronal pendulum observations in collaboration with Graham, helping the Earl of Macclesfield set up his well-equipped observatory in Shirburn Castle, and beginning his tenure at the Royal Observatory.

Bradley was appointed Astronomer Royal on the death of Halley in 1742. Fisher gives an illuminating picture of the networking behind this appointment. Bradley's earliest years at Greenwich were taken up with testing and rectifying the instrumentation, which had been neglected during the final years of Halley's life, often with the aid of observations made at Shirburn Castle. In 1749 he requested funding to remedy the dire state of the instruments and facilities at the observatory. This was supported by the Board of Visitors, Royal Society, and Admiralty with the result that George II agreed an award of £1000. He constructed the New Observatory (Transit House) building to house the quadrants and new transit instrument. The prime meridian defined by the latter became the origin for the Ordnance Survey. In 1750, he began observations for a Catalogue of 3222 stars, each star being observed 20–30 times, together with ancillary data including atmospheric pressure and temperature to allow correction for refraction. He was not satisfied with possible treatments of atmospheric refraction and the data remained unreduced.

Any biographer of Bradley has to contend with the fact that, after his death, all of his Greenwich observations (shades of Flamsteed!), correspondence, and other items passed to the executors of his estate. Fisher gives a good account of the long battle with the Board of Longitude for the papers followed by their subsequent poor handling by Bradley's successor at Oxford, Thomas Hornsby, with the result that some were lost. Eventually, Bradley's comprehensive observations for his Catalogue of 3222 stars were reduced by Bessel and published only in 1818.

This is a substantial work, based on abundant primary sources with endnotes to each chapter. Some of the references are not easy to decipher owing to the misuse of the abbreviation '*ibid*' where there is no connection with the immediately preceding references. Altogether, the book would have benefitted from the help of an editor, who could also have removed some of the repetition and re-ordered some of the material to improve the flow. That being said, the author has successfully restored Bradley to his rightful place with the fullest ever account of his scientific life and legacy. Along the way, we can learn much about the practice of astronomy at the time, giving another reason to recommend this book heartily. — Peredur Williams.

Power Laws in Astrophysics. Self-Organized Criticality Systems, by Markus Aschwanden (Cambridge University Press), 2025. Pp. 264, 25 × 18 cm. Price £125/$160 (hardbound; ISBN 978 1 009 56293 5).

The concept of self-organized criticality was introduced only in the late 1980s but its validity covers an enormous range of physical phenomena. One of the most familiar is the 'sandpit' model in which avalanches occur according to some instability. The result is often power laws in size distributions. This book is a very detailed discussion of the concepts of power laws in astrophysics with comparison to observations both from space and ground-based. In the realm of solar physics, which is the main expertise of the author, power laws in size distributions are extremely common and are particularly well illustrated in this book. For those not especially familiar with self-organized criticality, possibly a more general introduction to the subject might profitably be read in combination with this specialized monograph. — Ken Phillips.

A Brief History of Black Holes: And Why Nearly Everything You Thought You Know About Them is Wrong, by Dr. Becky Smethurst (Pan Books), 2023 (originally published 2022). Pp. 290, 19·7 × 13 cm. Price £10·99 (paperback; ISBN 978 1 5290 8674 4).

According to the back-cover blurb, Smethurst is YouTube's most popular astrophysicist. With an impressive list of awards, she is also an RAS Research Fellow at the University of Oxford, focussing on the interaction of supermassive black holes and galaxy evolution. In contrast to the next book I read[1,2], this is very much a book about astrophysics and the roles black holes play in it. The scope is broad and starts with background, both physical and historical, about stellar structure and evolution and General Relativity (GR) before coming to black holes themselves (some pre-GR ideas about black holes are briefly mentioned). Throughout the book, the history of the topic is well entwined with the astrophysics being discussed, an organic whole rather than a straight history of science about a topic which is still relevant or a book on astrophysics with historical footnotes. Traditional (non-quantum) black holes and other compact stellar remnants set the stage for more concrete astrophysics (the chapter on why black holes are not black is not about Hawking radiation, but about X-ray astronomy). Black-hole mergers and their detection *via* gravitational waves, the possibility that Planet 9 is a black hole, supermassive black holes, accretion discs, and the role of black holes in galaxy evolution are among the topics in the fifteen relatively short chapters. The final chapters deal more with the mathematical theory of black holes and Hawking radiation, though like the rest of the book in a non-technical manner.

The book is well written in an entertaining style and is a good non-technical introduction to the importance of black holes in astrophysics. Since her research is also on that topic, I feel safe in recommending it. I enjoyed reading it except for the very end. The book only briefly discusses the CMB, but I found it strange that while *WMAP* is mentioned, *Planck* is not. Although they make up only a small part of the book, the final pages discussing cosmology contain several mistakes. First, the density parameter is explicitly defined to include matter, radiation, and dark energy, but is followed by an almost standard textbook discussion for the case of no dark energy. But even that is not correct, because the description of eternal (asymptotically exponential in the case of a positive cosmological constant) expansion is conflated with the idea of the Big Rip, in which even (gravitationally or otherwise) bound objects will be torn apart, though that could happen only with a non-standard, highly speculative form of dark energy. If, as explicitly stated, the cosmological constant is not assumed to be zero, then the relation between geometry and destiny, *i.e.*, between spatial curvature and the future expansion (or contraction) of the Universe, is much more complicated. However, again the textbook version with no cosmological constant is presented. While it is correctly stated that *WMAP* measured the Universe to be at least very nearly spatially flat, that is characterized as being on the border between Big Rip and Big Crunch; in fact, there is no uncertainty at all in the concordance model of cosmology that the Universe will expand forever (unless something unknown has not been taken into account, but that would go beyond the concordance model); geometry and destiny are not so simply related. Those are not fine technical details but rather the most basic ideas in cosmology, so I find it rather strange that those and other basic misconceptions are also found within other popular-science books written by people who obviously know more than enough people who could have critically read the manuscript (*e.g.*, refs. 3,4). (There are a few other things a proof reader should have caught: Kirchhoff always has one 'h' too few and Secchi sometimes one too many; Rutherford won a Nobel Prize, but for chemistry, not physics.)

There are a few black-and-white figures scattered throughout the book. The brief bibliography contains twelve references, but it is not clear why those twelve (which are not mentioned explicitly in the text). One hundred and sixteen footnotes (easy to count since numbering doesn't restart with each chapter) will appeal to those who, like myself, like footnotes (especially when compared with endnotes). A twelve-page small-print index ends the book. The book does what it sets out to do well, but shouldn't have included the few pages on cosmology at all; even if they were correct, they don't really belong in a book about the astrophysics of black holes, so I can recommend it if the last chapter is skipped. — Phillip Helbig.

References

(1) B. Cox & J. Forshaw, *Black Holes: The Key to Understanding the Universe* (William Collins), 2023.
(2) P. Helbig, *The Observatory*, **145**, 129, 2025.
(3) P. Helbig, *The Observatory*, **144**, 38, 2024.
(4) P. Helbig, *The Observatory*, **144**, 201, 2024.

Annual Review of Earth and Planetary Sciences, Vol 52, 2024, edited by R. Jeanloz & K. H. Freeman (Annual Reviews), 2024. Pp. 692, 24 × 19·5 cm. Price $529 (for institutions; about £420) $126 (for personal copies; about £100) (hardbound; ISBN 978 0 8243 2052 2).

The latest volume of *Annual Review* covers a nice diversity of subjects that includes the biosphere, mantle composition and dynamics, the atmosphere, and the hydrosphere. An old Icelandic saying is that a good story should start with an earthquake and then build up to a climax. This year's volume seems to have paid attention to this, and starts with chapters on volcanism in Hawai'i and aftershock forecasting. Highly recommended. A chapter on microbial life brings home the message that this is the foundation, both in longevity and mass, of life on Earth. Microbial life is not just the icing on the cake. The development of this is covered by a following chapter on early Paleozoic evolution and the door is then closed by a chapter on the Pleistocene extinction. The interior of Earth is discussed in a variety of chapters on halogen cycling, diamonds, lithosphere, and mantle rheology. As regards the deeper mantle, despite all our work it seems still unclear whether it has a similar composition to the upper mantle (and thus convects as one with it) or not. Differences of up to 10% seem possible. Climate is represented by chapters on the stability of ice shelves and past hothouse climates. A chapter on carbon-climate feedbacks directly addresses the implications of the Paris Agreement. The situation is challenging, even if the main goal is met, which itself seems improbable. Uncertainties are large, but one thing we can confidently say is that natural carbon sinks will become less efficient with time. An interesting chapter deals with that part of deep groundwater that is locked in the lithosphere. For river-running enthusiasts, a chapter deals with the hydrotectonics of Grand Canyon groundwater, which presents a rare chance to monitor vertical water movement without the use of boreholes. Check out the book and find out what the Indonesian Gateway is! The volume finishes with an unusual chapter on the relationship between grain size and landscape. So if you feel like a bit of a change, then start reading the book from the back. — Gillian R. Foulger.

The Cosmic Microwave Background: Historical and Philosophical Lessons, by Slobodan Perović & Milan M. Circović (Cambridge University Press), 2024. Pp. 215, 25 × 17·5 cm. Price £39·99/$49·99 (hardbound; ISBN 978 1 108 84460 4).

As the subtitle states, this is a book on the history and philosophy of the CMB. However, it does not stray far from actual physics, and points are made with the help of concrete examples. The second author is someone I've often encountered in the history-and-or-philosophy-of-science literature, and the authors have a good grasp both of that and of astrophysics. The conventional narrative is that the CMB suddenly proved that the Steady State cosmological model was inviable. While the CMB is expected in the Big Bang scenario, it is not impossible in the Steady State theory, which is based on the idea that on a large-enough scale, the Universe looks the same at all places and at all times. Nevertheless, one would still like to have an astrophysical explanation for the CMB within the Steady State theory. For Fred Hoyle, one of the main motivations for the Steady State cosmology was that it in principle made all processes accessible to scientific inquiry, which might not be true of the Big Bang itself. However, counts of radio sources ruled out the Steady State model. Both supporters of the Steady State model and those of Big Bang cosmology investigated alternative explanations for the CMB, and it was not until features in the power spectrum were discovered about 25 years ago that the scales were finally definitively tipped in favour of a Big Bang origin for the CMB. That is not only an interesting story in itself, but also such dead ends are important because they illustrate how the scientific process actually works.

The thirty-one chapters are clearly structured into seven parts covering the basics of cosmology, the Big Bang, and ΛCDM (referred to, unusually, as λCDM); discovery of the CMB and the current standard model, but including a discussion of shortcomings in usual potted histories; the nature of (un)orthodoxy in cosmology; moderate unorthodoxies (CMB with Big Bang); radical unorthodoxies (CMB without Big Bang); the history of how the current orthodoxy came to be; anomalies in the CMB and wider issues such as the Anthropic Principle, boundary conditions in cosmology, and the Multiverse, using the CMB as a jumping-off point. Too long to quote here, the end of Chapter 9 ('Was the CMB a smoking gun?') is a good summary of the strategy of the book: a balance between questioning a too-streamlined view of history without questioning the state at which that history has (probably correctly) arrived; learning from blind alleys and misconceptions, some of which later proved useful in other contexts; and a good balance between astrophysics and philosophy by authors knowledgeable about both topics. To some extent, this book reminded me of a similar book with much broader scope[1] reviewed in these pages[2], though I found that the latter was sometimes a bit too broad and too forgiving. (At the same time, that book is conspicuous by its absence in the otherwise thorough sixteen-page reference list in somewhat smaller print, though two of his articles, one on essentially the same topic as his book, are cited.) An interesting idea is adapting the idea of biological exaptation to cosmology: features originally developed for one purpose are later put to another use (*e.g.*, feathers for heat regulation being used as components of wings for flying); similarly, ideas which were mistaken at the time might later prove useful in other contexts. The authors also use the history of CMB research to point out the "abject failure of simplistic social-constructivist notions about the sociocultural determination of the *content* of scientific theories" and the more 'mature' culture of debate compared to some previous controversies, avoiding "juicy tabloid details like the personal relationship of actors such as Hoyle and Ryle".

At best confusing is the two-page Chapter 28 which briefly sketches ideas about two (initially) puzzling phenomena: 'fingers of God' in the distribution of galaxies and the 'axis of evil' regarding the alignment of CMB multipoles. While the summaries are fine, the authors don't point out that the former is now understood (peculiar velocities of galaxies introduce redshift-space distortions so that the true shapes appear distorted when plotted in redshift space as opposed to distance), while the latter — on which the jury is still out but might be something genuinely interesting — is toned down by (correctly) suggesting some possible banal explanations. Otherwise, my only real complaint is that some citations in the text are not in the reference list; in some cases there are obvious mistakes (the year is off by one, for example), but in others (one of which is cited often) they appear genuinely to be missing. (I always wonder why authors do not use BibTeX or some other scheme to automate references, at least when not writing a book review for *The Observatory*.)

There are a few black-and-white figures scattered throughout the text. Eight pages of small-print endnotes follow the main text (which includes two appendices on relativistic cosmological models and dipole anisotropy). A four-page small-print index follows the reference list. Despite neither author being a native speaker of English (as far as I know), the language is good and both typos and questionable choices of style are few. The emphasis is on what the CMB can tell us about how science is (and has been) done rather than on the physics of the CMB itself, a basic knowledge of which is assumed. It is thus a good book for those with such knowledge who want to learn more about the history and philosophy of the field in the context of a concrete example. I've recently attended several conferences on the history and philosophy of science* and am often surprised about how well the participants are familiar with scientific details (though it is true that many were trained as scientists then switched to history and/or philosophy). Despite Feynman's claim that the philosophy of physics is as useless to physicists as ornithology is to birds, I think that it would be good if more working physicists were familiar with the history and philosophy of their field, both for its own sake and for the benefit it can bring to actual science; this book is a good starting point. — PHILLIP HELBIG.

References

(1) M. López-Corredoira, *Fundamental Ideas in Cosmology: Scientific, philosophical and sociological critical perspectives* (IoP Publishing), 2022.
(2) P. Helbig, *The Observatory*, **143**, 214, 2023.

*I'm writing this in 2025 January, a few days before a workshop on the philosophy of dark energy. Of nine conferences I attended last year, seven were on the history and/or philosophy of science (usually physics, here usually astrophysics, and there usually cosmology); among others were workshops on the philosophy of inflation and the philosophy of black holes. As a joke I asked a fellow participant when we could expect one on the philosophy of radio interferometry, but interestingly he didn't take it as a joke at all. (Interestingly, several of those conferences were co-organized by one of the two back-cover-blurb writers.)

Archimedes. Fulcrum of Science, by Nicholas Nicastro (Reaktion), 2024. Pp. 191, 22·5 × 14·5 cm. Price £15·99 (hardbound; ISBN 978 1 78914 922 7).

This biography of Archimedes of Syracuse (modern Siracusa, Sicily), the greatest mathematician in the ancient world, is a fine example of modern historiography. Its accounts of context, circumstance, and consequence combine to portray such a vivid tableau that you can imagine you're standing in the shadow of this remarkable polymath: engineer, inventor of engines of war, and pioneer of geometry. Over 1800 years elapsed before the next great mathematician walked on the stage, Isaac Newton, who praised Archimedes as one of the giants on whose shoulders he had stood. Historians have only meagre sources on the life of Archimedes. In his *Life of Marcellus*, Plutarch documents the defensive devices that Archimedes deployed while protecting Syracuse against the Romans' assault from the sea. Plutarch also lamented the death of Archimedes, killed by a Roman soldier. In one version of the story Plutarch adds celestial colour by noting that Archimedes was carrying mathematical instruments such as sundials, spheres, and quadrants. Recent scholarship adds the name of Archimedes to the story of the Antikythera Mechanism, an ancient analogue device recovered in 1901 from a shipwreck that allowed the user to simulate the motions of the Sun, Moon, and the five planets known to the ancients. With the expected restraint of an accomplished historian, Nicholas Nicastro airs the notion that "Archimedes' work on sphere-making *inspired* the calculating devices that followed."

What impressed me most about this title is the delightful manner in which it rises above familiar and well-worn recitals of myths, legends, and traditions by focussing on what we really do know about everyday life and the academic pursuit of knowledge in Syracuse in the third century BCE. The author offers a pretty good example of an accessible public history rather than a dull chronicle. Read and enjoy! — Simon Mitton.

Black Holes: The Key to Understanding the Universe, by Brian Cox and Jeff Forshaw (William Collins), 2023 (originally published 2022). Pp. 288, 19·7 × 13 cm. Price £19·99 (paperback; ISBN 978 0 00 839064 8).

There are of course many popular-science books on black holes, at a variety of levels and with a variety of emphases, such as the book I read just before this one[1,2]. However, the two books are very different. This book is about the mathematical theory of black holes. There is little material on astrophysics and that is only to understand the formation of astrophysical black holes. Both authors are professors of theoretical particle physics at the University of Manchester; Cox is well known as a popularizer and is also the Royal Society Professor for Public Engagement in Science. Those who take the trouble to understand a topic outside of their own field are usually good at explaining it, as I've noticed in other books (*e.g.*, refs. 3,4); that is certainly the case here. While there are only a few equations, there are several diagrams, many of them Penrose diagrams. This is the book if you want a thorough, correct, yet mostly non-mathematical introduction to Kruskal–Szekeres coordinates and want to have fun in the process.

After a brief history of black holes, the necessary background is built up piece by piece: Special Relativity, General Relativity (GR), Penrose diagrams, curvature, the interior of black holes, white holes and wormholes, and rotating (Kerr) black holes. Only after that do we meet collapsing stars, and then mainly to understand where many black holes come from. After that, the emphasis shifts to topics of current research: black-hole thermodynamics; Hawking radiation; the fate of objects before, during, and after crossing the event horizon; quantum entanglement; the holographic principle; AdS/CFT correspondence; and the connection between the previous two topics and quantum information. All are rather technical topics in the mathematical theory of black holes, yet the descriptions are both correct and easy to understand, with little mathematics. As such, this book is a very good introduction to those like myself who like a 'physics first' approach to GR: first understand the concepts then learn as much maths as necessary to work with them. While the entire book is good, I made a note of the fact that the chapters on white holes, wormholes, and Kerr black holes are particularly good. The only mistake I noticed is the old canard that John Wheeler coined the term 'black hole' (something Smethurst[1] gets right and which she discusses in some detail).

As almost always I notice a few matters of style which depart from my own preferences, but less so than in most books. There are many black-and-white figures, mostly space–time diagrams, scattered throughout the book, some of which also exist on the sixteen traditional glossy colour plates at the middle of the book. The four pages of endnotes are references to the technical literature (footnotes are proper footnotes). An eight-page small-print index ends the book. This is the best non-technical detailed introduction to the mathematical theory of black holes, a judgement which would probably stand even if there were others.

Recommended. — Phillip Helbig.

References

(1) B. Smethurst, *A Brief History of Black Holes: And Why Nearly Everything You Thought You Know About Them is Wrong* (Pan Books), 2023.
(2) P. Helbig, *The Observatory*, **145**, 125, 2025.
(3) W. D. Heacox, *The Expanding Universe: A Primer on Relativistic Cosmology* (Cambridge University Press), 2015.
(4) P. Helbig, *The Observatory*, **136**, 204, 2016.

Other Books Received

The Physics of Supernovae and Their Mathematical Models, by Alexey G. Aksenov & Valery M. Chechetkin (World Scientific), 2024. Pp. 279, 23·5 × 16 cm. Price £100 (hardbound; ISBN 978 981 12 8509 7).

A theoretical, and highly mathematical, monograph on supernovae, covering basic principles, numerical methods, and applications.

Introduction to Supergravity and Its Applications, by Horatiu Nastase (Cambridge University Press), 2024. Pp. 426, 26 × 18·5 cm. Price £64·99/$84·99 (hardbound; ISBN 978 1 009 44559 7).

Aimed at PhD students, this volume covers the basic formalism of supergravity suitable for a focussed first course.

OBITUARY

John Christopher Taylor (*1952–2024*)

John Christopher Taylor was born on 1952 March 25 the only son of William Albert Saxon Taylor and Lillian Alice Mildred Taylor. His father was in the RAF and stationed at Halton, Buckinghamshire, at the time. He was one of the RAF apprentices known as the Halton Brats, and he had joined up at the age of 16.

His early years were ones of constant moving, typical of the forces world — Blackpool, Gibraltar, Ramsgate, Chelmsford, Braintree. And, when his father left the RAF and eventually worked for Cambridge Instruments, the last family home was in Coton, outside Cambridge. His schooling was affected by the endless moves and for a time he attended Woodbridge in Suffolk as a boarder in order to have some educational stability. He was devoted to his father, devastated by his early death in 1979, and for the rest of his life could barely talk about him without tears in his eyes. His parents encouraged his very early leanings to all things scientific — a chemistry set at the age of seven which in those days contained things no child or adult would be allowed anywhere near today, and they put up with his experiments, giving him his own asbestos-lined shed where he miraculously survived his own cocktails and in particular his interest in explosives. His days in Woodbridge were terminated as a result of these experiments and in Oxford he became known as John the Bomb.

Undoubtedly the most important event in his life was when he was having his eyes tested by a Harley Street optician when he was 15. At the end of the consultation he asked the optician if he should wear glasses while using his telescope. The subject swiftly moved to astronomy and Mr. Roderick McIver Paton (1908–1969 and an FRAS) told him that he could no longer observe on account of his asthma and was forthwith going to give Christopher his 12½-inch reflecting telescope. The telescope was unusual in that both primary and secondary mirrors were mounted outside the wooden tube. This meant Christopher had to carry the optics from the house each evening, mount them on the tube and then carry out an alignment, a process which was refined and condensed into about ten minutes. The resulting performance of the 12½-inch Calver mirror justified this, allowing the duplicity of binary stars as close as 0·2 arc second to be ascertained. This has been his instrument for over 50 years with which he has made his own observations, all carefully recorded alongside his own sketches and drawings, and these are to be deposited now with the Royal Astronomical Society. The observing area in the garden is also home to the unusual folded 30-inch refractor[1,2] designed and built by the well-known optician John Wall. His knowledge of and interest in astronomy was phenomenal and he was always ready on a cold clear night to be out observing. His greatest interest was in double-star astronomy and his published work was largely in this area but he also had a deep interest in the history of astronomy and he was a founder member of both the Stratford Astronomical Society and the Society for the History of Astronomy. Travel plans often revolved around observatories — in France the Pic du Midi in the Pyrenees and the observatories in Paris and in Strasbourg — or the birth places of some of the great astronomers, and in 1999 Hanwell Community Observatory members made an expedition to Alsace to view the total eclipse.

He went up to Oxford in 1971 to read Chemistry at Lincoln College but he took a year out in order to do the necessary first-year work on his own so that he could switch to Physics. He began teaching when he returned to Oxford to do graduate work but on the first occasion he discovered the subject had been done and on the second, working on artificial diamonds, ironically the funding ran out. He remained in teaching for much of his life and for a time in the late 1980s was director of an American study-abroad programme based in Oxford.

He and Rowena met in 1979 and married in Ireland in 1981. Three years later they made their first purchase in Hanwell and over the following six years were able to add adjoining land and a further wing to the property. From a 1930s semi-detached house in Oxford they plunged into what became the Hanwell Project — unplanned but evolving in many directions that reflected their joint interests.

The gardens had been untouched for over 40 years but they slowly uncovered the planting scheme of the Berkeley family from the 1910s and 20s and began to follow through with species already on the site and many new ones — over 300 species have been planted in the gardens. The gardens have been opened since 2005 for the annual 'Stars and Snowdrops' weekend in February and thousands of people have been welcomed in those years, teas becoming a legend in the locality on those occasions. Christopher and Rowena were founder members of the Friends of Oxford Botanic Gardens and have hosted a sequence of visits as fund raising for the Gardens at different times in the year, most recently last August, despite Christopher's illness.

The telescope, of course, moved for the final time to Hanwell in the mid-1980s and after teaching astronomy evening classes, in 1998 a successful application was made by Christopher and his students for a Royal Society Millennium Award for public outreach, resulting in funds to build a 30-inch reflecting telescope for public star-gazing evenings, though these had already started, using the *McIver Paton* telescope. The 30-inch[3] was formally inaugurated in 2009 by Professor Alexander Boksenberg, former Director of the Royal Greenwich Observatory. Christopher was especially keen to encourage young members of what became the Hanwell Community Observatory and two of them went on to do PhDs in astrophysics. Two more are currently reading the subject at Cardiff University. On 2011, December 9 Christopher was elected a Fellow of the Royal Astronomical Society and was a regular attendee of the monthly meetings at Burlington House. — Rowena Archer and Robert Argyle.

References

(1) J. Wall, *JBAA*, **119**, 163, 2009.
(2) http://www.hanwellobservatory.org.uk/telescopes/john-wall
(3) J. C. Taylor, *The Observatory*, **130**, 37, 2010.

[Christopher and I corresponded for a period of about 30 years. Our occasional face-to-face meetings I will remember with great pleasure. — RWA]

Advice to Contributors

The Observatory magazine is an independent, on-line only, journal, owned and managed by its Editors (although the views expressed in published contributions are not necessarily shared by them). The Editors are therefore free to accept, at their discretion, original material of general interest to astronomers which might be difficult to accommodate within the more restricted remit of most other journals. Published contributions usually take one of the following forms: summaries of meetings; papers and short contributions (sometimes printed as *Notes from Observatories*); correspondence; reviews; or thesis abstracts.

All papers and *Notes* are subject to peer review by the normal refereeing process. Other material may be reviewed solely by the Editors, in order to expedite processing. The nominal publication date is the first day of the month shown on the cover of a given issue, which will normally contain material accepted no later than four months before that date. There are no page charges.

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(No.) Authors, journal, volume, page, year.

and for books:

(No.) Authors, [in Editors (eds.),] Title (Publisher, Place), year[, page].

where the items in square brackets are required only when citing an article in a book. Authors are listed with initials followed by surname; where there are four or more authors only the first author '*et al.*' is listed. For example:

(1) G. H. Darwin, *The Observatory*, **1**, 13, 1877.
(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.

Journals are identified with the system of terse abbreviations used (with minor modifications) in this *Magazine* for many years, and adopted in the other major journals by 1993 (see recent issues or, *e.g.*, *MNRAS*, **206**, 1, 1993; *ApJ*, **402**, i, 1993; *A&A*, **267**, A5, 1993; *A&A Abstracts*, §**001**).

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NOTES TO CONTRIBUTORS

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