THE OBSERVATORY

Vol. 141 2021 OCTOBER No. 1284

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2021 February 12 at $16^h\ 00^m$
held on-line

EMMA BUNCE, *President*
in the Chair

The President. I'm delighted to welcome all of you for our meeting this afternoon and I'm very pleased to see many of you joining us for the next instalment of the RAS Ordinary Meetings on-line. We will move on to our programme for this afternoon and today I'm delighted that we are having the Eddington Lecture which is going to be delivered by Professor Mansi Kasliwal who earned her first degree in Engineering Physics at Cornell University in 2005 and completed her doctoral work in astrophysics at Caltech in 2011. After a joint post-doctoral fellowship at Carnegie Observatories and Princeton University she joined the Caltech faculty in 2015 and she was awarded the Packard Fellowship in 2018. She's the principal investigator of GROWTH, the Global Relay of Observatories Watching Transients Happen, and as such Professor Kasliwal heads a worldwide network of telescopes for time-domain astronomy. So I'm delighted to introduce Mansi Kasliwal to give the Eddington Lecture entitled 'Our Dynamic Infrared Sky'.

Professor Mansi Kasliwal. [An extended summary of this talk is expected to appear in a future issue of *Astronomy & Geophysics*. The speaker explained that our dynamic Universe is adorned by cosmic fireworks: energetic and ephemeral beacons of light that are a million (nova) to a billion (supernova) times brighter than our Sun. Fireworks synthesize most elements in our periodic table — while supernovae synthesize the lighter elements, neutron-star mergers synthesize half the elements in the periodic table heavier than iron. The speaker demonstrated how to discover cosmic fireworks with robotic telescopes and how we undertake a global, panchromatic follow-up campaign to characterize the astrophysics and astrochemistry. Owing to the nuclear physics of bound–bound opacity, the infrared is the most sensitive probe of the heaviest elements (*e.g.*, gold, platinum, uranium, neodymium). She went on to describe a brand new wide-field infrared surveyor, *Palomar Gattini-IR*, and the next-generation *WINTER* (*Wide-field INfrared Transient ExploreR*), *DREAMS* (*Dynamic REd All-sky Monitoring Survey*), and *CryoScope* surveyors, and concluded by combining information from multiple messengers: light, neutrinos, and gravitational waves.]

The President. Mansi, thank you so much for a wonderful lecture and thank you for sharing your knowledge and expertise, it's been absolutely fascinating for me to learn about your topic. I'm going to hand over to Louise who's going to help us with the Q & A.

Dr. Louise Alexander. Jerry Stone had asked, actually before you got on to the *James Webb Space Telescope* at the end, how that would contribute to your work, so I don't know if there's anything else that you want to add to that.

Professor Kasliwal. The *James Webb Space Telescope* would be like the dream characterization machine for infrared fireworks. It is so sensitive because it's in space and doesn't have to wrestle with sky background, and it has such a large aperture that it can get infrared spectroscopy for us. In the case of say, neutron-star–neutron-star (NS–NS) mergers, with the *Spitzer* space telescope we were able to take images and say 'yes', there is an emission at 43 days. With the *JWST* we could actually disperse the light and say not only that there is emission but exactly which elements are made and which elements are synthesized in those at that late phase and, in fact, we have eight elements that we suspect were made. The next time two neutron stars merge and *JWST* is in the sky, it can go and tell us exactly which of those heaviest of the heavy elements formed. That's one example of something that it would do. Even for massive-star binaries, my former postdoc, Ryan Lau, has a programme to study and characterize massive Wolf-Rayet-star binaries with *JWST*. It will open our eyes into the Universe unlike anything else because it is such a powerful and sensitive spectroscopic machine in the infrared.

Dr. Alexander. Thank you. Benjamin Lewis has asked a question which is "Do we have a better handle now on the ratio of elements produced in NS–NS mergers?" I presume that's NS–NS mergers *versus* supernovae.

Professor Kasliwal. Absolutely. That's a great question. In a supernova that was obliterating a white dwarf, you would produce a lot of iron-group elements. If it were a core-collapse supernova, then you would have more of a mix but you would be limited to the first few rows of the periodic table. Now, in NS–NS mergers, most of the elements are actually dominated by elements much heavier than iron, so elements in the second, third, fourth, and fifth rows of the periodic table. And, in fact, amongst those, is about 0·04 solar masses of material, most of which is actually elements in the first *r*-process abundance peak and a tiny fraction are the heaviest of the heavy elements which is what powers that *Spitzer* emission that I also mentioned.

Dr. Alexander. I would just like to ask about your Antarctic mission because that sounds really exciting. When's that going to happen and what do you have to do to prepare for it?

Professor Kasliwal. There are two technology challenges that we need to solve before we can set off in earnest to the Antarctic. One is affordable detectors. The reason infrared has been so difficult to explore is that the detectors are astronomically expensive. There's a lovely project in Professor Don Figer's lab at Rochester Institute of Technology, which is to use molecular-beam epitaxy on silicon. Using this new technology, he's now got the detector quantum efficiency peaking at just short of 2·1 microns, and if you can push this to 2·35 microns then we'll be in business, and we'll have the detectors necessary to tile the focal plane. He should know the answer to this in a few months, and I'm waiting eagerly to find out whether these detectors can work at that same location in the electromagnetic spectrum where the sky is 40 times darker and where you can get that sort of sensitivity. The second challenge is thermal noise. When you push to longer wavelengths in the infrared, any sort of thermal noise can be a big problem. A senior engineer at Caltech Optical Observatories, Roger Smith, is now building a quarter-scale prototype of a fully cryogenic telescope-plus-instrument system which has a novel optics design. It's not a Schmidt telescope but it's still a very fast focal ratio and the whole thing is cold and cryogenic, so if this works at the quarter-scale then we can go to the full scale and take it to the Antarctic. Sometime in the next year or so I would know whether this is a realistic and achievable vision or not or whether there are still some major technological hurdles.

Dr. Alexander. It sounds really exciting. We've got one more question from Hugh Stanley: "There were patterns to the supernovae detections. Could you shed more light, excuse the pun, on what this number of detections have shown by their location?"

Professor Kasliwal. This is going back to the supernova distribution of 5000 supernovae by the *Zwicky Transient Facility*. The patterns that you see there are that actually the local Universe is quite a clumpy place, so galaxies like to cluster and come together. At the 200-megaparsec scale, if you take any particular piece of the sky it's four times more likely that there will be neighbours there than a uniform distribution. Certainly you would expect that there's more of a clumpy distribution where there's things like the Virgo Cluster, the Coma Cluster, all these magnificent galaxy clusters in our local Universe, but there's a lot of structure in some smaller regions of the sky. In the case of supernovae, because the *Zwicky Transient Facility* is doing an unbiassed search of the northern sky, it's helping even probe and unravel the structure in the Universe of where are all the stars that are exploding and what does the structure actually look like, so you could ask the inverse question which is that given the locations of the supernovae, what does this tell you about the structure of the Universe? We're starting to get numbers that are large enough to be able to answer just that. But that's a great observation.

The President. Thank you, Louise, and thanks again, Mansi, for such a wonderful lecture this afternoon. That's everything for this afternoon. Thanks to everybody for coming to the meeting today and as always for your continued support of the Royal Astronomical Society; and finally just to give notice that the next Ordinary Meeting of the Society will be in one month's time on Friday the 12th of March 2021 and I look forward to seeing as many of you as are available at that time.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2021 March 12 at $16^{h}\ 00^{m}$
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EMMA BUNCE, *President*
in the Chair

The President. Welcome everybody, good afternoon. I'm very pleased to see lots of you joining us this afternoon. I now have some announcements to make, and I begin by announcing the winners of the on-line RAS GCSE-student Astronomy Poster Competition which has been sponsored by Winton. The second prize and a £50 book token is awarded to Kiran Radway of the Royal Observatory Greenwich. You can see the poster just being shown up on the screen now and the title is 'Human Space Colonisation'. The first prize and a £100 book token is awarded to Lucas Farley of Marlborough College and that poster is just appearing on the screen now. Its title is 'Detecting the Geminids Using Radio Waves', so many congratulations to Kiran and Lucas and I think they might be on-line listening this afternoon. Congratulations on your fantastic posters, and these posters will be also displayed on the RAS website for you to go and have a look at in a little bit more detail.

On to our programme for this afternoon. Today's headline item is the Gerald Whitrow Lecture which is given every two years by an engaging and authoritative speaker on any topic in cosmology, including its philosophy. The 2020 RAS Gerald Whitrow Lecture will be given today by Professor Andrew Pontzen from University College London. Professor Pontzen has conducted exceptionally creative and innovative work in a variety of fields from the dynamics of galaxy formation and evolution, to the dynamics of General Relativity and cosmological perturbations as well as in the studies of the nature of dark matter and dark energy. He is an excellent public speaker and is highly sought after for radio and television interviews, and is part of the trajectory panel for the Cheltenham Science Festival which develops ideas for events and future directions in public outreach. I'm delighted now to hand over to Professor Andrew Pontzen to give his Gerald Whitrow Lecture entitled 'Dwarf Galaxies in Cosmology'.

Professor A. Pontzen. [It is expected that a longer summary of this talk will appear in a future issue of *Astronomy & Geophysics*. The speaker explained that understanding dwarf galaxies is crucial for verifying and improving our broader picture of galaxy formation in the Universe. They contain so few stars that their gravitational effects are almost entirely dominated by dark matter. They are also exquisitely sensitive to stellar processes that can heat and eject gas, which in turn prevent further stars from forming. The combination of these two factors make them enticing and yet challenging to study: they hold the potential to help identify the nature of dark matter, but first we must vastly improve our understanding of the interaction between stars, interstellar medium, and the Universe beyond. He also reviewed recent observational and theoretical progress in these areas, including through the 'genetically modified galaxies programme', which focusses on how the formation history of galaxies determines their present-day properties.]

The President. That's wonderful, thank you Andrew. Interesting thoughts to finish on there — that was an absolutely fantastic lecture, extremely clear and engaging. I can see there are some questions coming through, so I'm going to hand over to Louise who's going to help facilitate the Q&A.

Dr. Louise Alexander. The first one is from Tamar Safilahi: "What are the consequences of supernova feedback, and the following changes in the galaxy's properties due to the feedback such as the dark-matter profile, on the radial distribution of the globular clusters around galaxies?"

Professor Pontzen. Certainly these kinds of fluctuations in the gravitational potential can affect stars and can affect clusters as well, so there are a couple of things to think about here. The first is that those potential fluctuations that can pull out dark-matter can also pull out stars in just the same way — in fact stars behave almost just like dark-matter because, to simulators, they're like collisionless particles, so they can be pulled out and it can actually increase the overall half-light radius. I think the question is specifically about clusters of stars and so that can happen to the clusters of stars as well; but I think there's perhaps an even more interesting thing which was the Eridanus II example that I was just quoting to you, where, if you have something like a globular cluster of stars, you would typically expect it in a dwarf galaxy to sink quite quickly through dynamical friction. It's like a massive thing which focusses orbits of dark-matter around it and that causes a dynamical-friction effect that causes it to sink to the centre, and when it does so forces there will rip it apart quite easily. Whereas if you have a dark-matter core, it turns out that dynamical friction becomes very ineffective and so globular clusters or other types of star clusters don't sink to the centre so easily, and they can survive for much longer. The overall effect then is that you can chuck things out and you can also stop them falling in so easily as well, and so you generally expect there to be more star clusters in galaxies when you have these dark-matter-redistribution effects.

Dr. Alexander. Thank you. And then we've got another question from Simon Josey who said "Thank you for a very interesting talk. You showed four dwarf-galaxy rotation curves early on in your talk. Three had central densities that were too low and you suggested this was due to dark-matter redistribution by supernova-driven out-flows; however, the fourth rotation curve had a central density that was too high. What's the explanation in this case?"

Professor Pontzen. Yes, that's absolutely right and I think the particular paper I was showing was by Kyle Oman and his entire point was that there's a great diversity in these things. It's not a totally straightforward case of they're always too low. I think it's not entirely clear, but I don't think there's a single agreed-upon answer about why this diversity is there, but there are a few possible reasons. The idea that you can go straight from a rotation curve to inferring the mass in the galaxy is a slight oversimplification that I committed there, but actually you have to take into account the fact that it's not like there is gas there just going on perfectly circular orbits. In reality you don't have a perfectly flat thin disc so there are a lot of extra effects to take into account. One possible explanation you can give is that in some cases, just because of some peculiarity about the galaxy, maybe there's some shock wave going through the gas, or you might actually be over-interpreting the rotation curve. It's not really giving you an accurate indication of what mass is in there. People try to be very careful about this and I think overall that's not as much of a concern as it used to be. The other explanation is more of a physical one, that you have a galaxy where you've just had lots of bursts of star formation that would chuck the dark matter out, and if you've just had lots more gas cool down in the centre of that galaxy, that can temporarily drag dark matter with it, through something called adiabatic contraction. So it's possible that physically you are actually looking at a galaxy with an excess of dark matter because it's being gravitationally pulled in. Or the third thing is maybe it's some effect that we don't yet understand.

Dr. Alexander. Thank you. Steve Miller is asking "Since you have invoked Kuhn, he points out that scientists add auxiliary hypotheses on and on until the main paradigm can no longer support their weight, then you get a paradigm shift, so how close do you think you are to needing a paradigm shift?"

Professor Pontzen. I'm a huge fan of Kuhn, and I think that he's absolutely right, but I think it's only really possible to identify it in retrospect, that actually when you're doing normal science in his terms it's not really possible to be sure whether you're building up towards a paradigm shift like that or whether you are actually just discovering additional effects that always should have been taken into account. You know the Universe is just a complicated place. I'm slightly dodging the question but I honestly think that will only become clear in retrospect.

Dr. Alexander. One final question, because we're out of time unfortunately. This is from Hiranya Peiris: "Fabulous talk. Do you think that tuning feedback contributions to get better matches to data impacts the predictivity of galaxy-evolution models and hence impacts their ability to distinguish between cosmological models? Is there any prospect for improving feedback models without tuning by comparison to data?"

Professor Pontzen. Well, thanks very much. I should say Hiranya is one of the key collaborators in this, so hello Hiranya, thanks for the question. I think the short answer — and this of course is actually a very prevalent approach in the field — is to tune all of these difficult bits of physics that we don't really understand, tune the unknown parameters to match what we already know about the Universe. I think it's a hugely dangerous thing to do, sometimes it's necessary but when you do that you have to be very aware about what it's doing. It's collapsing down your ability to distinguish the cosmological questions that you were originally going after. There are ways around that: you know you can try and find observational signals that are very orthogonal, if you like, to the things that you've actually constrained on. So, for example, you could constrain on stellar masses but then go and test what's happening in the gas. I think that it gives you some kind of productivity that you can use if you're careful enough, but more generally I think it would be very nice to imagine that one day we will understand astrophysics well enough that we don't really need these parameters or at least not quite as many of them. That's actually what the *EDGES* (*Experiment to Detect the Global Epoch of Reionization Signature*) collaboration is trying to do, that we are trying to put in as little as possible in the way of tuneable knobs and rather write down what we believe to be true about the astrophysics. I think in the long term it would be very nice if everything goes in that direction but it's a huge ask because astrophysics is just such a complicated thing.

Dr. Alexander. Thank you very much, Andrew. I'm sorry that we're out of time. I'm going to hand back to Emma now.

The President. Thank you, Louise, and thanks again to Professor Andrew Pontzen for such a fantastic Gerald Whitrow Lecture. Thanks to everybody for coming to the meeting this afternoon. It's great to have you all here. All that remains for today is just to give notice that the next monthly A&G meeting of the Society will be on Friday the 9th of April and we look forward to seeing all of you then.

A PERIOD STUDY OF THE W URSAE MAJORIS-TYPE ECLIPSING BINARY GSC 03465–00810

By Christopher Lloyd[1], †*Ian Miller*[2], *Daryl Janzen*[3], *and Yenal Öğmen*[4,5]

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GSC 03465–00810 is a cool, $T_{eff} \approx 4960$ K, short-period W UMa system with a photometric amplitude of $0^m{\cdot}3$, and no obvious O'Connell effect. The O–C residuals of the times of minima clearly show that the system has a third body but the period is poorly constrained with $P > 4000$ d. The most likely period is $P = 4111 \pm 46$ d, and the corresponding light-travel-time semi-amplitude is $0^d{\cdot}0089$, with $e = 0{\cdot}47 \pm 0.04$ and the close-binary period $P_0 = 0{\cdot}27668359(4)$ d. For $P \approx 4000$ d the possible mass of the third body ranges from $m_3 = 0{\cdot}42 - 0{\cdot}62\ M_\odot$ for the combined mass of the close binary $m_{12} = 1{\cdot}0 - 2{\cdot}0\ M_\odot$, so there may be a significant third-light contribution. The upper limit of P is constrained only by perceived acceptable masses of the system. The eccentricity, $a \sin i$, and the light-travel time of the third-body orbit all increase with increasing period. The peak magnitude of $V = 14{\cdot}62$, distance of 900 pc, and almost zero reddening suggest that the system has $M_V = 4{\cdot}8$, and may be $0^m{\cdot}5$ more luminous than systems of similar period.

Introduction and observations

GSC 03465–00810 ($14^h\ 02^m\ 05^s{\cdot}061$ +46° 11′ 00″·33 (*Gaia* EDR3) = UCAC4 681–054961) was originally identified as variable by Miller[1] while making observations of the UGWZ candidate ASASSN–16fy. The light-curve shows the characteristic W UMa shape with a range in V of 14·65–14·95, with the secondary eclipse about $0^m{\cdot}05$ less deep. The star was independently discovered by the ASAS-SN project[2,3] and is catalogued under the name ASASSN-V J140205·06+461100·4. It is also included in the recent large-scale study of over 71 000 W UMa variables from the ASAS-SN Variable Catalogue[4].

The initial time-series observations were made at the Furzehill Observatory over ten nights between 2016 June and 2017 December. These were made with a 0·35-m SCT and SXVR-H16 CCD camera, and the images were processed using the AIP4WIN aperture-photometry package. For one run a V filter was used but the others were unfiltered but calibrated as V to give CV magnitudes. Additional observations were made specifically of GSC 03465–00810, to record the light-curve, and especially the eclipses. A second set of time-series

†It is with great sadness that we report the passing of Ian Miller (1946–2020) during the preparation of this paper.

observations was made using the 0·4-m custom RC Optical Systems OTA and FLI ML4710 camera of the Skynet Robotic Telescope Network's *PROMPT-USASK* telescope, located at the University of Saskatchewan's Department of Physics and Engineering Physics Sleaford Observatory. Seven runs were made during 2020 and 2021 to determine times of minima. These observations were in *V* and *CV*, and were processed using the ASTROIMAGEJ photometry package. A further two runs were made from the Green Island Observatory using a 0·35-m SCT and SBIG ST8XME camera, and processed using the MAXIM DL aperture-photometry package. All the images were bias-, dark-subtracted and flat fielded, and then reduced by their respective observers relative to stars 141 (= GSC 03465–00417) and 143 (= GSC 03465–00604) of the AAVSO's *V*-magnitude sequence X16261ZJ for ASASSN-16fy to give *CV* or *V* magnitudes. A log of the time-series observations is given in Table I. From the longer time-series runs it was possible to determine times of individual primary and secondary minima using the Kwee–van Woerden method[5], and these are listed in Table II.

Further data were taken from synoptic surveys when sufficient observations were available to populate the phase diagram over an appropriate range of dates. The Catalina Real-Time Transient Survey (CRTS)[6] provided 164 *V*-band observations which were divided into three approximately equal blocks covering the years 2005–7, 2008–10, and 2011–13. The data were folded on the fixed mean period of the appropriate data set and the times of minima determined from either a 4-harmonic Fourier fit, or, if there were sufficient observations, using the Kwee–van Woerden method in the phase diagram to provide composite times of minima. The times derived are not sensitive to the period used. The *Pan-STARRS* DR1 survey[7] provided 73 observations during 2010–2014 divided almost equally between the *g*, *r*, *i*, *z*, and *y* bands. These were fitted with a 4-harmonic Fourier series, with the magnitude offsets allowed to float, and produced a surprisingly consistent phase diagram with σ = 0·038, from which a pair of minima was derived.

TABLE I

List of the time-series observations

UT Date	*JD*	*Hrs.*	*N*	*Band*	*Observer*
2016 Jun 17	2457557·421 – ·553	3·2	165	*CV*	Miller
2016 Jul 25	2457595·419 – ·485	1·6	60	*V*	Miller
2017 Nov 06	2458063·700 – ·737	0·9	33	*CV*	Miller
2017 Nov 08	2458065·694 – ·757	1·5	59	*CV*	Miller
2017 Nov 13	2458070·692 – ·757	1·6	60	*CV*	Miller
2017 Nov 17	2458074·688 – ·713	0·6	20	*CV*	Miller
2017 Nov 25	2458082·666 – ·781	2·8	106	*CV*	Miller
2017 Nov 26	2458083·708 – ·781	1·7	62	*CV*	Miller
2017 Dec 12	2458099·650 – ·789	3·3	137	*CV*	Miller
2017 Dec 19	2458106·622 – ·637	0·4	15	*CV*	Miller
2020 May 30	2458999·738 – ·779	1·0	30	*V*	Janzen
2020 May 31	2459000·760 – ·847	2·1	62	*V*	Janzen
2020 Jun 01	2459001·708 – ·833	3·0	89	*V*	Janzen
2020 Jun 02	2459002·709 – ·848	3·3	53	*V*	Janzen
2020 Jun 16	2459016·722 – ·869	3·5	11	*V*	Janzen
2020 Jun 21	2459021·723 – ·869	3·5	104	*V*	Janzen
2020 Jul 03	2459034·260 – ·427	4·0	198	*CV*	Öğmen
2021 Feb 25	2459270·692 – ·003	6·1	42	*CV*	Janzen
2021 Mar 20	2459294·263 – ·390	3·0	152	*CV*	Öğmen

TABLE II

Times of minima

HJD	*Error (d)*	*Min.*	*Cycle*	*O–C (d) Linear*	*O–C (d) LTTE*	*Band*	*Data set*
2454172·8026	0·0008	2	0·5	0·0036	−0·0008	*V*	CRTS
2455005·8897	0·0008	2	3011·5	−0·0036	0·0001	*V*	CRTS
2455006·0270	0·0005	1	3012·0	−0·0046	−0·0009	*V*	CRTS
2456077·0639	0·0013	1	6883·0	−0·0099	0·0026	*V*	Pan-STARRS
2456077·1998	0·0014	2	6883·5	−0·0124	0·0002	*V*	Pan-STARRS
2456092·8330	0·0006	1	6940·0	−0·0118	0·0008	*V*	CRTS
2456092·9723	0·0006	2	6940·5	−0·0108	0·0018	*V*	CRTS
2456756·8694	0·0023	1	9340·0	−0·0160	−0·0035	*V*	ASAS-SN
2456757·0118	0·0023	2	9340·5	−0·0119	0·0006	*V*	ASAS-SN
2457120·0197	0·0015	2	10652·5	−0·0129	−0·0023	*V*	ASAS-SN
2457120·1556	0·0012	1	10653·0	−0·0154	−0·0048	*V*	ASAS-SN
2457477·0852	0·0011	1	11943·0	−0·0076	−0·0004	*V*	ASAS-SN
2457477·2228	0·0014	2	11943·5	−0·0083	−0·0011	*V*	ASAS-SN
2457557·4615	0·0020	2	12233·5	−0·0078	−0·0016	*V*	Miller
2457849·7844	0·0010	1	13290·0	−0·0012	0·0008	*V*	ASAS-SN
2457849·9216	0·0015	2	13290·5	−0·0023	−0·0003	*V*	ASAS-SN
2458065·7366	0·0025	2	14070·5	−0·0005	−0·0020	*V*	Miller
2458070·7199	0·0016	2	14088·5	0·0025	0·0009	*V*	Miller
2458082·7557	0·0010	1	14132·0	0·0025	0·0007	*V*	Miller
2458083·7245	0·0010	2	14135·5	0·0029	0·0011	*V*	Miller
2458099·7728	0·0010	2	14193·5	0·0036	0·0015	*V*	Miller
2458227·4626	0·0007	1	14655·0	0·0039	0·0001	*g*	ZTF
2458227·6001	0·0007	2	14655·5	0·0031	−0·0007	*g*	ZTF
2458230·7837	0·0004	1	14667·0	0·0048	0·0009	*r*	ZTF
2458230·9218	0·0004	2	14667·5	0·0045	0·0007	*r*	ZTF
2458234·9290	0·0023	1	14682·0	−0·0001	−0·0040	*V*	ASAS-SN
2458235·0689	0·0048	2	14682·5	0·0014	−0·0025	*V*	ASAS-SN
2458236·8683	0·0023	1	14689·0	0·0024	−0·0015	*g*	ASAS-SN
2458237·0065	0·0031	2	14689·5	0·0022	−0·0017	*g*	ASAS-SN
2458291·6533	0·0006	1	14887·0	0·0040	−0·0004	*g*	ZTF
2458291·7915	0·0006	2	14887·5	0·0039	−0·0005	*g*	ZTF
2458293·5886	0·0006	1	14894·0	0·0025	−0·0019	*r*	ZTF
2458293·7275	0·0005	2	14894·5	0·0031	−0·0013	*r*	ZTF
2458561·1429	0·0007	1	15861·0	0·0038	−0·0000	*r*	ZTF
2458561·2815	0·0007	2	15861·5	0·0041	0·0003	*r*	ZTF
2458566·9526	0·0007	1	15882·0	0·0032	−0·0006	*g*	ZTF
2458567·0922	0·0007	2	15882·5	0·0044	0·0007	*g*	ZTF
2458611·7749	0·0014	1	16044·0	0·0027	−0·0006	*g*	ASAS-SN
2458611·9133	0·0014	2	16044·5	0·0028	−0·0005	*g*	ASAS-SN
2458643·0405	0·0007	1	16157·0	0·0031	0·0002	*r*	ZTF
2458643·1803	0·0009	2	16157·5	0·0045	0·0017	*r*	ZTF
2458648·0214	0·0006	1	16175·0	0·0037	0·0009	*g*	ZTF
2458648·1594	0·0007	2	16175·5	0·0034	0·0005	*g*	ZTF
2458918·6117	0·0006	1	17153·0	−0·0026	−0·0016	*g*	ZTF
2458918·7530	0·0006	2	17153·5	0·0004	0·0014	*g*	ZTF
2458931·3407	0·0010	1	17199·0	−0·0011	0·0001	*r*	ZTF
2458931·4791	0·0013	2	17199·5	−0·0010	0·0002	*r*	ZTF
2458985·5684	0·0020	1	17395·0	−0·0033	−0·0014	*g*	ASAS-SN
2458985·7083	0·0017	2	17395·5	−0·0018	0·0001	*g*	ASAS-SN
2459000·7856	0·0014	1	17450·0	−0·0038	−0·0016	*V*	Janzen
2459001·7567	0·0010	2	17453·5	−0·0010	0·0011	*V*	Janzen
2459021·8157	0·0010	1	17526·0	−0·0015	0·0009	*V*	Janzen
2459034·4046	0·0005	2	17571·5	−0·0017	0·0008	*CV*	Ogmen
2459270·8273	0·0004	1	18426·0	−0·0052	0·0004	*CV*	Janzen
2459294·3443	0·0002	1	18511·0	−0·0063	−0·0004	*CV*	Ogmen

Substantive observations of GSC 03465–00810 by the ASAS-SN project began in 2013 and continue up to the present. From 2013–2018 on average 100 *V*-band observations were made each year but with the adoption of many new instruments and the transition to the Sloan *g* filter the number of observations has greatly increased, such that during 2018–2020 the star was observed more than 200 times per year. The individual observations are typically made in groups of three in the space of $0^{d}\cdot003$ or 4 minutes, although in about 30% of cases there are only two observations, and in 5% there is just a single one. These groups were averaged to produce a mean data set where the median errors were $0^{m}\cdot035$ and $0^{m}\cdot048$ in *V* and *g*, respectively. Points with errors above the 95th percentile in each band were rejected so as to remove the most obviously suspicious data. The data were divided into seasonal sets with 24–80 *V*-band values and 84–117 *g*-band values. The ASAS-SN data were also fitted with a 4-harmonic Fourier series and the magnitude offsets between the four cameras, two for each band, were minimized in the determination of the eclipse timings.

Data from the *Zwicky Transient Facility*[8] are available from 2018–2020, mostly in the *zg* and *zr* bands. These observations are very unevenly distributed with more than half the data being taken in 2018 alone. As before the times of minima were also determined from a 4-harmonic Fourier fit, using two sets from 2018 and one each from 2019 and 2020, in both bands. All the times of minima are collected in Table II and the O–C diagram of the residuals with respect to a linear ephemeris is shown in Fig. 1.

The O–C diagram

The residuals have a broadly sinusoidal variation with a range of about $\pm 0^{d}\cdot01$ on a time-scale of around 4000 d, and clearly suggest the presence of a third

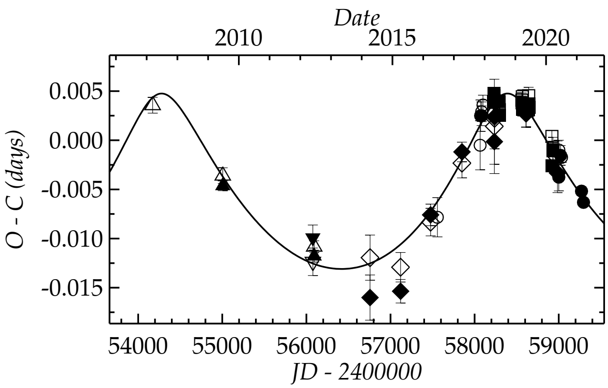

Fig. 1

The O–C diagram showing the weighted LTTE fit using the parameters given in Table III. The symbols identify the different data sets; CRTS (upward triangles), *Pan-STARRS* (downward triangles), ASAS-SN (diamonds), *ZTF* (squares), and time-series data (circles). Open symbols identify secondary minima.

body. The observed times of minima are fitted to a standard form of a linear ephemeris for the eclipsing binary plus an offset due to the light-travel-time effect (LTTE), so

$$HJD_k = T_0 + P_0 C_k + \Delta T_k \quad (1)$$

where T_0 and P_0 are the epoch zero and period of the close binary, C_k is the cycle number at minimum k, and ΔT_k is the LTTE offset at minimum k. The most widely used LTTE expressions are given by Irwin[9,10], but the less common expression given by Scott[11] as described more recently by Hilditch[12], has been used here, in which the light-travel time is,

$$\Delta T_k = A[(\cos E_k - e)\sin\omega + (1 - e^2)^{1/2}\sin E_k \cos\omega] \quad (2)$$

where E_k is the eccentric anomaly at minimum k, e is the orbital eccentricity, and ω is the argument of periastron of the orbit of the close-binary pair in reaction to the motion of the third body. The constant $A = (a_{12}\sin i)/c$ is the semi-amplitude of the light-travel time where $a_{12}\sin i$ is the projected semi-major axis of the orbit, and c is the speed of light. The Irwin and Scott approaches use the same parameters but Irwin's expression takes its origin as the geometric centre of the orbital ellipse, whereas Scott's takes the origin as the barycentre of the orbit. In both cases the fit to the observed times of minima and the parameters are the same, but Irwin's residuals are symmetrically distributed around zero while Scott's are offset, reflecting the eccentricity of the system, and this is mirrored in a slightly different T_0. The fitting was performed using Markwardt's wonderfully robust implementation of the Levenberg–Marquardt algorithm through MPFIT[13] from the MINPACK-1 package[14]. The parameters fitted are the close-binary period and zero point of the linear ephemeris, P_0 and T_0, and similarly for the third-body orbit, P, the time of periastron T, as well the eccentricity, e, the argument of periastron, ω, and the semi-amplitude of the light travel time, A.

The data are very inhomogeneous and this is reflected in the wide range of formal errors on the timings. There is also some inconsistency in the observations that suggests that some of the errors are underestimated. Another issue is that the early minima are determined from data spread over two or three years, so although the timings are near the median date of the observations there is still some additional uncertainty in the epoch of the timings. Having said that, both the weighted and unweighted solutions (see Table III) converge on $P \approx 4000$ d from a range of initial values. These periods are close to the

TABLE III

Light-travel time solution

Parameter		*Unweighted fit*	*Weighted fit*	
T_0	=	2454172·6590(11)	2454172·6607(6)	(JD)
P_0	=	0·27668358(8)	0·27668359(4)	(d)
A	=	0·00918(41)	0·00895(22)	(d)
e	=	0·42(6)	0·47(4)	
ω	=	56 ± 10	81 ± 5	(°)
T	=	2458145 ± 97	2458343 ± 41	(JD)
P	=	4111 ± 117	4111 ± 46	(d)
$a_{12}\sin i$	=	1·59(7)	1·55(4)	(AU)
χ^2_v	=	1·0 by definition	2·32	

TABLE IV

Third body orbital parameters and P_0 for fixed P

Period (d)	e	ω (°)	A (d)	a_{12} sin i (AU)	P_0(d)	χ^2_v
4000	0·47(4)	81(5)	0·0088(2)	1·53(4)	0·27668365(2)	2·42
5000	0·53(3)	59(4)	0·0110(3)	1·91(5)	0·27668305(3)	2·06
6000	0·56(3)	49(3)	0·0136(3)	2·35(6)	0·27668252(5)	1·84
7000	0·59(3)	43(3)	0·0160(4)	2·77(7)	0·27668210(6)	1·75
8000	0·67(3)	39(3)	0·0183(5)	3·18(8)	0·27668177(8)	1·71
9000	0·64(3)	37(3)	0·0206(5)	3·57(9)	0·27668147(10)	1·68
10 000	0·66(3)	35(2)	0·0228(6)	3·95(10)	0·27668122(11)	1·66
15 000	0·73(2)	30(2)	0·0328(10)	5·68(17)	0·27668038(16)	1·62
20 000	0·77(2)	28(2)	0·0419(14)	7·26(24)	0·27667986(20)	1·61

length of the data and correspond to a local minimum in χ^2. Shorter periods quickly become unrealistic as the solutions struggle to fit the early points, and longer-period solutions are driven to long, largely indeterminate periods, higher eccentricities, and larger values of *A*.

These solutions have been explored by fixing the third-body period, *P*, over a range from 4000 to 20 000 days, with the results given in Table IV, but the same trends continue to much longer periods. The quality of the longer-period fits actually increases with *P* but this is because only part of the orbit is covered and the parameters are almost completely unconstrained, in particular the close-binary period P_0, which is not the case at $P \approx 4000$ d, and here also *P* itself is more constrained. By way of illustration the O–C diagram for the fit to fixed $P = 10\,000$ d is shown in Fig. 2. Due to the uncertainty, $P \approx 4000$ d is regarded as the minimum period but for reasons given below the true period is likely to be towards this end of the range. Extrapolations of the different solutions suggest that it should be possible to discriminate between the short period, $P \approx 4000$ d, and longer periods within 2–3 years.

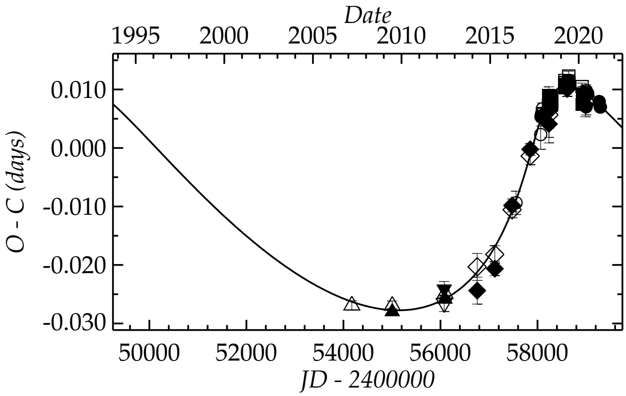

FIG. 2

Illustrative O–C diagram showing the weighted LTTE fit at fixed $P = 10\,000$ d and unconstrained close-binary period P_0. The symbols are as Fig. 1.

Parameters of the third-body orbit have been explored by using the well-known expressions for the mass function (see *e.g.*, Hilditch[12]),

$$f(m) = \frac{4\pi^2}{GP^2}(a_{12}\sin i)^3 = \frac{(m_3 \sin i)^3}{(m_{12}+m_3)^2} = \frac{(1-e^2)^{3/2}}{2G}PK^2 \quad (3)$$

where G is the gravitational constant, P and i are the third-body period and inclination, respectively, a_{12} is the semi-major axis of the close-binary pair, m_{12} is the mass of the close-binary pair, m_3 is the mass of the third body, and K is the velocity semi-amplitude. Given values of P and $a_{12}\sin i$ it is possible to derive $f(m)$ through Equation 3 and then the corresponding value of m_3 can be solved by iteration.

The fixed-period solutions in Table IV provide values of $a_{12}\sin i$ for a range of P, for which the minimum mass of the third body has been calculated for a range of combined masses of the close pair, m_{12}, over the range 0·9–2·1 $M_\odot$, which corresponds approximately to two early-M-type and two early-G-type stars respectively. The plot of the derived $m_3\sin^3 i$ is shown in Fig. 3. From the W UMa period–mass relationships of Gazeas & Stępień[15] and Kouzuma[16] the primary component of the close binary is likely to have $m_1 \approx 0{\cdot}9\ M_\odot$ so the mass range of Fig. 3 should accommodate most likely mass ratios. It is clear that in general $m_3\sin^3 i$ is relatively large compared with the mass of the close pair, with $q = m_3/m_{12} \sim 0{\cdot}4$, if $i \sim 90°$.

The other quantity that can be calculated from the mass function (Equation 3) is the semi-amplitude of the radial-velocity curve of the close binary in the third body orbit, which gives $K \approx 5$ km/s irrespective of the period.

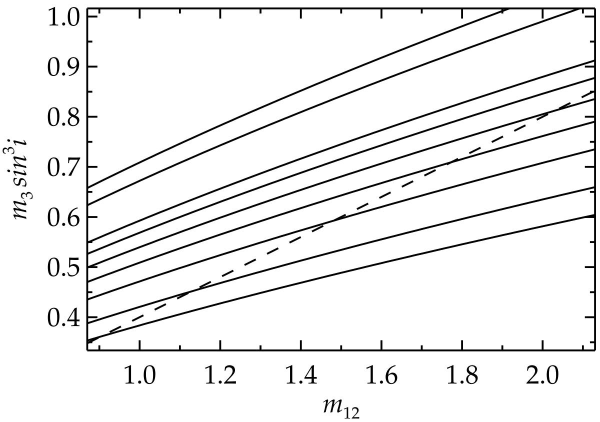

Fig. 3

The variation of the minimum third-body mass, $m_3\sin^3 i$, as a function of the combined mass of the close pair, m_{12}, for fixed $P = 4000...10\,000, 15\,000, 20\,000$ d, using the values from Table IV. The solution for $P = 4000$ d lies at the bottom and the longer periods yield progressively larger masses. For m_{12} in this range the mass ratio, $q = m_3/m_{12} \sim 0{\cdot}3$–$0{\cdot}5$, if $i \sim 90°$. The dotted line shows the solutions where $q = 0{\cdot}4$. Viable solutions exist for $P > 10\,000$ d but require increasingly unrealistic masses.

Discussion

Cool W UMa stars have the minimum angular-momentum configuration of binary systems so the perennial question is how the angular momentum of the original, presumably detached binary, has been lost. There are various well-explored routes for this that invoke stellar winds, magnetic effects, and evolutionary mass transfer and loss, and also angular-momentum transfer in an hierarchical triple or multiple system (see, *e.g.*, Gazeas & Stępień[15], Szalai *et al.*[17], Yildiz & Doğan[18]). Close-binary stars are frequently found in multiple systems[18,19], and the companions to W UMa stars run the whole gamut from low-mass ($m_3 \sim 0{\cdot}15\ M_\odot$) third bodies, *e.g.*, AM Leo[20], YY Eri[21]; through intermediate, *e.g.*, V523 Cas[22], and relatively high-mass ($m_3 \sim 0{\cdot}8\ M_\odot$) companions, *e.g.*, VW Cep[23], ER Ori[24]; to quadruple systems with two binaries, *e.g.*, TZ Boo, V2610 Oph[19], and astrometric systems. The likely third-body minimum mass for GSC 03465–00810 appears to fall in the middle of this range, with lower masses being expected for shorter periods.

GSC 03465–00810 lies at galactic co-ordinates $l = 91^\circ{\cdot}3$, $b = +66^\circ{\cdot}4$, so the extinction in this direction should be low. From the infrared dust maps with the Sloan recalibration the maximum reddening, $E_{B-V} = 0{\cdot}01$[25,26], and E_{g-r} from the Bayestar2015 and 2017 3D dust mapping is consistent[27]. The photometrically derived effective temperature for GSC 03465–00810 is $T_{\rm eff} = 4986(41)$ K from the *Gaia* DR2 data[28] and $T_{\rm eff} = 4950$ K from Sloan photometry[29]. Using the Rochester calibration[30], both suggest a spectral type of K2·5V, and this is also consistent with the mean V–K_s and *WISE* *W*1–*W*2 colours. The optical–near-IR spectral-energy distribution has been constructed using catalogued magnitudes, but due to the variability of the star those based on individual measurements may suffer larger than expected uncertainties. Magnitudes have been taken from *GALEX* NUV[31], Carlsberg Meridian Catalogue 15 r'[32], SDSS Photometric Catalogue, Release 12 *ugriz*[33], *Gaia* EDR3 *G*, *BP*, *RP*[34], ASAS-SN *V*, *g*[2,3], *ZTF g*, *r*[8], *Pan-STARRS grizy*[7], 2MASS JHK_s[35,36], and *WISE* *W*1, *W*2, *W*3, and *W*4[37,38]. These have been compared with standard spectra from Pickles' Stellar Flux Library[39] through a minimization scheme. Assuming zero reddening, the best fit is found for the K2V library spectrum, with the 1-σ range approximately K0V–K3V. The spectral-energy distribution and the best-fit spectrum are shown in Fig. 4, together with the 5000 K black body.

The distance from the latest *Gaia* EDR3 calibration, $d = 900 \pm 30$ pc[40,41], which combined with a peak brightness, $V = 14{\cdot}62$, and essentially no extinction, gives $M_V = 4{\cdot}8$ for the system. Mateo & Rucinski[42] provide a period–luminosity relationship for cool W UMa systems and for their general linear calibration, the period of GSC 03465–00810 yields $M_V = 5{\cdot}3$, so the system may be $0^{\rm m}{\cdot}5$ brighter than expected. If this is due to a third-light contribution then it is large, at ~ 60% of the luminosity of the system, and broadly equivalent to one of the components of the close binary.

GSC 03465–00810 lies in the sparsely-populated tail of the main period distribution of Mateo & Rucinski and on the break point with the shortest-period system with $P_0 < 0{\cdot}275$ d, which has a different period–luminosity relationship. The statistics in the ASAS-SN sample of W UMa systems are much better and also suggest a falling away of $T_{\rm eff}$ and luminosity of the shortest-period systems[4,43]. The effective temperature and period place the system well below the transition zone between A-type and W-type stars, so even without a photometric solution the system is almost certainly a W-type system.

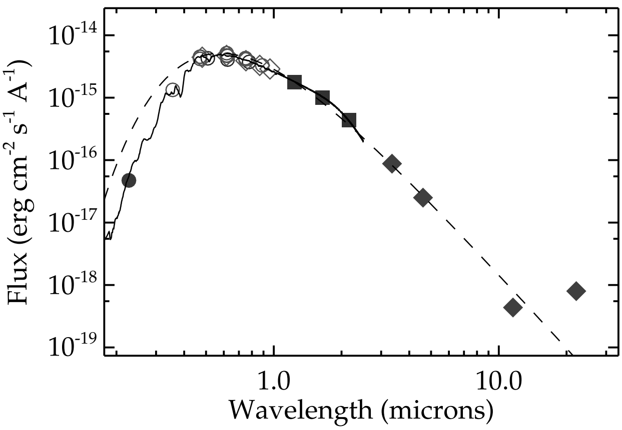

FIG. 4

The spectral-energy distribution with the less-confused points being *GALEX* NUV, 2MASS J, H, K_s, and *WISE* $W1$–$W4$. The best-fit K2V spectrum is shown as the solid line, and the 5000 K black body as the dashed line.

Using the fit to the LTTE it is possible to correct the photometric phase diagrams for the displacement caused by the motion of the third-body orbit. The combined time-series data are shown in Fig. 5 where magnitude offsets to the individual runs are allowed to minimize the dispersion. Most of these were taken specifically to observe the minima so the maxima were often caught at the beginning or end of the night, which accounts for the increased scatter. Most of the runs were made unfiltered, to improve signal-to-noise, but this also reduces the consistency of the light-curves due to differential-extinction effects.

Similarly the phase diagrams of the ASAS-SN V and g data and the *ZTF* g and r data have been corrected in the same way in Figs. 6 and 7. For the ASAS-SN data, magnitude offsets have been allowed for the different cameras, two for each band. None of these light-curves show a clear or consistent O'Connell effect so despite the components lying towards the short period, low-temperature, low-mass end of the W UMa range there is no obvious indication of chromospheric activity[44–46].

Conclusions

GSC 03465–00810 is a short-period W UMa system with $P_0 = 0{\cdot}27668359(4)$ days and lies on the cusp of the main body of cool systems and the shortest-period stars[4,42]. It has a photometrically derived effective temperature $T_{\rm eff} \approx$ 4960 K[28,29] which suggests a spectral type of K2·5 V[30]. Based on the period, calibrations for other W UMa systems suggest that the mass of the primary $m_1 \sim 0{\cdot}9\ M_\odot$[15,16], and that the system is expected to have $M_V = 5{\cdot}3$. The measured $M_V = 4{\cdot}8$, so the system may be $0^{\rm m}{\cdot}5$ brighter than expected[42].

The O–C residuals of the times of minima clearly show that the system has a third body with a minimum period, $P \approx 4000$ d, and with an upper limit constrained only by the acceptable masses of the system. It should become

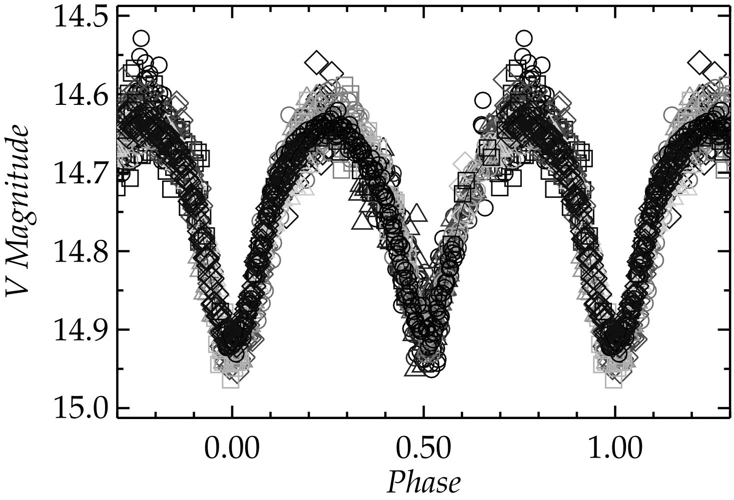

FIG. 5

The *V*- and *CV*-band time-series runs corrected for the LTTE using the weighted solution shown in Fig. 1. The different runs are shown with different symbols. The additional scatter around the maxima is largely observational as described in the text.

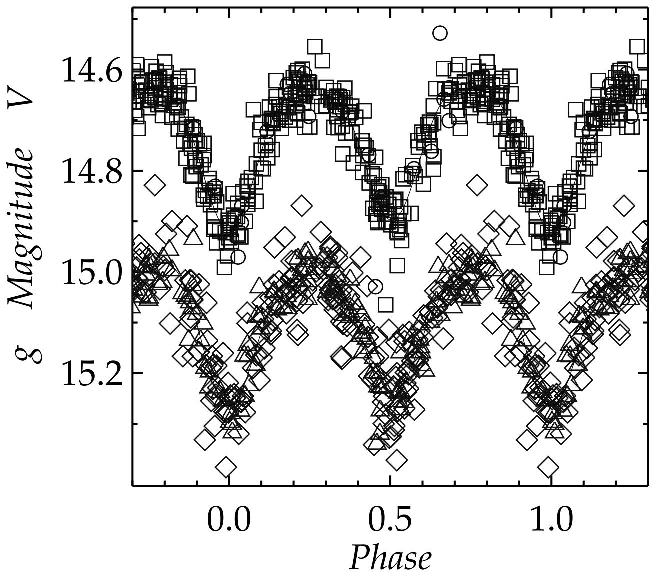

FIG. 6

Phase diagrams of the ASAS-SN *V*- and *g*-band data corrected for the LTTE. The circles and squares show the *V* data, and the diamonds and triangles the *g* data. The two bands are shown at their correct levels.

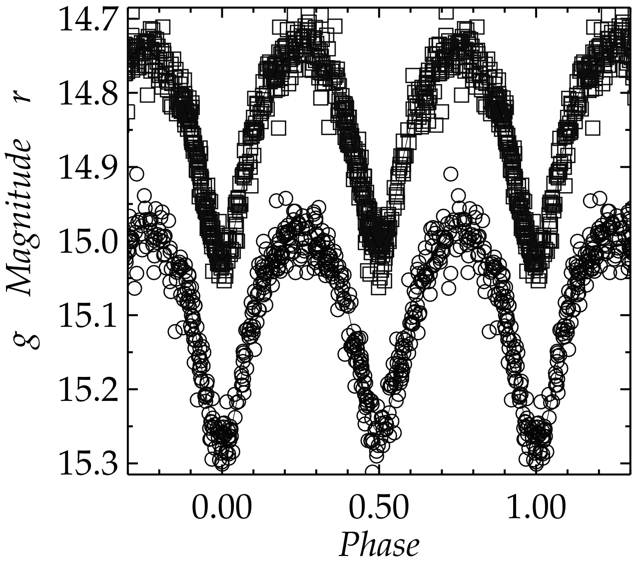

FIG. 7

Phase diagrams of the *ZTF g*- and *r*-band data corrected for LTTE. The *g*-band data (circles) are shown at their correct level while the *r*-band data have been offset for convenience.

clear within 2–3 years whether $P \sim 4000$ d or much longer. The eccentricity at the minimum period is, $e \approx 0{\cdot}40$ and this increases with increasing period to $e \approx 0{\cdot}65$ at $P = 10\,000$ d. For $P = 4000$ d the possible mass of the third body ranges from $m_3 = 0{\cdot}42$–$0{\cdot}62\ M_\odot$ for $m_{12} = 1{\cdot}0$–$2{\cdot}0\ M_\odot$.

Acknowledgements

The authors gratefully acknowledge helpful comments from the referee. The authors are pleased to acknowledge the use of the NASA/ADS, the *Simbad* database and the *VizieR* catalogue access tool. The authors are also grateful to the University of Saskatchewan for time on the *PROMPT-USASK* telescope at the Department of Physics and Engineering Physics, Sleaford Observatory.

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REDISCUSSION OF ECLIPSING BINARIES. PAPER 6: THE F-TYPE SYSTEM V505 PERSEI

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V505 Per is a detached eclipsing binary containing two F5V stars in a 4·22-d circular orbit. We use a light-curve from the *TESS* satellite and published radial-velocity measurements to establish the properties of the system to high precision. The masses of the stars are $1{\cdot}275 \pm 0{\cdot}004\,M_{\odot}$ and $1{\cdot}258 \pm 0{\cdot}003\,M_{\odot}$, and their radii are $1{\cdot}294 \pm 0{\cdot}002\,R_{\odot}$ and $1{\cdot}264 \pm 0{\cdot}002\,R_{\odot}$. Adding published effective-temperature estimates, we measure precisely the luminosities and absolute bolometric magnitudes of the stars, and the distance to the system. The distance is slightly shorter than that obtained from the *Gaia* EDR3 parallax, a discrepancy most easily explained by uncertainty in the 2MASS *K*-band apparent magnitude. We reanalyse existing light- and radial-velocity curves from three previous studies of this system and conclude that, in this case, formal errors are reliable for the spectroscopic orbits but not light-curves, that error bars from a residual-permutation algorithm are suitable for light-curves but not spectroscopic orbits, and that published results are not always reproducible. The precisions in the measured properties of V505 Per are high and among the best ever obtained for a detached eclipsing-binary system.

Introduction

Detached eclipsing binaries (dEBs) offer the possibility of measuring the physical properties of stars to high precision and accuracy without any reliance on theoretical models of stellar evolution, so represent a direct probe of how stars evolve[1] and an important testbed for the verification and refinement of theoretical models[2–6]. High precision and accuracy in the measured mass and radius is vital for this work, as is a precise measurement of the effective temperature ($T_{\rm eff}$) and chemical composition of each star[7,8]. The reliability of mass and radius determinations can be assessed by comparison of the results from multiple independent analyses of individual or different datasets for the same dEB[9,10].

In this work we present a detailed analysis of the dEB V505 Persei, which consists of two very similar F5 V stars. Our analysis is based on three published radial-velocity (RV) studies, three published light-curves, and a new light-curve obtained by the NASA *Transiting Exoplanet Survey Satellite*[11] (*TESS*) mission. This forms part of our project to revise systematically and improve the measured physical properties of known dEBs[12–16], in particular those which can be included in *DEBCat**, a catalogue of dEBs with mass and radius measurements to precisions of 2% or better[17].

V505 Persei

In this work we present an analysis of the dEB V505 Per (Table I) based on its light-curve from *TESS* and on published RVs. V505 Per is an F-type system containing two very similar stars on a circular orbit with a period of 4·22 d. The discovery was announced by Kaiser[25] under the guise of SAO 23229 and with a period of 2·111 d, half the true value. Kaiser *et al.*[26] presented nine times of minimum light estimated visually and established the first ephemeris; they noted that their period of 2·1110084 d might be half the true value if the primary and secondary minima were of similar depth (as indeed turned out to be the case).

Marschall *et al.*[27] obtained spectroscopy and found that the system was double-lined and with an orbital period of 4·22 d. Marschall *et al.*[28] (hereafter MA97) presented a detailed study of the system based on 63 échelle spectra and a light-curve comprising 1324 data points in the *B* and *V* filters. They determined the masses of the stars to high precision, but their radius measurements were good to only 2·3% (primary, hereafter star A) and 5·5% (secondary, hereafter star B)

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

Table I

Basic information on V505 Per

Property	*Value*	*Reference*
Henry Draper designation	HD 14384	18
Hipparcos designation	HIP 10961	19
Tycho designation	TYC 3690-536-1	20
Gaia EDR3 designation	455772347387763840	21
Gaia EDR3 parallax	16·069 ± 0·020 mas	21
TESS designation	TIC 348517784	22
B magnitude	7·30 ± 0·01	20
V magnitude	6·88 ± 0·01	20
J magnitude	6·070 ± 0·067	23
H magnitude	5·793 ± 0·036	23
K_s magnitude	5·771 ± 0·020	23
Spectral type	F5 V + F5 V	24

due to the scatter in their photometry as well as the intrinsic indeterminacy of the ratio of the radii of a dEB showing deep but partial eclipses.

Munari *et al.*[29] (hereafter MU01) studied V505 Per in the context of investigating what might be achieved using *Gaia* photometry and spectroscopy for dEBs. RVs were obtained from 20 échelle spectra of the calcium infrared triplet (849·8, 854·2, and 866·2 nm), and they used the *Hipparcos* light-curve of this object. The mass measurements were less precise than those of MA97, as they were deliberately based on data of lower quality in order to mimic *Gaia*. The radii were measured to much higher precision (1·4% for star A and 2·6% for star B) despite being obtained from a light-curve with only 11 data points during eclipse. The authors did note that this is a *formal* error but made no attempt to determine a true uncertainty.

Tomasella *et al.*[24] (hereafter TO08) reanalysed V505 Per based on 36 new échelle spectra and 627 light-curve data-points in B and V. They obtained mass measurements in good agreement with those of MA97, but radius measurements with much smaller error bars (less than 1%) despite the similarity of the light-curves presented by the two works. They also measured the atmospheric parameters of the stars ($T_{\rm eff}$ and [M/H]) *via* a χ^2 analysis of the spectra — the use of the χ^2 statistic on observations with significant modelling uncertainties (*e.g.,* high-resolution theoretical spectra[30,31]) is questionable.

Finally, Baugh *et al.*[32] used high-signal-to-noise échelle spectra to measure the photospheric lithium abundance of the components of V505 Per, both of which are in the lithium dip ($T_{\rm eff} \sim 6400$ to 6800 K; refs. 33, 34). They found that its lithium was less depleted than expected for its age, confirming the hypothesis that the different rotational evolution of stars in short-period binaries affects their lithium depletion.

Observational material

In this work we concentrate on the light-curve of V505 Per obtained using the NASA *TESS* satellite[11], which observed it in Sector 18 (2019/11/02 to 2019/11/27). The observations cover four primary and six secondary eclipses, with one primary eclipse lost to the mid-sector pause for downlinking the data from the satellite to Earth (Fig. 1). These data were downloaded from the MAST archive* and converted to relative magnitude. We retained only those data points with the QUALITY flag equal to zero.

* Mikulski Archive for Space Telescopes, https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html

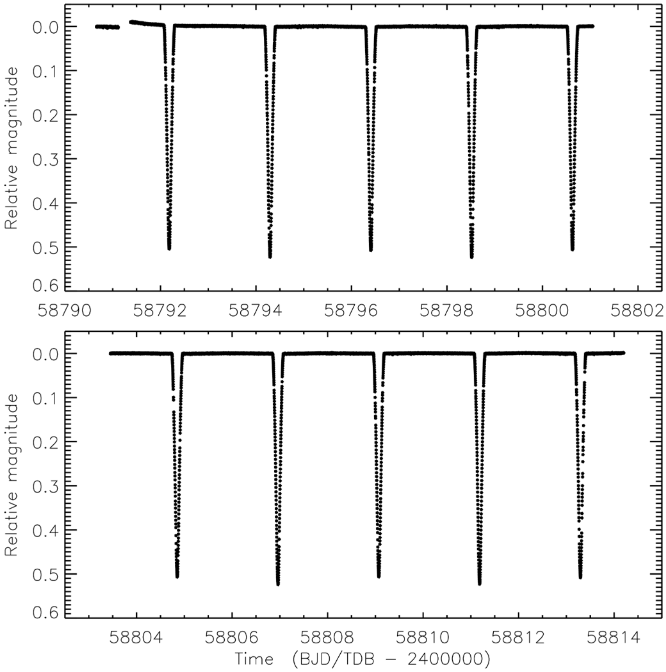

Fig. 1

TESS Sector 18 short-cadence photometry of V505 Per. The two panels show the data before and after the mid-sector pause for download of the data to Earth[11].

The *TESS* data were obtained in short-cadence mode, with a sampling rate of 120 s. We chose to use the simple aperture photometry (SAP) data rather than the pre-search data-conditioning (PDC) alternative[35]. This is because the PDC data are processed with the aim of finding shallow planetary transits, an approach that often introduces artefacts in light-curves of stars such as dEBs with a strong intrinsic variability. Of the 17 554 data points, 14 805 have a QUALITY flag of zero and were retained for further analysis.

Analysis of the TESS light curve

We first analysed the *TESS* photometry of V505 Per in order to establish the most reliable photometric parameters of the system. For this we used version 41 of the JKTEBOP* code[36,37], which is suitable for systems with well-separated stars[10]. We used the definition that the primary eclipse is deeper than the secondary eclipse, and set star A to be the star eclipsed during primary eclipse. The two stars are very similar, but star A is slightly hotter, larger, and more massive than star B.

To save computation time and to avoid problems with slow changes in the brightness of the system due to instrumental effects, we extracted from the *TESS* light-curve every data point within one eclipse duration of the midpoint

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

of an eclipse. We fitted for the sum ($r_A + r_B$) and ratio ($k = r_A/r_B$) of the fractional radii, defined by $r_A = R_A/a$ and $r_B = R_B/a$ where R_A and R_B are the true radii of the stars, and a is the semi-major axis of the relative orbit. We also fitted for the orbital inclination (i) and ephemeris (P and T_0), and for the central surface-brightness ratio of the two stars ($\mathcal{J}$). Limb darkening was included using the quadratic law[38] with theoretical coefficients from Claret[39]. The same limb-darkening coefficients were used for both stars, a reasonable step due to their similarity: the linear coefficient was fitted and the quadratic coefficient was fixed. Third light was held at zero because fits with it included as a free parameter returned almost identical results with an insignificant and negative amount of third light. The orbit was also assumed to be circular as we found no evidence for eccentricity. The other fitted parameters were the coefficients of nine straight lines applied to the out-of-eclipse brightness of the system, one for each eclipse.

The best fit is shown in Fig. 2 and is a very good description of the data; the scatter around the best fit is only 0·49 mmag. The parameter values determined are given in Table II. The residuals have a slightly non-Gaussian distribution, with a longer tail to fainter magnitudes. This effect is typical in *TESS* light-curves (*e.g.*, refs. 14 and 16).

The uncertainties in the fitted parameters were determined in three ways: Monte Carlo (MC) and residual-permutation (RP) algorithms[40,41] and by splitting the data into three subsets each containing three consecutive eclipses. For each parameter we adopted the larger of the MC and RP alternatives; we used the third method only as a consistency check due to the small-number statistics intrinsic to the current case. In Paper 5 (ref. 16) we found that the

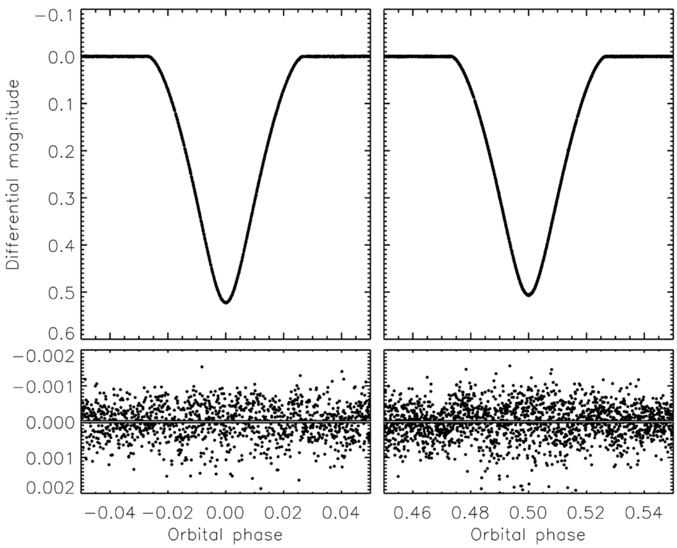

FIG. 2

The *TESS* light-curve of V505 Per (filled circles) around the primary (left) and secondary (right) eclipses. The best fit is not plotted as it is indistinguishable from the data. The lower panels show the residuals of the fit with the line of zero residual overplotted in white for clarity.

TABLE II

Parameters of the best JKTEBOP fit to the TESS light-curve of V505 Per. The uncertainties are 1σ. The same limb-darkening coefficients were used for both stars.

Parameter	*Value*
Fitted parameters:	
Primary-eclipse time (BJD/TDB)	2458798·516720 ± 0·000005
Orbital period (d)	4·2220216 ± 0·0000023
Orbital inclination (°)	87·9166 ± 0·0030
Sum of the fractional radii	0·170906 ± 0·000035
Ratio of the radii	0·9788 ± 0·0019
Central-surface-brightness ratio	0·97775 ± 0·00050
Third light	0·0 (fixed)
Linear limb-darkening coefficient	0·261 ± 0·005
Quadratic limb-darkening coefficient	0·23 (fixed)
Derived parameters:	
Fractional radius of star A	0·086370 ± 0·000078
Fractional radius of star B	0·084536 ± 0·000091
Light ratio	0·9367 ± 0·0037

three error estimates agreed well, and thus were likely to be reliable even in cases where there were significant correlations between some parameters. We found that the RP uncertainties were larger than the MC uncertainties by typically 50%, so these were adopted as our final uncertainties.

Analysis of published light-curves

Three previous works have studied V505 Per using a variety of light-curves and with a range of approaches to understanding the uncertainties in the derived parameters. We therefore attempted to reproduce these results. We were unfortunately not able to obtain the light-curves from MA97 so these were excluded from our analysis.

MU01 used the *Hipparcos* and *Tycho* light-curves[19,20] to evaluate the results potentially achievable for dEBs using the *Gaia* satellite. We obtained these data* and analysed the *Hipparcos* observations. We did not include the *Tycho* data as they are much more scattered than the *Hipparcos* magnitude measurements so contribute negligible additional information. The data were modelled using JKTEBOP with r_A, r_B, i, J, T_0 and out-of-eclipse brightness as the fitted parameters. We fixed the limb-darkening coefficients to theoretical values[42] for the V-band. The orbital period was fixed to the value given in Table II. Uncertainties were obtained using MC and RP simulations. The results are compared in Table III to those from MU01 for r_A, r_B, and i. We find consistent values but with uncertainties larger by factors of between 2 and 4. Uncertainties in r_A and r_B were not given by MU01 so we have used the (fractional) uncertainties for the true radii of the stars and neglected the much smaller contribution to these from the uncertainty in the semi-major axis. We confirm that the uncertainties found by MU01 are underestimated.

TO08 analysed their own BV photometry, to which they added the BV photometry from MA97 obtained during eclipse, using the Wilson–Devinney

*http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=I/239/hip_main&recno=10953

TABLE III

Comparison of measured fractional radii and orbital inclination for different analyses and different datasets for V505 Per

Source	r_A	r_B	i (°)
MA97	0·0861 ± 0·0022	0·0844 ± 0·0043	87·83 ± 0·02
MU01	0·0930 ± 0·0013	0·0757 ± 0·0020	88·18 ± 0·11
This work (*Hipparcos* data)	0·0914 ± 0·0049	0·0782 ± 0·0059	88·09 ± 0·22
TO08	0·0860 ± 0·0009	0·0846 ± 0·0009	87·95 ± 0·04
This work (TO08 *B* data)	0·0901 ± 0·0017	0·0833 ± 0·0021	87·90 ± 0·14
This work (TO08 *V* data)	0·0914 ± 0·0029	0·0816 ± 0·0046	87·89 ± 0·27
This work (*TESS* data)	0·08637 ± 0·00008	0·08454 ± 0·00009	87·917 ± 0·003

code[43,44]. Our own analysis of these data necessarily omits the MA97 photometry so is not directly comparable. We modelled the TO08 *BV* light-curves separately using the same approach as in the previous paragraph. We find significantly different results (Table III): those from TO08 agree well with the (presumed) definitive values from *TESS* whereas our own analysis of the TO08 data do not. After extensive investigation we can only explain this as due to our inability to include the MA97 data. Our uncertainties are significantly larger, and we attribute this to differences in the datasets plus the apparent reliance by TO08 on formal errors computed by the Wilson–Devinney code. Formal errors are known to underestimate the true uncertainties of the fitted parameters[12,45,46] and should not be used[47].

Analysis of published radial velocities

The three previous detailed studies of V505 Per (MA97, MU01, TO08) have each presented new RV measurements of the system. It is an obvious goal to combine these and thus obtain the greatest precision in the resulting spectroscopic orbit. We have performed independent fits of each of the datasets for two reasons. First, we wish to combine the different orbits using the velocity amplitudes, and one of the three previous studies did not present their own values of these quantities. Second, this presents the opportunity to investigate the reliability of the error bars obtained using various methods.

To do so we obtained the RVs from the PDF files of the three papers* and fitted them each with JKTEBOP. We fixed the orbital period to the value in Table II and fitted for the velocity amplitude and systemic velocity of each star plus a phase offset. We assumed a circular orbit and scaled the error bars of each dataset in order to force a reduced χ^2 of $\chi^2_\nu = 1$. Error bars were obtained using the MC and RP approaches. Whilst the MC algorithm should be suitable for this work, the RP algorithm may not be. This is because the precision of RVs depends on *orbital phase* rather than *time* due to the phenomenon of line blending[48,49], and because the RP approach does not account for differences in error bars between individual observations.

*The PDF version of MA97 was obtained from the NASA ADS website and appears to be an image of the original paper. Selectable text is embedded within the file but seems to have been assembled *via* optical character-recognition software. On cross-checking the data file with the original paper it was found that a lot of the '5's had been misidentified as '3's.

TABLE IV

Spectroscopic orbits obtained from each of the three RV datasets. All quantities are in km s⁻¹. The three systemic velocities are for the stars combined, star A and B, respectively. The bracketed quantities were not given by MU01 but were calculated by the current author from quantities that were.

Source	K_A	K_B	V_γ	$V_{\gamma,A}$	$K_{\gamma,B}$
MA97	88·93	90·30	0·040		
	±0·14	±0·14	±0·074		
This work (RVs from MA97)	88·91	90·28		0·00	0·01
Formal errors	±0·14	±0·14		±0·08	±0·11
MC errors	±0·14	±0·14		±0·10	±0·11
RP errors	±0·15	±0·14		±0·01	±0·01
MU01	(89·58)	(90·98)	−0·41		
			±0·39		
This work (RVs from MU01)	90·23	91·85		−0·65	−0·52
Formal errors	±0·51	±1·36		±0·31	±0·93
MC errors	±0·52	±1·36		±0·31	±0·96
RP errors	±1·59	±1·82		±0·81	±1·78
TO08	89·01	90·28	0·21		
	±0·08	±0·09	±0·02		
This work (RVs from TO08)	89·27	90·35		0·41	0·01
Formal errors	±0·12	±0·16		±0·08	±0·11
MC errors	±0·12	±0·15		±0·08	±0·11
RP errors	±0·25	±0·55		±0·21	±0·34
Final values	89·12	90·31			
	±0·09	±0·12			

The results of this analysis are shown in Table IV. The formal error of each parameter from the covariance matrix is included in the table to aid interpretation of the numbers. The RVs from MA97 are those obtained with a synthetic template with a line broadening of 10 km s⁻¹. Table IV shows that the three sets of RVs agree well; the MU01 RVs are the least good but it should be remembered that they were deliberately obtained with a lower resolution and signal-to-noise ratio in order to mimic what *Gaia* was expected to achieve. It is also notable that the formal and MC error bars agree very well — formal errors are reliable in simple fits where no parameters are strongly correlated[50]. The RP errors are more fragile and can either under- or over-estimate the uncertainty, so are less suitable for application to RV measurements. The published uncertainties are generally in agreement with those found here, but can sometimes underestimate the true uncertainties.

Table IV also contains the final adopted velocity amplitudes for the two stars, obtained as a weighted mean of the JKTEBOP results for the MA97 and TO08 RVs. Whether or not the MU01 RVs are included makes a negligible difference (+0·03 km s⁻¹ for K_A and +0·01 km s⁻¹ for K_B) as they have much lower weight than the other two datasets. We did not calculate a mean value for the systemic velocities as the different datasets may not be on the same RV system and we have no use for such a value in the current work. Fig. 3 shows the fits to all three sets of RVs. They are displayed together in the main panel but the residuals are shown separately for clarity.

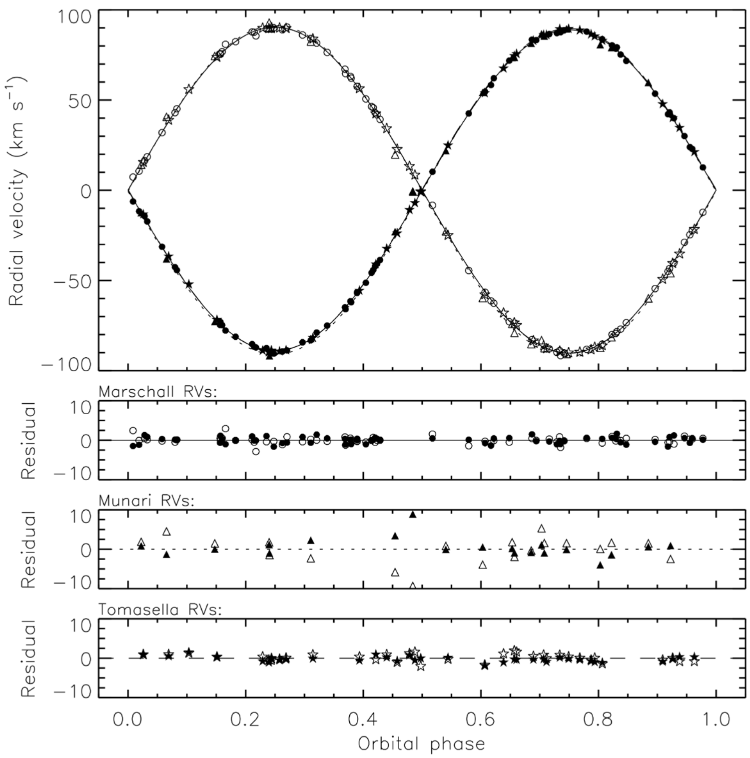

FIG. 3

The fitted spectroscopic orbits compared to the RVs from the three different sources. The circles show RVs from MA97, the triangles show RVs from MU01, and the stars show RVs from TO08. In each case the RVs for star A are shown using filled symbols and the RVs for star B using open symbols. The best fits found in the current work for each source of RVs are shown using solid, dotted, and dashed lines, respectively. The main panel shows the RVs and fits, and the lower panels show the residuals of the fit for each source of RVs (labelled).

Physical properties of V505 Per

The analyses above have led to final values for various parameters of the system which can be used to determine the physical properties of the stars. We did so using r_A, r_B, P, and i from Table II, and K_A and K_B from Table IV. To these we added the T_{eff} values of the stars from TO08 (see next paragraph), the apparent magnitudes of the system given in Table I after converting the 2MASS magnitudes to the Johnson system, and an interstellar extinction estimate of $E(B-V) = 0{\cdot}002 \pm 0{\cdot}002$ mag obtained using the STILISM* on-line tool (Lallement *et al.*[52,53]). These numbers were fed into the JKTABSDIM code[54], which calculates the physical properties using standard formulae[55] and propagates uncertainties using a perturbation analysis. The results of this work are given in Table V.

*https://stilism.obspm.fr

TABLE V

Physical properties of V505 Per defined using the nominal solar units given by IAU 2015 Resolution B3 (ref. 51).

Parameter	*Star A*	*Star B*
Mass ratio	0·9868 ± 0·0016	
Semi-major axis of relative orbit ($R^{\rm N}_\odot$)	14·984 ± 0·013	
Mass ($M^{\rm N}_\odot$)	1·2745 ± 0·0036	1·2577 ± 0·0030
Radius ($R^{\rm N}_\odot$)	1·2941 ± 0·0016	1·2637 ± 0·0017
Surface gravity (log[cgs])	4·3194 ± 0·0010	4·3343 ± 0·0010
Density ($\rho_\odot$)	0·5880 ± 0·0017	0·6232 ± 0·0021
Synchronous rotational velocity (km s^{-1})	15·508 ± 0·019	15·143 ± 0·021
Effective temperature (K)	6512 ± 50*	6464 ± 50*
Luminosity log($L/L^{\rm N}_\odot$)	0·434 ± 0·013	0·399 ± 0·013
$M_{\rm bol}$ (mag)	3·656 ± 0·033	3·743 ± 0·034
Distance (pc)	61·19 ± 0·62	

*Taken from TO08 but with increased error bars

For the $T_{\rm eff}$ measurements of the stars we adopted those from TO08, but increased the uncertainties to ±50 K as the $T_{\rm eff}$ scale of F-dwarfs is not currently pinned down more precisely than this[56–58]. The surface-brightness ratio determined from our modelling of the eclipses is consistent with the ratio of the $T_{\rm eff}$s given by TO08; it also confirms to high significance that the ratio of the $T_{\rm eff}$ values is below unity and thus star A is hotter than star B. Detailed comparisons with theoretical predictions should account for this by comparing the $T_{\rm eff}$ of star A and the ratio of the $T_{\rm eff}$s rather than the two $T_{\rm eff}$ values directly[49].

The properties of the system are measured to an exceptionally high precision: 0·26% in mass and 0·13% in radius. The excellence of these results can be attributed to the availability of multiple sets of high-quality RVs and the remarkable light-curve obtained using *TESS*. Only a few other EBs have properties measured to a comparable precision (*e.g.*, AI Phe[10] and FM Leo[59]). We determined the distance to the system using the calibration of *K*-band surface brightness *versus* $T_{\rm eff}$ presented by Kervella *et al.*[60], finding 61·19 ± 0·62 pc. This is slightly below the distance of 62·23 ± 0·08 pc found from the parallax of the system in *Gaia* EDR3. We note that Bailer-Jones *et al.*[61] obtained a distance of 62·03 ± 0·10 pc from their re-interpretation of the *Gaia* EDR3 parallaxes using priors from a three-dimensional model of the Milky Way. The dominant contributor to the uncertainty in our distance measurement is the K_s-band apparent magnitude from 2MASS.

Although the two stars are very similar, their masses and radii differ by much more than the measurement errors, so a comparison with the predictions of theoretical stellar evolutionary models is of interest. For this we chose the PARSEC models[62] and overlaid their predicted properties on the observed ones in the mass–radius and mass–$T_{\rm eff}$ diagrams. We found a good fit to all properties for a fractional metal abundance of Z = 0·017 and an age of 1050 ± 50 Myr. Predictions for Z = 0·014 or Z = 0·020 significantly over- or under-predict the measured $T_{\rm eff}$ values so can be ruled out.

TO08 measured the metallicities of both stars to be [M/H] = –0·12 ± 0·03 *via* χ^2-fitting synthetic spectra to the observed spectra. The heavy-element mixture adopted for the PARSEC models equates to a solar value of $Z_\odot$ = 0·01524 so the measured [M/H] corresponds to Z = 0·0116. This conflicts with the results of the comparison in the mass–radius and mass–$T_{\rm eff}$ diagrams, suggesting that a reappraisal of the photospheric chemical composition is warranted.

Summary

V505 Per is a dEB containing two F5V stars on a 4·22-d circular orbit. Time-series photometry and RVs have been presented and analysed in three publications, and a light-curve from the *TESS* satellite has recently become available. We determined the physical properties of the system based on the *TESS* data and the published RVs. We measured the masses to a precision of 0·26% and the radii to a precision of 0·13%. Analysis of the existing data for the system led to the conclusion that formal errors can be trusted for RVs, where correlations between parameters are weak, but not for light-curves, where parameter correlations are often strong. Including the precise $T_{\rm eff}$ and metallicity values from TO08, V505 Per becomes one of the dEBs with the most precisely determined basic physical properties.

We find that the PARSEC theoretical stellar-evolutionary models provide a good match to the measured masses, radii, and $T_{\rm eff}$ values for an age of approximately 1 Gyr and a modestly supersolar metal abundance. As TO08 found both stars to have a slightly subsolar metallicity, we conclude that a detailed spectroscopic chemical abundance analysis should be performed for this system.

Acknowledgements

We thank Lina Tomasella, Claud Lacy, and Guillermo Torres for their help in trying to find the elusive light-curves published by MA97. We also acknowledge a helpful report from an anonymous referee and useful comments from Dariusz Graczyk. This paper includes data collected by the *TESS* mission. Funding for the *TESS* mission is provided by the NASA's Science Mission Directorate. The following resources were used in the course of this work: the NASA Astrophysics Data System; the *Simbad* database operated at CDS, Strasbourg, France; and the arχiv scientific paper preprint service operated by Cornell University. I acknowledge that this work may give the impression that I am obsessed with error bars.

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CORRESPONDENCE

To the Editors of 'The Observatory'

Celestial Angular Momentum and Disc Formation: A Query.

The question posed below would seem not to be commonly noticed in the literature of dynamical astronomy but it is surely worthy, nonetheless, of consideration as a discussion-point in undergraduate teaching, at least, if not as something deeper. The undersigned would therefore be very interested in the relevant thoughts of any readers of *The Observatory* versed in these matters.

Considering a very-many-body system composed of masses in roughly circular orbits whose planes are randomly orientated in space, it is trivially obvious that the scalar magnitude, h, of the system's resultant orbital angular momentum $\mathbf{h} = \sum_i \mathbf{h}_i$ will be maximized if and only if those planes are rotated to make the individual orbital angular-momentum vectors $\mathbf{h}_i$ parallel. On the naïve assumption that this rotation could occur without affecting the total orbital energy, E, it would immediately follow that, for such a system, the $\mathbf{h}_i$-aligned flat-disc configuration is, uniquely, that of (global) maximum h for given E; it now follows immediately by the Principle of Reciprocity in constrained optimization[1] that such a dynamical state is, conversely, one of *minimum* E for given h.[2] The purely mathematical reciprocity principle of course knows nothing of the conservation of angular momentum but when that is also reckoned with in considering the physical process of alignment of the $\mathbf{h}_i$ vectors it is clear that their individual scalar magnitudes must shrink greatly as disc formation proceeds, in order to conserve their resultant. As it is easily shown that, for any approximately circular bound orbits, energy and angular momentum are monotonically increasing with respect to each other, it follows that the flat-disc arrangement possesses a huge energy-advantage for the given, conserved total **h**.

Thus, granted only some internal dissipation, the result is an almost effortless explanation for the ubiquity of flat-disc structures among celestial systems sufficiently isolated to be considered **h-**closed to a fair approximation — all the way across the cosmic scale-spectrum from planetary systems and the 'proplyds' so memorably revealed by *HST* in the Orion nebula in the 1990's, to spiral galaxies such as NGC 4565 (or indeed, bearing in mind that wonderful 2MASS image, our own Galaxy[3]) some 10^7–10^8 times larger. The mechanism is clearly both ubiquitous and powerful. The obvious question then is why, at the intermediate scale, are there apparently *no flat star clusters*?

Can it really be that this childishly elementary dynamical argument can tell us something non-trivial about the complexities of the formation-mechanisms of such multifarious very-many-body systems? While it is a nice thought that a universe without friction would therefore be a universe without either planetary systems or spiral galaxies, we can hardly appeal to the absence of local friction to explain the absence of flat star clusters. Can protoplanetary clouds only, in fact, become discs *after* the coalescence of the central star, and galaxies likewise only when they already contain a central supermassive black hole? For the point, of course, is that star clusters in general contain no such dominant central mass.

Yours faithfully,
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2021 February 5

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(1) G. Chrystal, *Algebra* Vol. II 1889, p. 52. To judge by a straw poll of a dozen or so such works on the writer's shelves, modern texts on analysis and 'advanced calculus', on the other hand, are curiously coy on the Principle of Reciprocity but it is nonetheless almost obvious intuitively, is indeed easily proven, and is fertile in non-trivial consequences — as, I hope, this letter demonstrates. One manifestation at least is familiar in the physical sciences, in the alternative reciprocal 'maximum entropy for given energy' and 'minimum energy for given entropy' formulations of the 2nd-Law condition for thermodynamic equilibrium of a closed system. For a passing reference to the role of reciprocity in the isoperimetrical problems of the calculus of variations — all that the writer has been able to find in the standard modern texts of applied analysis — see Courant & Hilbert *Methods of Mathematical Physics* Vol. I, 1963, p. 258. Chrystal's proof derives from the algebra of inequalities and can be extended immediately to any pair of real-valued functions (E & h here) of any denumerable set of independent variables (here the inclinations α_i of the individual $\mathbf{h}_i$ vectors to their conserved resultant **h**), and so applies directly to the astronomical problem.

(2) In reality, the process of alignment brings the orbiting masses closer together on average, so decreasing the system's total gravitational potential energy and thence, by the Virial Theorem, its value of E — the E-*versus*-h minimization therefore holds *a fortiori*.

(3) "The evolution of the Milky Way disc appears overall to have been only very minimally affected by outside influences […] The disc's evolution is largely driven by internal processes." Prof. J. Bovy in 2020 February RAS talk 'The Milky Way in the era of large surveys', as reported in *The Observatory*, **140**, 166, 2020. That is, disc formation in an **h**-closed system.

Kapteyn in Leiden

In his review[1] of van der Kruit's biography of Kapteyn[2], Argyle wrote that Kapteyn "was to remain on the staff of Groningen for the remainder of his life". Kapteyn retired in 1921 at the age of 70, and the next director of the Astronomical Laboratory (later the Kapteyn Laboratory and now the Kapteyn Institute) in Groningen was his former student Pieter van Rhijn. Presumably, as a former full professor and director, Kapteyn became an emeritus upon retirement. After his thesis in Leiden and a further three years there, Kapteyn had become professor of astronomy and theoretical mechanics in Groningen in 1877 and spent the rest of his life there. Even though Kapteyn died already in 1922*, there is an interesting detail missing.

Argyle mentioned a symposium in Groningen on Kapteyn[3], which I attended (I was working at the Kapteyn Astronomical Institute at the time). I remember Willem de Sitter's grandson Wolter Reinold de Sitter (a professor of civil engineering) mentioning at that symposium that towards the end of his life Kapteyn had worked in Leiden. Checking the proceedings reminded me of the details: in 1918, the director of Leiden Observatory, E. F. van de Sande Bakhuijzen, died unexpectedly. Willem de Sitter (who had been Kapteyn's first doctoral student and after a few years in Groningen (including a couple of years

*Kapteyn died in Amsterdam in the home of the astronomer Ejnar Hertzsprung, who was also his son-in-law, being married to Kapteyn's daughter Henrietta; Kapteyn's granddaughter by them was named Rigel.

working in Cape Town) spent most of his academic career in Leiden) then became temporary director (and later director until his death in 1934). Since de Sitter was in ill health, a major topic was the search for a successor. (He didn't die until much later, when he was succeeded by Hertzsprung, and remained productive as a scientist, even though his health had worsened after a 1919 operation for gall-bladder stones and as a result of tuberculosis.) Both Kapteyn and de Sitter recognized the importance of reorganizing the Observatory and increasing the director's salary (which Kapteyn thought to be so low that no-one from outside the Netherlands could be recruited). The younger de Sitter's contribution[4] is concerned mostly with this reorganization and the politics of filling the positions, all very interesting, and that story ends with one vacant position since Anton Pannekoek had been passed over because of his left-wing political views. [See thesis abstract on p. 269 — Ed.] As a result, the elder de Sitter persuaded Kapteyn to accept a position as assistant director on a one-day-per-week (formally 1/6) basis. Kapteyn accepted, saying in a letter from 1920 June 13 that "[w]ith a [yearly] salary of three thousand guilders, I will be completely satisfied." So would I: 3000 guilders in the first two decades of the 20th Century had a purchasing power of about €40 000 today[5], not bad for one day per week. In 1900, Kapteyn received 6000 guilders as his annual salary as professor. By 1910, his annual income was 8500 guilders; because he had reached the maximum professorial salary, the difference must have been due largely to payment for his summer work at Mount Wilson[6]. In the same letter, Kapteyn demonstrated prescience by noting that Oort, if he first takes his doctoral degree in Groningen (which he would do in 1926), if his thesis "attracts the attention of astronomers, and if he then works for some time in Leiden as assistant and there too continues to develop outstanding qualities, then he could be your man." Oort became lecturer in Leiden in 1930 and professor in 1935 (upon the death of de Sitter) and director from 1945 until 1970. (Oort died in 1992. ADS lists 229 publications, 83 of which are after 1970.)

I enjoyed the symposium in Groningen on Kapteyn, which featured speakers such as Adriaan Blaauw, Michael Feast, Robert W. Smith, Owen Gingerich, Gerard Gilmore, Michael Perryman, Piet van der Kruit, Maarten Schmidt, and Lodewijk Woltjer. It was jointly organized by van der Kruit and Klaas van Berkel, the latter from the department of history at the University of Groningen. When, as often at conferences, there was discussion about the deadline for proceedings contributions, there was a bit of a clash of cultures when the historians arrived with their contributions already in final form and literally read their papers at the symposium.

Yours faithfully,
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REVIEWS

The Spacefarer's Handbook: Science and Life Beyond Earth, by Bergita Ganse & Urs Ganse (Springer), 2020. Pp. 295, 23·5 × 15·5 cm. Price £19·99/$27·99 (paperback; ISBN 978 3 662 61701 4).

Although hundreds of professional spacefarers have experienced the weightlessness of outer space and looked back at our beautiful blue planet, at the time of writing they have been joined by only a few wealthy adventure-seekers. The ranks of these space tourists are likely to be swelled in the years to come as companies such as Virgin Galactic carry paying volunteers above the atmosphere, and entrepreneurs such as Elon Musk strive to turn offers of trips around the Moon and Mars into reality.

This book is intended as a general introduction to space travel for anyone contemplating such an adventure. Each chapter provides a general summary of the main topics that any non-professional astronaut might want to learn more about. These include how to become a spacefarer, the design and construction of spacecraft, how to fly a spacecraft, living in weightlessness, and space medicine. The final chapter gives a fairly brief overview of future prospects for exploration and colonization. However, the authors also introduce topics such as space law, terraforming, astrobiology, and extraterrestrial life. Although the Moon and Mars are rightly seen as the primary destinations for future human expeditions, even more hostile and remote worlds are touched upon, including Io, Titan, and Pluto.

Many examples are given from the Apollo and Space Shuttle programmes, but discussion of projects led by companies such as Virgin Galactic and SpaceX would be more relevant as commercial enterprises play an ever greater role in today's rapidly changing space industry. The lists of references at the end of each chapter are also surprisingly short and not very helpful. However, this is a well-written, useful — and sometimes light-hearted — introduction for anyone who wants to know more about humanity's efforts to leave planet Earth. — Peter Bond.

Human Enhancements for Space Missions: Lunar, Martian, and Future Missions to the Outer Planets, edited by Konrad Szocik (Springer), 2020. Pp. 291, 24 × 16 cm. Price £99·99/$139·99 (hardbound; ISBN 978 3 030 42035 2).

Sixty years ago, Yuri Gagarin became the first human to escape the bonds of gravity and experience — for a short time — the alien environment of outer space. Since then, hundreds of people have followed in his footsteps, although only 12 have so far set foot on another world. This select group will soon be joined by pioneers from the United States, China, Europe, and elsewhere. After a return to the Moon, the next destination in humankind's journey into the cosmos will be Mars, another world with an environment far more hostile than Antarctica.

For decades, visionaries have foreseen the establishment of human colonies on distant worlds, with the creation of permanent habitation, agricultural greenhouses, scientific-research facilities, and mines. This all remains a long way off, but for the contributors to this book, such steps are only one aspect of humanity's expansion. In its 19 chapters contributed by different authors, the book addresses the general theme of human enhancement for the purposes of long-term human space missions to the Moon, Mars, and beyond. The authors discuss the pros and cons of the "enhancement" — mostly biological — of astronauts living and working in hostile space environments, although ethical and theological aspects are also addressed. Among the possibilities discussed are genetic modification, use of nanotechnology and nanoprobes, hibernation on long journeys, and anti-aging therapy.

Throughout the book, human enhancement in space is regarded as an option that must be seriously considered if our species is to expand its presence across the Solar System in the decades ahead, although various ethical, religious, and moral objections are also raised. The book is based on the premise that humankind will not turn its back on the opportunity to explore and colonize other worlds, deciding instead that the benefits outweigh the costs and risks. This is an on-going debate and one that is likely to intensify if humans continue to strive to become a truly multi-planet species. — Peter Bond.

A Cabinet of Curiosities. The Myth, Magic and Measure of Meteorites, by Martin Beech (World Scientific), 2021. Pp. 580, 23 × 15 cm. Price £115/$128 (hardback; ISBN 978 981 122 491 1).

One of the obvious problems of astronomy is the lack of the tactile element. You can look, but you cannot touch. An exception is the meteorite. These rocky and metallic gifts from the cosmos fall to Earth, can be collected, and then examined in intricate isotopic, physical, chemical, and mineralogical detail. They provide us with a nuanced insight of the dawn of our planetary system. The fireball that heralds their arrival can be frightening and their impact with the Earth's surface can be disastrous. Meteorites are also newsworthy, much sought after, and expensive.

Martin Beech is an emeritus professor of astronomy at Campion College, University of Regina, Saskatchewan, Canada. He has researched extensively into the meteorite-fall phenomena, the trails and light-curves of the incident body as it is retarded in our atmosphere, and the strewn fields of the fallen meteorite fragments. He has also investigated impact statistics, fireball archives, and the meteorites' asteroidal parenthood. Beech is an enthusiastic meteorite fan, and this enthusiasm shines from every page of this impressive book. It is a superb introduction to the subject, being comprehensive but not overburdened with minutiae. What I liked especially was his emphasis of the relationship between meteorites and humanity. We read of meteorite shenanigans: when Robert Peary came across some huge iron meteorites in Greenland he did not dispute their ownership, he simply stole them and then sold them to an American museum. Then there is the acquisitiveness of the collectors, the confusion of early scientists as to origin, the insistence that meteorites hold the vital key to planetary origin, and the surprise that a small fraction of our museum collections actually came from the Moon and Mars. Terrestrial impact cratering looms large, and I loved the sections that reviewed the effects of meteoritical phenomena on artists and science-fiction writers. Beech stresses the statistical basis of the subject. If, for example, you find a strange rock in your garden there is a 1 in 400 chance of it being a meteorite. Their rarity is mitigated by the fact that 100 000 with masses greater than 1 kg hit Earth every year, the vast majority being lost.

As an introduction to the subject this book has the level just right. Where equations are needed they are given, and there are plenty of references, and a multitude of illustrations and graphs. And the book also does not shy away from the more contentious topics. Lithopanspermia, electrophonic sounds, megacryometeors, hylomorphism, the late heavy bombardment, sonic booms, and sulphurous smells all feature.

I recommend this book very strongly. Rather unusually for a science book, terms like 'great read' and 'page turner' actually apply. — David W. Hughes.

An Introduction to Comets: Post-Rosetta Perspectives, by Nicolas Thomas (Springer), 2020. Pp. 503, 24 × 16 cm. Price £64·99/$89·99 (hardbound; ISBN 978 3 030 50573 8).

My shelves are groaning under the weight of comet text-books. Two particular volumes stand out. A collection of reviews from 1982 edited by Wilkening called *Comets* is from the pre-spacecraft era, a time when we had never seen a comet nucleus and could only speculate on what it might look like. The sequel *Comets II* was published in 2004. It was twice as heavy and made use of all of the post-*Halley* science available at the time. Much of the basic understanding of comets hadn't changed between the two volumes but a lot of the detail had. Both of these volumes are very worthy but a hard slog for the general reader. A more approachable read was Brandt & Chapman's *Introduction to Comets*, also from 2004. By this time spacecraft fly-bys and advanced ground-based instruments had started to give us a detailed understanding of these mysterious visitors.

This new book is a very welcome and timely addition to the collection. It makes use of the tremendous amount of science arising from the *Rosetta* mission to Comet 67P/Churyumov–Gerasimenko, and it brings up to date our understanding of these, sometimes frustrating, but always fascinating frozen objects that represent the left-overs from the Solar System's formation. The book goes into a lot of detail, some of it at PhD level, but since it is written by a single author, it all fits together logically and so it can be read and understood by more-general readers.

There are lots of equations, but most of them are not too frightening and the book has something which I wish other authors would adopt. It uses a standard notation throughout and has a comprehensive table of symbols with a cross reference to the introducing section so that you don't need to spend hours searching the text to find out what 'Afρ' means.

The author was closely involved with much of the *Rosetta* science and it shows. This is an excellent, comprehensive, and up-to-date description of comets, and I thoroughly recommend it. — Nick James.

Asteroids, by Clifford J. Cunningham (Reaktion), 2021. Pp. 190, 23 × 17 cm. Price £25 (hardbound; ISBN 978 1 78914 358 4).

This is one of the series of astronomical books that follows on from the earlier (and generally successful) series subtitled 'Nature and Culture' from the same publisher. Regrettably, the astronomical works have been rather a mixed bag. Although the author undoubtedly knows his subject, the information is not particularly clearly presented. The description of Near-Earth-Objects (NEOs) is a case in point. Although we are told that there are four classes of NEOs: Apollo, Amor, Aten, and Atira, the situation is immediately obfuscated by mention of the Ajuna and Alinda dynamical classes. Although the criteria by which objects fall into one class or another are described, the descriptions are rather muddled, and anyone not fully familiar with the subject will find it difficult to understand why an object is considered to belong to one particular class, rather than another.

Unfortunately, the author allows his own personal prejudices to show. He speaks disparagingly of the IAU and its advocacy of certain terms, such as 'minor planet', rather than 'asteroid'; and the use of 'dwarf planet' and 'small solar-system bodies'. 'Bode's Law' is discussed, but there is no mention of the fact that the 'Law' was originally proposed by Johann Titius and is known to many as the 'Titius–Bode Law'. There is a distinct tendency to fail to explain topics, and instead rely upon references to published journal papers. (There are no explanatory 'Notes', and this deficiency is extremely annoying at times.) As an example, we may take the assertion that the concept of the Late Heavy Bombardment has been disproved. On page 84, the author states "By 2019 the model had collapsed under the weight of evidence to the contrary." A reference is given to a paper by Hartmann — 'History of the Terminal Cataclysm Paradigm' (*Geosciences*, **9**, 285, 2019), but we are never told what this 'evidence' is. (It presumably relates to the selective sampling at the sites of the *Apollo* and *Luna* landings, and the dates of impacts derived from those samples.)

The author accepts without hesitation the significance of the Chicxulub impact, and on page 85 makes the rather surprising statement that "debris from the impact travelled through the solar system, landing on Mars, Saturn's moon Titan, and Jupiter's moons Europa and Callisto, in the process perhaps seeding those objects with living microbes from Earth." We have enough difficulty in proving the existence of debris from the impact on Earth, and I seriously doubt that we have any evidence whatsoever for material that has landed on other bodies in the Solar System.

Page 50 shows a photograph of the asteroid 6478 Gault, showing it with two tails. In comets, of course, two tails may be ascribed to dust and ions, but there is no mention of why Gault should show two such distinct tails. Instead we are informed that Gault's rotation has been accelerating for perhaps 100 million years, possibly as a result of the Yarkovsky effect. Sorry–YORP: Yarkovsky–O'Keefe–Radzievskii–Paddick effect.

Discussion of Trans-Neptunian Objects is reasonably comprehensive although little mention and discussion is made of the extreme inclination of some of these objects.

There is a puzzling statement on page 108: "... such ancient craters, called crayons, exist on stable continental cores." I know that 'stable continental cores' are referred to as 'cratons', but 'crayons' for impact craters?

I fear that I cannot agree with the statement on the blurb that this is "The most engaging book ... on asteroids, ... and should be on the shelf of every person interested in asteroids." For some details of asteroids, I would still turn to the very old 1979 volume *Asteroids*, edited by Gehrels, in the original University of Arizona series. — STORM DUNLOP.

Introductory Notes on Planetary Science: The Solar System, Exoplanets and Planet Formation, by Colette Salyk & Kevin Lewis (IoP Publishing), 2020. Pp. 190, 26 × 18·5 cm. Price £75 (hardbound; ISBN 978 0 7503 2210 2).

This is an undergraduate textbook based on courses given at Vassar College, Poughkeepsie, and John Hopkins University. Let me start by introducing some more adjectives. As well as 'undergraduate' I should say science-major, excellent, well-written, well-referenced, well-illustrated, honed, thorough, concise, and well thought out. It is the sort of textbook you write after you have given the course a good few times, and you know what you are up to. It is also the text book you write if you really understand students. When it comes to university courses, with their lectures, home-works, tutorials, and final examinations, your typical student just needs to know what is required. They need a 'goldilocks' text book that is not too thin and not too thick, not too hard and not too easy, but just right. And this is exactly what Salyk and Lewis have provided. And our planetary world should be extremely grateful.

The book assumes that you are up to university first-year standards in mathematics and physics. It then divides the subject into nine topics. We start by defining the term 'planet', and then considering the form of the solar energy source. Chapters three and four consider orbits and the restricted three-body problem. We then have a detailed discussion of extrasolar planets. Chapters six, seven, and eight review planetary interiors, surfaces, and atmospheres. The book ends with a comprehensive chapter on planetary formation. The text abounds with terms like geostrophic balance, Hadley circulation, Jeans' mass, oligarchic growth, Toomre stability criterion, planetary migration, tidal circularization, hot Jupiters, and mean-motion resonances. I recommend it most strongly. It is spot on. I did however have one little caveat. It skates over the mysteries. It gives the impression that our understanding is nearly complete. I always liked to tease my students with a few left-field questions. Was Mercury once a satellite of Venus? Why does Venus spin so slowly? Why has Earth only one moon? Why do Jupiter and Saturn go round every ten hours? Why has Uranus been tipped over? Why does the system end at Neptune? How many comets are left? Does every planetary system have an asteroid belt? Why have we only got eight planets? How does planetary origin depend on stellar mass and singularity? And so on. At least it gives them the impression that there is still plenty of work to do — DAVID W. HUGHES.

The Physical Processes and Observing Techniques of Radio Astronomy: An Introduction, by Thomas G. Pannuti (Springer), 2020. Pp. 393, 23·5 × 15·5 cm. Price £44·99/$59·99 (paperback; ISBN 978 3 319 16981 1).

Radio astronomy is increasingly accessible as part of the undergraduate teaching curriculum, both as a practical activity and as part of the broader study of astrophysics. This book sets out to provide an undergraduate-level introduction to the physics, astrophysics, and observing techniques of radio astronomy — an ambitious goal in 400 pages and one that necessarily requires a rather superficial approach in some areas since the assumed starting point is almost no knowledge of observational astronomy or the relevant physics beyond high-school level. Nevertheless the book does cover most of the key topics, and the student will find chapters on basic astronomy and physics, radio observations, and Solar System, Galactic and extragalactic radio astronomy which would all be of value to the intended readership. The radio astronomy presented is in many respects that of the first decade of this century — while *ALMA* does get a mention, the reader will look in vain for any mention of *MeerKAT* or *LOFAR*, still less the *Square Kilometer Array*, and developments such as wide-band continuum observations are passed over. Some other important topics are absent — for example, there is no mention of radio surveys, which underpin all of the discussion of astrophysical objects in later chapters, and in the section on radio observations, although Fourier transforms and the convolution theorem are presented to the reader, there is no explanation of the process by which measured visibilities from an instrument like the *VLA* are turned into images. More seriously, the book is marred by a comparatively large number of typographical and factual errors, many minor, but some, as in the discussions of cosmological look-back time, broad-band AGN spectra, Doppler boosting or ultra-high-energy cosmic rays in the extragalactic chapter, passing on quite significant misunderstandings to the reader. In its effort to cover all topics in a small volume, the book can also be unevenly paced in its science sections, spending pages on speculative interpretation while skipping over basic observational facts. On the positive side, it is well illustrated with colour figures, has a good set of sample problems with answers, and is significantly cheaper than the two-volume offering for the same undergraduate market by Marr, Snell and Kurtz (CRC Press, 2016). For those looking for a short one-volume text, it is certainly worth considering. — MARTIN HARDCASTLE.

Seeing the Unseen: Mount Wilson's Role in High Angular Resolution Astronomy, by Harold A. McAlister (IoP Publishing), 2020. Pp. 279, 26 × 18·5 cm. Price £30 (hardbound; ISBN 978 3 7503 2206 5).

At the turn of the 20th Century astrophysics was in its infancy. Until the application of the spectroscope stars were regarded at point sources in the sky, little was known about sizes or masses. Remarkably the concept of measuring stellar diameters first appears to have been noted by the French physicist Armand Hippolyte Louis Fizeau in 1851, but it was not until 1867 that the idea of measuring a stellar diameter was made the object of a mathematics prize. An attempt on Sirius by Edouard Stephan in 1873 failed because the star's diameter was far below the resolution of the instrumental set-up which he used (a pair of slits on an 80-cm reflecting telescope).

The breakthrough was made by Albert Michelson who realized that the aperture required to resolve stellar diameters was in the region of tens of feet, and he came up with an experiment to place two flat mirrors 20-feet apart at the top of the 100-inch reflector on Mount Wilson. The beams would then be brought together on to a pair of slits placed in front of an eyepiece located near the declination axis. In 1920 December the diameter of Betelgeuse was determined.

These are the basic facts but the author has greatly expanded the details of those observations, and those involved in them. We get to know more about Michelson and Francis Pease, John Anderson and Paul Merrill, and how the observations were made. For instance, once the telescope was slewed to the target the flat mirrors needed to be adjusted in order to search for the fringe patterns, so a man was placed on the interferometer bar at the top of the telescope. Pity the poor individual, one John Kimble, who spent the night in the dark and the cold — they were tougher in those days.

Michelson's setup could also be used to measure precisely the relative positions of binary stars, notably Capella. Such was the accuracy achieved on the star by Anderson and Merrill that, interpolating a 2015 orbit back to 1920 (about 335 orbital periods), the residuals were only about 1 degree in position angle and 2 milli-arcseconds (mas) in separation, which, during the orbital cycle, ranges between 40 and 60 mas.

Between the 1920s and 1970s there seemed little appetite for stellar interferometry apart from a few ingenious instruments, including those used by William Wickes and Willet Beavers, but the most productive of which was William Finsen's eyepiece interferometer. The development of speckle interferometry by Labeyrie started a renaissance in high-angular-resolution imaging, led prominently by the author, followed by the development of ground-based separated-aperture imaging — the *NPOI* and Mark III instruments in the USA, *SUSI* in Australia, and most recently the *CHARA Array* at Mount Wilson, again led by the author, nicely completing the circle.

I looked at a recent paper using *CHARA*[1] data, as the array is now operating using all six of its 1-metre mirrors, and which nicely demonstrates the remarkable power of this instrument. Six measurements of the relative positions of the components of the Wolf-Rayet binary WR133 over a year has yielded a visual orbit, only the third known for a WR system, which, in combination with a *Gaia* EDR3 distance of 1·86 kpc, yields masses of 22·5 solar masses for the O9 supergiant and 9·6 solar masses for the WN5 component, the errors in the masses being 15% in each case. Each position in the orbit is determined with a quoted error of about 4 micro-arcseconds. For comparison, the *CHARA* baseline is up to 330 metres, some 50 times greater than Michelson's value, whilst the smallest resolved separation of the components of WR133 was just 0·6 mas.

This volume is part of a large batch of new titles from IoP Publishing. The prices seem to be trimodally distributed; fortunately this book is in the lowest category. There is no index. The page size is slightly larger than usual, possibly to help accommodate the many photos and diagrams which it contains. Even so, the size of some of the images does not do the author justice. Nevertheless, this is a compelling description of a specialized, but fascinating, area of observational astronomy, which also pays full attention to the human aspect, and it is written by an enthusiastic authority who has spent a lifetime at the cutting edge of his subject. — Robert Argyle.

Reference

(1) N. D. Richardson *et al.*, *ApJ Letters*, **908**, 3, 2021.

Cosmic Messengers. The Limits of Astronomy in an Unruly Universe, by Martin Harwit (Cambridge University Press), 2021. Pp. 380, 25 × 17·5 cm. Price £29·99/$39·99 (paperback; ISBN 978 1 108 84244 0).

This is a weighty tome, both literally (910 g) and figuratively, with ambitious goals. In his preface, Harwit explains that this is the concluding volume in a trilogy, the first two being *Cosmic Discovery* (Harvester Press 1981, republished by CUP in 2019) and *In Search of the True Universe* (CUP 2014). All three volumes deal with broad issues, with the first two addressing, respectively, how new astronomical phenomena are often unveiled by the advent of new instrumentation and how new approaches in theoretical physics have led to new astronomical insights.

In the current volume, Harwit studies how information reaches us from across the Universe in this age of multi-messenger astronomy. He poses two fundamental questions: "How much will it cost, and how long will it take, to discover the major astronomical phenomena [that] available cosmic messengers may ultimately reveal?" In his attempt to answer these questions he tries to compile a list of instruments needed now and in the future to observe most of the useful information available in the Universe. For convenience he calls this the Cosmic Toolkit and the first part of the book reviews the messengers we currently know about and how they may be detected; an important theme is the distinction between the messengers and the messages they convey. The data are more secure than the interpretation, which has evolved as more data have been collected from more messengers.

Another important point, discussed in the second part of the book, is that the known messengers have bounded energies. In other words, each messenger is detectable only over a particular range of energies, the limits being imposed by basic physical processes. The different ranges of energy are summarized in Fig. 3.16, with messengers grouped into four categories. Energy bounds for five particular messengers are given in Table 3.1. Part 2 also discusses gravitational waves, starting with early attempts at direct detection and working through the detection of black holes, micro-quasars (*e.g.*, SS433), and binary pulsars to the final detection in 2015 by the *Advanced LIGO* facility and its implications for black-hole and neutron-star mergers. Gravitational lensing is also discussed in detail.

Part 3 moves on to a different approach, historically tracing instrumental achievements to date and listing fundamental limits on the information that any known messengers will ever be able to transmit. He starts with a discussion of the detection of what we now call exoplanets. The pioneer in the search, Peter van de Kamp, chose what is perhaps the hardest of three methods of detection: direct astrometric detection of movement of an image in the plane of the sky. Sadly, his telescope had too little angular resolution to produce a reliable result and his claimed two planets around Barnard's star are now known not to exist. Bizarrely, the first planets to be discovered were around a pulsar, revealed by slight periodic variations in the pulse timing. But planets around more normal stars were first detected in 1995 by the third method: periodic variations in the radial velocity of a star. This is now one of the main methods used for detecting exoplanets. The rest of this section of the book is more general, examining the kind of information that can be provided by any class of messenger and arguing that the five parameters that he has identified specify the design requirements for the instruments and observations needed to detect them. The development of electromagnetic detection from 1919 to 2019 is neatly illustrated in Fig. 6.1, which shows the range of wavelength and angular resolution in six different years, 20 years apart. The wavelength range now covers essentially all that is possible, with interstellar absorption marking a boundary to the radio range and pair production preventing detection of very-high-energy gamma rays.

This leads on naturally to a discussion of the bounds of discovery space. To quote Harwit (p. 212): "… the basic laws of nature will render instrumental improvements beyond certain bounding limits futile, simply because cosmic processes do not generate or else transmit information reliably beyond those bounds." He then goes on to look in more detail at issues of reliable transmission, with an interesting digression into the discovery of fast radio bursts, and issues of resolving power of all three kinds (angular, temporal, and spectral), both for electromagnetic messengers and for other carriers. He concludes that the full Cosmic Toolkit may be available within the next couple of centuries.

The fourth and final part is called 'The Pace of Progress'. It sums up progress to date, considers the expense both of providing the observational facilities needed and of dealing with the consequential sociological changes, and makes projections into the future. He begins by distinguishing between 'golden events', single events that open up new avenues of research, and the 'logic tradition', where new results emerge only after a great deal of work on the interpretation of data, such as large surveys. Table 7.3 summarizes the major astronomical discoveries since 1979, labelling each of them as a golden event or in the logic tradition. In the next chapter, Harwit then uses current discoveries and arguments from statistics and probability to conclude that there may be a limit of some 90 distinct major phenomena that can be discovered by observation, 60 of which are already known. Given the size of the current international workforce, and the resultant acceleration of the rate of progress, this limit might be reached in a couple of centuries. The final chapter discusses how and why the expansion of the workforce occurred and the funding and other problems that the increasing costs of large projects have produced. He explores in some detail the sociological changes arising from large projects and from the growth of a large group of expert young researchers without permanent posts. The book ends with a variety of short sections, including a brief discussion of extra-terrestrial intelligence.

A nice feature of the book is the historical material and the series of short pen-portraits of people who have contributed to the development of the subject. These are scattered through the text in the places where their contribution is described. The book uses cgs rather than SI units, which is a pity but perhaps inevitable. Because Harwit is trying to cover all important points, crossing every *t* and dotting every *i*, the style comes across as dense and a little laboured in places. However, these are minor points and, overall, this is an interesting and challenging book, albeit with some pessimistic conclusions. Will there be any worthwhile problems to work on in a few centuries' time? — Robert Connon Smith.

Astronomy's Quest for Sharp Images: From Blurred Pictures to the Very Large Telescope, by Pierre Léna (Springer), 2020. Pp. 271, 23·5 × 15·5 cm. Price £22·99/$29·99 (paperback; ISBN 978 3 030 55810 9).

This slim, well-written book contains at least all that the non-specialist might need to learn about the developments and achievements of adaptive optics in astronomical telescopes. It follows Léna's own involvement through all the relevant stages as he encountered them, from the nascent years right up to the present, with even some ideas about the near future of this specific branch of astronomical science. In style, layout, and language it is best suited to the armchair reader rather than a class-room student, though the information is all there. I was a bit puzzled as to its intended readership until I came across Springer's own description of this series: "It bridges the gap between very basic popular science books and higher-level textbooks, providing rigorous yet digestible forays ... it goes beyond a beginner's level, introducing you to more complex concepts that will expand your knowledge of the cosmos". That puzzle was largely triggered by the tendency of Léna's story to hover between the poetic and the dramatic, and by its near insistence that all the achievements were French accomplishments (if augmented on occasion by a few German ones). And it is a story, not a textbook, constructed more as an elaborate journal than as a scientific treatise, and as such it is indeed both rigorous and digestible, though inevitably a little slanted towards the French side of the Atlantic.

Léna is a central figure throughout this drama of what he terms "the war on blur", or attempts to overcome the limitations imposed by both optics and atmospheric seeing, and the people who are mentioned were known personally to him. One certainly gets, and can appreciate, strong elements of 'story' as the battle to overcome this dual dragon is finally won. The injections of drama ease the turgidity of a purely scientific account, though some may be a little fanciful, such as the magic of a clear dusk at Paranal (Chile) and the rich potential it offered to visiting astronomers, or the description of Labeyrie (whose laboratory took the form of a 'boule' at the Plateau de Calern Observatory in SE France), which attributes to ecological empathy his riding somewhat romantically to work on a horse of endangered species, while the story circulating the observatory featured an altercation with his neighbour who had then parked his car in an obstructive position. At times the excitement at new ideas and new results does seem a little forced, and if everyone with whom Léna came into contact truly was 'brilliant' as stated, then that is what it took to win this aggressive battle in order to obtain truly sharp images with a ground-based telescope.

The language is fluent, the writing clean and clear, and the assembly of unfolding facts almost chronological. It concludes with two appendices (one listing distances and angles characterizing observed image sizes, the other giving thumbnail summaries of the telescopes and instruments mentioned in the book), an eight-page bibliography, a helpful six-page glossary (so you need not get out of your armchair), and a five-page index to the *dramatis personae*. Moreover, from his Paris professorship and a veritable host of responsibilities among astronomical researchers in Paris, Léna also shares his deep pleasure in teaching a generation of students who are keen to learn. It's a good read for both astronomer and layperson, even if the *Marseillaise* does sound a little too strongly. — ELIZABETH GRIFFIN.

Common Envelope Evolution, by Natalia Ivanova, Stephen Justham & Paul Ricker (IoP Publishing), 2020. Pp. 176, 26 × 18·5 cm. Price £120 (hardbound; ISBN 978 0 7503 1561 6).

Common-envelope evolution is an important phase in the life-cycle of binary stars, if the orbit is sufficiently small for the atmosphere of one star to engulf the other when the former evolves off the main sequence. The binary orbit can shrink, the common envelope can be ejected, and mass transfer can take place between the components. The mechanism is important in the production of cataclysmic variables and novae. There is an interesting range of possible outcomes from the process, involving various combinations of degenerate objects, some of which underpin the processes of type-Ia SNe and kilonovae. Therefore knowledge of the physics of the phenomenon is of importance to a number of branches of astronomy and astrophysics.

While there is an extensive literature of common-envelope-evolution papers in astrophysics journals, to my knowledge there has been no comprehensive textbook that collects this information together, until now. This volume presents itself as a graduate text, but will be useful to anyone who wants a convenient reference to the collective knowledge of the field. The various chapters cover the underlying physics and the separate stages of the evolutionary processes. There is also a chapter devoted to the numerical methods and computer codes that are needed to model the complex physics, coupled with a useful evaluation of how far these codes can be trusted. Every chapter ends with a comprehensive bibliography. Overall, this book is an excellent and handy companion for astrophysicists who need to understand common-envelope evolution in relation to their research.

In the modern world, one question to consider is how best to access this material. The headline price of £120 may seem somewhat eyewatering for a fairly slim volume. However, if it is central to the work of an individual, it is probably worth the investment to have a personal copy, rather than rely on access to it from a library. I would also note that it can be found on-line for less than £100. A Kindle edition is a further £20 cheaper. The publishers make it available as an E-book for £99.

Whatever medium you prefer, this is an excellent book, written by leading experts in the field. It is thorough and accessible to both graduate students and researchers. I recommend it wholeheartedly. — MARTIN BARSTOW.

The Cosmic Evolution of Galaxy Structure, by Christopher J. Conselice (IoP Publishing), 2020. Pp. 149, 26 × 18·5 cm. Price £120 (hardbound; ISBN 978 0 7503 2668 1).

This interesting monograph provides a personal view of the links between observed properties of galaxies, in terms of both their internal structures and constituents, and their relationship with larger structures and neighbours, in order to try to infer details of the build-up of stars and the recycling of gas within the observed galaxies, and their ultimate appearance today.

The advocacy for extrapolating from quantitative non-parametric measurements, used to describe galaxy morphology using a few numbers, to address the global ebb and flow of matter into galaxies provides an interesting discussion, distinct from the common picture of matching simulated universes to the results of the deepest observations made in cosmological survey deep fields using the *Hubble Space Telescope*, and *Webb*, *Rubin*, and *Roman* telescopes in the foreseeable future. The clear discussion of the changes in appearance and selection effects of imaging as redshift increases is nicely presented, and discussing the potential utility of low-surface-brightness, low-mass galaxies for probing differences in the formation process in both the densest and sparsest regions of the Universe was interesting, along with the prospects for using diffuse starlight around galaxies to reveal more about their histories.

That there remain potential 'unknown unknowns' argues for the likelihood of exciting new discoveries when deep fields from the next generation of telescopes become available; however, the prospects for *Webb* revealing more about the conditions under which distant active galaxies fuel, shine, and drive feedback, and especially to check on the role of obscuration, allied with *ALMA*, in order to ensure that the visible morphology really can be used to reveal the true distribution of emitted light and constituent matter within, might add to the complexity, and require additional care in making these inferences. That the *Square Kilometre Array* offers to reveal much more about the gas involved in the process of galaxy evolution, along with the potential additional and complementary probe of active galaxies and the hot circumgalactic medium to come from *Athena* flying in the 2030s, offer to give an intriguing look back at these predictions once the forthcoming dust settles. — Andrew Blain.

Introduction to the Interstellar Medium, by Jonathan P. Williams (Cambridge University Press), 2021. Pp. 209, 25 × 18 cm. Price £39·99/$49·99 (hardbound; ISBN 978 1 108 48080 2).

For many decades, it has been recognized that the study of the interstellar medium of the Milky Way galaxy and of external galaxies is not only a vital and essential component of astronomy, but is also an excellent platform on which to base a lecture course that explores physics operating in an unfamiliar and extreme environment. Consequently, many courses have been developed and several appropriate textbooks have been provided to meet these twin needs. This book is the latest and excellent example of such a textbook; it has grown out of lecture notes that Jonathan Williams wrote during two decades of graduate teaching at the University of Hawaii. It is aimed at courses for advanced undergraduates or beginning postgraduates. It will also surely meet the writer's hope that "the book's broad perspective will help more seasoned researchers to make new connections".

The range of the contents of this new book is fairly standard for such books. A survey of essential physics is presented concisely, followed by brief chapters on interstellar dust, and on atomic, ionic, and molecular regions. A chapter on gas dynamics enables star formation and galactic structure to be introduced.

The book is thoroughly illustrated with figures, many of which have been specially created by the author, using freely-available databases. These figures are therefore perfectly attuned to the needs of the accompanying text. Each chapter contains notes that lead the reader to other texts (sometimes more advanced) and to some relevant research papers. Thought-provoking questions are supplied at the end of most chapters.

I recommend this book without reservation. It will meet the needs of postgraduates perfectly, while being also accessible — if fairly demanding — for undergraduates. The book is well-written and produced. — David A. Williams.

Angelo Secchi and Nineteenth Century Science: The Multidisciplinary Contributions of a Pioneer and Innovator, edited by Ileana Chinnici & Guy Consolmagno (Springer), 2021. Pp. 381, 24 × 16 cm. Price £109·99/$149·99 (hardbound; ISBN 978 3 030 58383 5).

This book arises from the celebration of the bicentenary of Angelo Secchi's birth and can be considered as a companion to Ileana Chinnici's 2019 biography recently reviewed in these pages[1]. To readers whose knowledge of Secchi is limited to his being a pioneer of stellar spectral classification, the wide range of his activities described here will come as a revelation.

First, in Part I, we are given biographical material and the context in which Secchi lived and worked. He became a Jesuit and lived through the Risorgimento. Owing to the hostility to the Jesuits at the time of the 1848 revolution, he left Italy for Stonyhurst College in England and then went to Georgetown College in the USA. There he became acquainted with local scientists, especially Matthew Maury, superintendent of the US Naval Observatory, who stimulated Secchi's interest in physical meteorology. With the re-establishment of the Papal Government the following year, the Jesuits were able to return to Rome and Secchi became Director of the Collegio Romano Observatory. He set about his task with vigour, establishing a new astronomical observatory on the roof of St. Ignatius Church. Risorgimento caught up with him in 1870 when Rome became part of the Italian state — although Secchi himself was highly regarded by the Italian authorities. The pressures and events are well described, especially in the chapters by Tanzella-Nitti and Chinnici. Secchi comes across as thoughtful and loyal.

Part II, making up about half of the book, comprises a series of essays describing the many different fields of Secchi's endeavours. Apparently his favourite topic was solar physics. Ermolli and Ferrucci report his work in a fine chapter. Starting in 1858, Secchi made regular observations of the solar chromosphere and prominences in Hα to study their relationship with sunspots and faculae on the solar disc. His observations covered the Carrington Event and he also noted the spectacular aurora visible from Rome and disturbances recorded by his magnetometers at the time. This chapter includes impressive images of sunspots and prominences. Another highlight is the account of Secchi's planetary observations which includes reproductions of the original drawings of Mars during the 1858 opposition. Not being a planetary observer, I appreciated learning that the blue–green tint given to the Martian maria was a well-known subjective effect from colour contrast with yellow or orange surroundings and that the true colour of the maria was nearer to reddish–grey.

Compared with the accounts of his other activities, Secchi's pioneering work on stellar spectroscopy receives surprisingly brief treatment. I would have liked to have read more on the evolution of his ideas about stellar spectra and expected more on their relation with earlier studies, including that by Donati, and his refutation of Norman Lockyer's suggestion that he had merely adopted Lewis Rutherfurd's classification scheme[2]. It would also be interesting to know more about Secchi's relationship with Jules Janssen (Paris). Secchi's first observation of the spectrum of a star was jointly with Janssen through the direct-vision spectroscope the latter brought with him on his visit to Rome in 1862. But Janssen was later barred from the Collegio Romano Observatory (p. 149). What went wrong?

Secchi was a good organizer as well as a scientist, which was manifest in his meteorological work. Besides theoretical studies, and the construction of an automated weather station, he organized the 'Telegraphic Meteorological Correspondence'. This network exchanged weather observations made at stations on both coasts of the Papal States, which Secchi coordinated at the Collegio Romano with a view to forecasting storms. Other chapters describe Secchi's use and development of instrumentation, and cover a diverse range of activities, including geodesy, the time service, sundials, lightning conductors, building standards, and provision of drinking water — Secchi was also an advisor to the Papal State.

The remainder of the book is taken up with subsequent events, including a rather lengthy account of the failure to build a monument to Secchi, and surveys of his correspondence. Altogether, there is an impressive amount of well-presented information in this book, but I would have liked more on Secchi's relations with other scientists. For example, there is mention of the dispute with Lorenzo Respighi and its effect on collaboration with other spectroscopists (p. 306) and some analysis of this would have been welcome.

The chapters in this book are fully referenced and often give original text as well as translations of quotations. There are numerous illustrations, many excellent. The book will fit well in a specialist library and is a good monument to Secchi, who loved his science, writing "We are not yet at the end of the wonders: we will be at the end only when we cease to study." — Peredur Williams.

References

(1) R. McKim, *The Observatory*, **141**, 33, 2021.
(2) J. B. Hearnshaw, *The Analysis of Starlight* (Cambridge University Press), 1986, pp. 63–66.

Sir James Jeans: Scientist, Philosopher, and Musician, Through Space and Time in the First Half of the 20th Century, by Christopher V. Jeans, incorporating material translated from a Russian biography by the late Alexander V. Kozenko (Cosmogonic Press), 2020. Pp. 294, 25·5 × 18 cm. Price £25 (paperback; ISBN 978 1 5272 7855 4).

James Hopwood Jeans was the eldest (born 1877 September 22 in Lancaster, England) and longest-lived (died 1946 September 16 in Surrey, England) of the trio, with Arthur Stanley Eddington (1882–1944) and Edward Arthur Milne (1896–1950), of British astronomers who dominated stellar astronomy in the UK for the first third or more of the 20th Century. If you feel inclined to add Fowler, you have to decide between Alfred (1868–1940, the first General Secretary of the International Astronomical Union) and Ralph H. (1889–1944, first to associate non-relativistic degenerate gas with white-dwarf stars, and the choice of S. Chandrasekhar to be his advisor when he came to England from India in 1930).

My copy of the book was a gift from the (living) author, sent to me upon the advice of Martin Rees. And, when I asked editor Stickland if he would be interested in a review of a biography of Jeans by his son, the response was that the only Jeans he knew was Sir James, and surely it wasn't possible ... ? But it was, and is. Christopher Victor (called Pandi or Pandy within his family) is the middle child of Sir James and his second wife, Susi Hock Jeans (born 1911 Vienna, d. 1993 Surrey, England, married 1935), an outstanding organist. If you are an old and faithful member of the International Astronomical Union, you perhaps heard her play for us all on the occasion of the General Assembly in Brighton, UK, in 1970, including music by William Herschel. Jeans's first wife, Charlotte Tiffany Mitchell (1877–1934, married 1907) had been a considerable heiress, which enabled the family to live in reasonable comfort through war and depression and allowed Sir James (as from 1928) to resign from his Cambridge lectureship in 1912 and hold only more-or-less honorary positions thereafter. Neither enjoyed entirely robust health: he had had tuberculosis in 1899 and heart problems from mid-life onward; she had some more-or-less chronic condition, conceivably congenital syphilis. Their one child, daughter Olivia, also died relatively young, in 1951, of some combination of arthritis, anorexia, and influenza, leading to pneumonia.

Now, what all is in this book? Lots of family lore; some absolutely fabulous photographs (the best I've seen of the first two Solvay conferences — sadly marred by the centre fold coming down the middle of each); a chronological exploration of Jeans as a scientist; and a chapter on his philosophical writing, roughly contemporaneous with Eddington's efforts in the same direction.

Let me assume that you know about the Jeans mass and length, the Rayleigh–Jeans formula for the long-wavelength side of a black-body distribution, his conclusion that the current conditions in binary-star orbits and stellar distributions in globular clusters and galaxies require at least 10^{12} years to come about, requiring a very old Universe and stellar energy coming from complete annihilation of matter, and instead pull out some gems that may not be familiar.

First there is a 1920 September letter from JHJ to Rutherford, then head of the Cavendish Laboratory in Cambridge, suggesting that he make an offer to Albert Einstein to beef up their mathematical-physics side, on the grounds that Einstein is quite likely to want to leave Germany quite soon (true) and that "You will never re-establish the school of math physics out of the material at present available in England."

Then there is a 1939 July hand-written letter from George Bernard Shaw "Dear Sir James," asking whether Newton might have been aware of "anything that his gravitational system did not account for or that contradicted it?" He has already been told by Eddington that the perihelion of Mercury won't do, because "this is post-Laplace". Shaw was preparing his play, *In Good King Charles's Golden Days*, for publication; Jeans attempted to sort out his thinking on the topic, and got a thank-you note dated ten days later. That particular play challenges astronomy in another way. The Queen accuses Charles of some enormous number of infidelities, which the King attempts to divide into events per day since their marriage, and gets the correction for Leap Years wrong. Late in life, Professor Raymond Arthur Lyttleton of Cambridge cherished a hand-written postcard from Shaw, thanking him for the correction of the "old author's errors" presumably in a letter that does not survive.

There are surprises: Jeans through most of his adult life was a 'national conservative' and firm eugenicist, who thought that the long-term best form of government would be neither democracy nor socialism, but during his college days he belonged to a "socialist-liberal mutual support organization for working people" called the Query Club at Trinity. Another 'fun' item: Jeans sat the Cambridge mathematics tripos the same year as G. H. Hardy, both after two years' study rather than three, and Jeans came equal second, Hardy only fourth. Perhaps less fun is a description of the three-way debates among Jeans, Eddington, and Milne at some of the RAS meetings around 1931 January. Milne, by slightly outliving the other two, got the last word on some of these items.

The volume has quite a lot of astrophysics (*etc.*) near the middle, including stellar structure (Jeans *vs.* Eddington *vs.* Milne) and stellar dynamics, with nucleosynthesis credited to yet another Fowler (William A.) and Hoyle (no mention of the Burbidges).

Chapter 9 (of 10) deals with physics and philosophy, deriving largely from Jeans' 1942 book of the same name. I already knew that Sir James, along with Sir Arthur, had aroused the ire of British philosopher L. Susan Stebbing (first woman to hold a chair of philosophy in the UK, at Bedford College, University of London, in the last decade of her relatively short life, 1885–1943). I therefore held off reading that chapter until I could get hold of a copy of her 1937 book, *Philosophy and the Physicists* (notice 1937 is well before 1942). She lists as "the Works that have Provoked this Book" two by Max Planck (1933, *Where is Science Going?* and 1936 *The Philosophy of Physics*); two by Jeans (1930, *The Mysterious*

Universe, and 1933, *The New Background of Science*), and no fewer than eight by Eddington (ranging in time from 1920, *Space, Time, and Gravitation* to 1933, *The New Background of Science*). There are, correspondingly, many more mentions of ASE than of JHJ through the text, but she clearly had no use for either (and one initially shudders to think what she would have made of Eddington's *Fundamental Theory*, which appeared only after her death and his; but 'unshudders' realizing that she would not have known how to attack a volume of mathematics).

I then tackled in alternation, pages of Jeans on Jeans' philosophy and Stebbing's attacks on both Sir James and his writings. She is, however, pretty much finished with him on page 44, concluding "The point of the foregoing criticisms is that these cloudy speculations of Sir James Jeans cannot properly be regarded as affording the common reader [her phrase for what we would now call the interested lay person] any clear information as to the philosophical implications of the new physics". She then goes on to hammer away at Eddington right through to page 279. The issues between them all include the existence of free will and something (that at least used to be) called realism *vs.* idealism. Susan, according to her Wikipedia entry, was an anti-idealist, but I am inclined to think that the real problem in her mind was that these mathematicians and physicists were calling part of what they did philosophy, while not having had sufficient professional training in the field to use words in the way she thought proper. If they had shied away from calling their thoughts philosophy and just written "This is the way I think about the world around us, and if I can manage to explain some of the aspects of quantum mechanics and relativity clearly, despite being required to use every-day words, you might be inclined to think the same way", Prof. Stebbing would not have found it necessary to write her 1937 book (of which I have only a Dover reprint, withdrawn from the library at some place called Clinton Hall, Oxford). Curiously, the present Jeans-on-Jeans volume cites the proceedings of a 1943 May 19 Symposium on 'The New Physics and Metaphysical Materialism' sponsored by the Institute of Physics, the Mind Association (in which Stebbing was much involved), and the Aristotelian Society, in which the participants were Jeans, Stebbing, R. B. Braithewaite, and E. T. Whittaker. I have not tried to find the report in the *Proceedings of the Aristotelian Society*, **43**, 185.

One final oddity: Pandi's book has a number of photographs of his father, including a few in his 40s. And suitable web-prowling will find for you a set of photos of Prof. Stebbing that resides in the National Portrait Gallery and records her toward the end of her life. I was astounded at how similar they look.

In any case, this volume is definitely worth having, especially for the family stories and the illustrations of family, friends, furniture, Favrile glass, and much else, surely not to be found anywhere else. Thus my deep thanks to the late Alexander V. Kozenko for writing the original Russian biography of James Hopwood Jeans and to Christopher Vincent (Pandi) Jeans for the expansion into this fascinating volume! —VIRGINIA TRIMBLE.

The Invisible Universe: Dark Matter, Dark Energy, and the Origin and End of the Universe, by Antonino Del Popolo (World Scientific), 2021. Pp. 276, 23 × 15·5 cm. Price £70/$78 (hardbound, ISBN 978 981 122 943 5).

While the title suggests a typical popular-science book on cosmology, in addition to the expected topics there is more on particle physics than is usual in such a book (though with the aim of providing background for exotic particles as dark matter). Also somewhat unusual for such a book is a chapter on possible ways in which the Universe could end. In a recent review[1], another book was described as part of a series of books "required to distinguish themselves from typical lecture notes in at least one of three ways: exceptionally clear and concise, an undergraduate introduction to a more advanced or non-standard topic, or a novel approach to teaching". Actually, every book should have one of those justifications, or one equally important, but I found that lacking here; similar information can be found in many books. Also, this book suffers from bad editing (mainly due to the lack of a native-speaker(-level) proof-reader) and lack of a uniform level; at the very least, more specialized terms should be briefly explained. I'm sure that the author knows what he wants to convey, but some readers will be confused. For example, the connection between geometry and destiny for universes without a cosmological constant (spatially closed ones (positive spatial curvature) will collapse in the future; spatially open ones (zero or negative spatial curvature) will expand forever) is mentioned several times, but also the fact that it no longer holds if the cosmological constant is allowed to be non-zero. Those familiar with cosmology will know what is meant, but they are not the target readership; a more structured narrative would help.

Since the review copy is a galley proof, presumably some shortcomings will be corrected in the final version (colour instead of black-and-white photos, especially since colours are referred to? Probably; English instead of Italian labels in some figures? Hopefully). There are several figures and the main text is followed by four appendices on inflation, structure formation, the Higgs mechanism, and neutrino masses; the book ends with a couple of pages of 'bibliography' consisting of books at a similar level (though with several typos and incomplete information). My impression is that the author enjoyed writing the book; one notices that it is not just a collection of information available elsewhere (though that information itself is, of course), but rather the author's own personal take (*via* emphases and narrative) on what is essentially a snapshot of current thinking in cosmology. I don't always agree (for example, non-particle dark-matter candidates are given short shrift), but agreement with the author is not necessary to recommend a book. However, typos, matters of style, language, and the uneven level render it less than a joy to read. — PHILLIP HELBIG.

Reference

(1) P. Helbig, *The Observatory*, **141**, 145, 2021.

Foundations of Quantum Cosmology, by Martin Bojowald (IoP Publishing), 2020. Pp. 335, 26×18·5 cm. Price £120 (hardbound; ISBN 978 0 7503 2458 8).

'Quantum Cosmology' is a term that has a long history, dating back to the 1960s' efforts of DeWitt, Misner, and Wheeler to apply quantum mechanics to the entire Universe. Thus there should be a wave function of the Universe, which encodes the probability of there being a particular global metric, to say nothing of the perturbations within it that make it possible for us to exist. Like many quantum problems this can be approached in part semi-classically: the early 1980s witnessed the creation of the revolutionary idea of inflation, where a suitably chosen scalar field could set up a homogeneous and flat expanding universe. Moreover, by applying the same tools of quantum field theory in curved space-time that had allowed Hawking to deduce black-hole evaporation, it was established by 1982 that quantum fluctuations in the inflationary era could seed metric fluctuations with properties consistent with the ones we infer from cosmological observations. These were historic advances, but major questions were left unanswered: inflation emerged out of some pre-inflationary initial conditions, and the semi-classical theory could not say how these originated. Subsequent efforts were made to address this within full quantum cosmology (*e.g.*, the Hartle–Hawking 'no boundary' proposal), but it is fair to say that the problem is not considered settled. In part, that is because the answer involves Planck-scale physics at the earliest times, and so a full answer is presumably bound up with a quantum theory of gravity. Despite decades of activity in string theory and alternatives, this is not yet in place.

But even if the subject of Quantum Cosmology is unfinished business, enough has been learned in the past half century to make it worth trying to summarize the current position for a new generation. I was therefore pleased and interested to see the new book by Martin Bojowald, as it promised to cover the issues that are left out of most cosmology texts. Bojowald has form, both as a productive researcher in this area, and as the author of a previous book on the subject (a 2011 *Lecture Notes in Physics* volume). In the event, though, I found the book difficult to get into, which I think is because of issues of balance. There is an opening chapter on classical aspects, but it is heavily compressed: seven pages on inflationary cosmology, and 14 pages on the whole of cosmological perturbations, which are our main observational window into matters that may relate to the quantum origin of the Universe. There then follow two long and relatively formal chapters on classical and quantum dynamics before Chapter 4 jumps into 'minisuperspace models', which is jargon for the quantum cosmology of models constrained to be homogeneous. One might hope to be able to read this just to get an overview of the important ingredients, but I found the treatment had a detailed character that prevented this. For example, at a certain point the reader is assumed to know what the Wheeler–DeWitt equation is, but I looked in vain for a major section setting this out systematically. Probably this material is hiding somewhere, despite its absence from the list of contents; but because the book lacks any index at all, it is hard to say. This is a major omission, and not one that is easy to understand when TEX allows you to make one semi-automatically. This is followed by a chapter on quantum gravity, which I might have expected would occur prior to applications. The structuring of this is also strange: different models are discussed in various subsections, often only a handful of pages, suddenly expanding to 23 pages for string theory. I thought there would surely be a separate section on loop quantum gravity, but again the term is absent from the contents although it is used in the subsection on 'Canonical Quantum Gravity' as if one is supposed to be familiar with it. The book closes with a chapter on inhomogeneous cosmologies, where again I found it difficult to extract a feeling for the key ideas.

So overall my feeling is that this is not a book I could recommend to students seeking further expansion of their understanding of the foundations of cosmology. It could probably be read with profit by someone with a good prior understanding of the subject, but not as a route into the subject. Apart from the lack of an index, it also has the pedagogical deficiency that there are no exercises (not even unsolved ones). From all these points of view, a much better alternative seems to be the 2017 *Classical and Quantum Cosmology*, by Calcagni (Springer). This is at a lower technical level, and probably seeks to serve a different readership. But for a cosmologist who, like me, does not work full-time on quantum issues, it makes a more approachable choice. — JOHN PEACOCK.

Multiverse Theories: A Philosophical Perspective, by Simon Friederich (Cambridge University Press), 2021. Pp. 214, 25 × 17·5 cm. Price £49·99/$64·99 (hardbound; ISBN 978 1 108 48712 2).

Few topics in cosmology are as hotly debated as the Multiverse: for some it is untestable and hence unscientific; for others it is unavoidable and a natural extension of previous science. There are well-known and respected cosmologists on both sides of the debate. There is no shortage of literature on the Multiverse: the volume edited by Carr[1] demonstrates the extent to which the Multiverse has become mainstream; Tegmark has written an influential popular account[2] (reviewed[3] in these pages). So can this book by philosopher of science Simon Friederich (a busy young man, not yet 40, with doctorates in both physics and philosophy — from Heidelberg and Bonn, respectively — as well as a *Habilitation* in philosophy from Munich, and with five daughters, a tenured position in Groningen, and even his own interpretation of quantum mechanics[4]) offer anything new? Yes. At the beginning of the last chapter, he states explicitly what the reader who has come that far will have noticed: "Throughout the discussion of multiverse theories in this book, I have set aside the most heated discussions about the multiverse and ignored the most scathing criticism of such theories ...." Also interesting is the fact that "[t]he considerations on multiverse theories in this book are somewhat unusual ... for they have been developed and compiled by someone who has never had any strong feelings about their central topic ...." The result is an interesting book which is not only about the Multiverse but also about the epistemology of the Multiverse.

Tegmark[2] had defined four 'levels' of Multiverses: the Level I Multiverse is what many call the Universe (his Universe being what many call the observable universe).* The Level II Multiverse consists of other universes (or Tegmark's Level I multiverses), perhaps with different values of the constants of nature, different laws of physics, or different initial conditions. The Level III Multiverses are the many worlds in Everett's interpretation of quantum mechanics; the Level IV Multiverse is Tegmark's own Multiverse of mathematical structures. Level I is accepted by essentially everyone, Levels II and III† by many, while Level IV is speculative. The bulk of the book is concerned with the Level II Multiverse (which is usually meant if it is not specified in detail), though the penultimate chapter discusses, and rejects as incoherent, Levels III and IV and also David Lewis's 'Multiverse' of modal realism[5].

The three chapters in Part I set the stage and discuss in general terms fine-tuning for life, which, along with the Anthropic Principle, is entwined with some of the ideas of the Multiverse. Three more chapters in Part II continue the discussion of fine-tuning in the Multiverse, including a new argument by Friederich which avoids the inverse gambler's fallacy, a common charge against multiverse arguments. Those chapters have some overlap with, but are more technical than, the discussion in the book by Lewis & Barnes[6] (also reviewed here[7]).

*Most people wouldn't think of the stuff outside of our horizon as being in another universe or as being part of the Multiverse, but at least Tegmark is consistent in his terminology. Also, there are some similarities: by definition we cannot observe things outside the observable Universe, but nevertheless no serious scientist doubts that such things exist.

†There is some evidence that Everett's many-worlds interpretation has become more popular in the last few decades. However, quantifying that is rather difficult. As Penrose quipped, "There are probably more different attitudes to quantum mechanics than there are quantum physicists. This is not inconsistent because certain quantum physicists hold different views at the same time."

Three chapters in Part III discuss the idea of testing multiverse theories, making extensive use of Bayesian reasoning (already introduced in the third chapter). An interesting related topic, puzzles of self-locating belief, is discussed in Chapter 9, where we meet Sleeping Beauty, Lazy Adam, the Pretentious Philosopher, and the Principal Principle. The first chapter in Part IV rejects, as mentioned above, some multiverse theories, while the final chapter is a dispassionate discussion on whether the Multiverse is a scientific idea (either a hypothesis or a consequence of other theories). Friederich takes the possibility seriously that we might actually live in a Level II Multiverse, but also points out the difficulties, both technical and sociological ('researcher degrees of freedom') in actually being able to obtain compelling evidence one way or the other. As long as the Multiverse is not ruled out, some parameters in physical theories might be 'environmental' rather than fundamental and thus inexplicable *via* conventional progress in theoretical physics. Friederich sees the question of understanding the value of the cosmological constant as an example of such a parameter; it might never be understood within the context of a conventional physical theory. On the other hand, the questions of the identity of dark matter and whether some sort of modified gravity might also be an explanation for some phenomena for which dark matter is invoked are largely independent of the question whether we live in a Multiverse.

There are no figures, and a few footnotes. Almost all equations concern probabilities. As almost always, I would have phrased some things differently with respect to style, but there are few actual typos and I noticed no factual mistakes. The book is well written despite (as far as I know) Friederich not being a native speaker of English. In the last several years I have thought much about many of the topics covered by the book. Much of the corresponding discussion is in the philosophy rather than the physics literature and thus might present something of a barrier to physicists interested in the epistemology of the Multiverse. Friederich's book is a good bridge across that gap and otherwise a good introduction to the topic, with many citations in the text and a corresponding 12-page list of references in small print which point the reader to more detailed discussion of various topics (thankfully including titles of articles); the book ends with a two-page index in even smaller print. I recommend it highly. — Phillip Helbig.

References

(1) B. J. Carr ed., *Universe or Multiverse?* (Cambridge University Press), 2007.
(2) M. Tegmark, *Our Mathematical Universe* (Allen Lane), 2014.
(3) P. Helbig, *The Observatory*, **134**, 150, 2014.
(4) S. Friederich, *Interpreting Quantum Theory: A Therapeutic Approach* (Palgrave Macmillan), 2014.
(5) D. Lewis, *On the Plurality of Worlds* (Blackwell), 1986.
(6) G. F. Lewis & L. A. Barnes, *A Fortunate Universe: Life in a Finely Tuned Cosmos* (Cambridge University Press), 2017.
(7) P. Helbig, *The Observatory*, **137**, 243, 2017.

THESIS ABSTRACT

Anton Pannekoek, Marxist Astronomer Photography, Epistemic Virtues, and Political Philosophy in Early 20th-Century Astronomy

By Chaokang Tai

Anton Pannekoek (1873–1960) was both an innovative astronomer and influential Marxist thinker. This dissertation discusses Pannekoek's astronomical research both in the context of the historical development of astronomy and his own Marxist philosophy. Each of the three chapters covers a different aspect of his research: the first discusses his efforts to represent the appearance of the Milky Way, the second his statistical research on the distribution of stars in the Galaxy, and the third his contributions to the astrophysics of stellar atmospheres. The focus throughout these chapters is on three historiographical themes: the impact of photography on astronomy, Pannekoek's epistemic virtues, and the connections between his astronomy and Marxism. Photography, on a practical level, enabled Pannekoek to conduct observational research despite lacking an observatory. On an epistemological level, it allowed him to reduce, but not eliminate, the human aspect of observation. Pannekoek's photographic research illustrates that photographic plates were material objects that travelled and required significant labour to transform them into scientific knowledge. The focus on Pannekoek's epistemic virtues, in particular his emphasis on judgement and thoroughness, highlights the differences between his scientific methodology and that of his contemporaries. It also clarifies how he adapted this methodology according to the practical constraints of his particular situation and his personal convictions. Finally, investigating the relationships between Pannekoek's astronomy and his Marxism uncovers numerous ways in which these were interconnected: in his philosophy of mind, in analogous ways of thinking about systems, and in his ideas on scientific and societal progress. In doing so, this thesis provides a more unified and complete description of Pannekoek's entire professional life. — *University of Amsterdam; defended 2021 March*.

A full copy of the PhD thesis can be requested from c.k.tai@outlook.com

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OBITUARY

Domenico Gellera (1941–2021)

Domenico Gellera was born on 1941 May 18 in Lodi, a city close to Milan, into a family of modest economic resources, so, still at a young age, he had started working as an apprentice turner in a factory in the Lodi area. He soon became enthusiastic about astronomy, but in the 1960s an amateur astronomer was an isolated person, left to himself, because at that time in Italy there were no associations of amateur astronomers or astronomy publications, and instruments for observing the sky could not easily be bought, as they can now. Domenico did not lose heart, and, taking advantage of his excellent skills as a mechanic, he designed and built a magnificent refractor with a German equatorial mount, on which he placed an 11-cm-diameter Zeiss semi-apochromatic objective, and with this instrument he started observing the sky in 1963. He called his small private observatory the *Specola Astronomica di Lodi*.

He was a passionate observer of visual double stars which he measured until 1992 using the aforementioned instrument, together with a self-built wire micrometer. In 1989 he had purchased a double-image micrometer, produced in a limited edition, by the French company MECA-PRECIS, the design being based on the experience and advice of visual-double-star observers who were members of the *Commission des Étoiles Doubles* of the *Société Astronomique de France*.

One of Gellera's most interesting original works was the production of about one thousand measurements relating to 320 double stars with separations between 4″ and 24″ contained in the *Astrographic Catalogue*, part of a catalogue of 5883 binaries compiled by A. Pourteau and extracted from the *Carte Photographique du Ciel*[1]. To carry out this work he built a two-axis comparator, of which he carefully determined the instrumental errors (related to the screws and the orthogonality of the axes) using precision photoengraved gratings, manufactured by the Heidenhain company. For the measurements he used the O prints (blue passband) of the Palomar Observatory Sky Survey (POSS), produced from the original plates taken with the 48-inch Schmidt telescope of Palomar Observatory in 1953, about 50 years after those of the *Carte du Ciel* used by Pourteau. In most cases, Gellera's measurements were the first and only measurements of these Pourteau pairs made after their discovery.

Always using the same comparator and the same POSS prints, Domenico then measured 104 faint double stars, with a separation between 3″ and 60″, taken from W. J. Luyten's *NLTT Catalogue*, with the intention of re-measuring them on the prints of the subsequent second POSS survey that would be carried out with the same 48-inch Schmidt instrument.

After retirement and the cessation of his observational activity, brought on by the deterioration of his health, he was one of the founding members, and later also Vice President, of the Brera ARASS (Association for the Restoration of Ancient Scientific Instruments), a non-profit association with headquarters in the Palazzo (Palace) Brera in Milan. The purpose of this association is the recovery of historical scientific instrumental heritage, both publicly and privately owned.

The ARASS started a collaboration with the Astronomical Observatory of Brera (now INAF – OAB), so Domenico took part in the restoration of the historic *Merz* refracting telescope, of 22-cm aperture, with which Giovanni Virginio Schiaparelli, starting in 1875 February, observed the planet Mars and many double stars. This instrument is now perfectly restored and functioning, and is located on the roof of the Brera Palace in Milan, in the original dome. He also participated in the restoration of other important ancient instruments, such as the 26-cm *Reinfelder* refractor of the INAF – Trieste Astronomical Observatory, and he worked in the initial part of the recovery and functional restoration of the famous 49-cm *Merz–Repsold* refractor used by Schiaparelli starting in 1886, until the end of 1990 October. Since 2017 September this refractor has been in the pavilion dedicated to Space in the National Museum of Science and Technology Leonardo da Vinci in Milan. Among the restoration works carried out by ARASS he was very much involved in the functional restoration of historic tower clocks such as that at the Palazzo Brera where the Astronomical Observatory and ARASS are located.

He collaborated with the Double Star Section of the Webb Society (UK), published articles in professional astronomical journals, such as *Astronomische Nachrichten* (today *Astronomical Notes*), and even, as a co-author, in the prestigious *Astronomy and Astrophysics Journal, Supplement Series*.

For the construction of the two-axis comparator and for the search technique for faint double stars of the Sky Survey operated with professional telescopes, he was mentioned in Chapter 22 (*What the amateur can contribute*) of the book on visual-double-star observing edited by Robert Argyle[2].

Domenico Gellera was a person of few words and a disarming modesty. Those who had the opportunity to know him more closely for professional and friendship reasons, remember him as a generous person. Registered with the Italian Association of Organ Donors (AIDO), he had long ago arranged for the donation of his corneas, a gesture of love and hope for his fellow citizens. He also stipulated that his equipment and his extensive, specialized library, of books, magazines, scientific publications, papers, and astronomical photographs, should be transferred to the ancient *Collegio San Francesco* in Lodi, managed by the Barnabite Fathers.

After suffering from a heart condition for a long time, a heart attack took him away at the age of 79, on 2021 March 11. — Marco Scardia & Luca Maccarini.

Reference

(1) http://webbdeepsky.com/dssc/dssc3.pdf
(2) R. W. Argyle ed., *Observing and Measuring Visual Double Stars, 2nd Edition* (Springer), 2012

[Eds. Note: I had the pleasure of corresponding with Domenico Gellera for 40 years but it was only in 2009 that we met face to face for the first time. He was as self-effacing, modest, and charming in the flesh as he had been in his letters. He was also a very generous man; some time later I received a parcel from him. Inside were the two volumes of measures by the great Italian double-star observer Baron Ercole Dembowski, a man whose painstaking observational work with a 7-inch refractor inspired both of us. The subsequent treatment of the instrumental errors represented a paragon of scientific thoroughness which was so appreciated by Sherburne Burnham and Robert Aitken. —RWA]

OBITUARY NOTICES

Leonard Matula (1942–2021)

Readers of *The Observatory* will have, I'm sure, enjoyed the book reviews and letters submitted by Leonard Matula in recent years, but it came as a shock to me that he had succumbed to Covid-19 earlier this year.

Most of our communications were by phone from his home in Temple City, California, and we would enjoy lengthy conversations on all manner of topics. Like me, Leonard was not really an 'e-fan', much preferring the solid comfort of a book in the hand over one in the aether to be read on a screen. To that end, he had become an enthusiastic collector and had established a formidable library, in part by finding a home for books thrown out by libraries, such as that at Caltech, when pressed for space. But he was a collector of much more, such as telescopes, binoculars, models, *etc.*, but especially of memories which he included in his reviews, particularly in the 'From the Library' series he instigated in these pages.

Leonard was born in Chicago on 1942 August 15 and passed away in Pasadena on 2021 January 9. I shall miss his enthusiasm greatly. — DAVID STICKLAND.

Peter S. Conti (1934–2021)

Following a car accident near his home in Colorado, Peter Conti died on 2021 June 21. A full obituary has been prepared by Henny Lamers and Ed van den Heuvel for the AAS and will be available shortly.

I first met Peter at the Lick Observatory headquarters at UC Santa Cruz in 1969 September at the start of my PhD project on metallic-line A stars, in which subject Peter was one of the key players. An affable and encouraging supervisor, he gathered much of the data for my project by way of coudé spectra from the 120-inch telescope on Mount Hamilton, and gave my career in astronomy the perfect start (*MNRAS*, **161**, 193, 1973). Much later, when Allan Willis (see these pages **138**, 349, 2018) had steered me in the direction of hot stars, my path fortuitously crossed that of Peter once more; he was again a major influence on the field. I am deeply saddened by his passing, a feeling that will be shared by his many colleagues. — DAVID STICKLAND.

Here and There

AT THE SPEED OF LIGHT?

At the far end is the optical table with lasers that pass through the gas. — *Sky & Telescope*, 2021 May, p. 37, figure caption.

SMALL WORLD

POEMMA consists of two identical spacecraft circling Earth in the same orbit, some 300 kilometers behind each other. — *Sky & Telescope*, 2021 May, p. 19.

A RIVAL FOR METHUSELAH

... two maps published by Ptolemy in 1482. — *The Times*, 2021 May 8, p. 51.