THE OBSERVATORY

Vol. 137 | 2017 JUNE | No. 1258

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2016 December 9 at 16^h 00^m
in the Society of Antiquaries Lecture Theatre, Burlington House

J. C. Zarnecki, *President*
in the Chair

The President. Good afternoon, ladies and gentleman. Welcome to this open meeting of the Society of Antiquaries. [Laughter.] No, it is the RAS but it's interesting to be in slightly unfamiliar surroundings, so congratulations on having found us. My next duty is a very pleasant one — it's to hand over an award: the RAS Herschel Medal for 2016. That is awarded to Professor James (or Jim) Dunlop, and I wonder if he could come up, and I will start by reading the citation before awarding the medal. The citation reads as follows: "The Herschel Medal in Astronomy is awarded to Professor James Dunlop. In the golden age of our current paradigm for galaxy formation, the hierarchical Cold Dark Matter Universe, and before the discovery that the Universe needs an unknown dark energy to explain its present acceleration, Jim Dunlop was discovering that galaxies as old as the Universe — perhaps even older! — existed just a couple of billion years after the Big Bang.

That surprising discovery towards the end of the 1990s found corroboration among colleagues in a series of papers which led to the acceptance of another seemingly contradictory paradigm — the baryonic downsizing in galaxy formation, which sees the most massive galaxies forming first in the Universe. Professor Dunlop's fortitude to trespass the known territory pushed the frontiers of extragalactic astrophysics and observational cosmology towards the limits of knowledge. He discovered the first dust-enshrouded galaxies at redshift larger than 3 and played a key role in shifting the understanding of galaxy evolution into the yet unknown territory of sub-millimetre cosmology.

Presently Professor Dunlop, Head of the Institute of Astronomy in Edinburgh, leads the most ambitious international programme to discover and understand the first galaxies, at epochs when the Universe saw its first light. Understanding cosmic re-ionization, which tells about the link between the primordial Universe and galaxy formation, is a primary goal of modern astrophysics and cosmology. For these reasons Professor Dunlop is awarded the Herschel Medal." [Applause.]

So we now move to the advertised programme, and we start with the talk associated with the Patricia Tomkins Undergraduate Prize. This will be given by Ms. Samantha Stever from the Université Paris–Saclay, and the title is 'Investigation of alternative capacitor designs for high-sensitivity astronomical applications'.

Ms. Samantha Stever. I'm here with you today to talk about the work I did during my Masters degree, which was with the Astronomy Instrumentation Group at Cardiff University, although I'm presently at IAS in Paris doing my PhD.

I would like to present some overall context to this work to illustrate the point of everything I'm doing. The detectors that I worked on apply particularly to millimetre and sub-millimetre astronomy. This régime falls between the far-infrared and microwave wavebands, which is a particularly difficult waveband in observational terms. This is mostly due to the fact that water vapour in the atmosphere creates absorption bands, which make the atmosphere largely opaque to mm/sub-mm radiation at low altitudes. We can see that radio, by contrast, is totally observable even at low altitudes on Earth, whereas the atmosphere, even at high altitudes, blocks UV and gamma rays (thankfully for everybody on Earth). There are also instrumental challenges in sub-mm work because of the previous points, but also because the technology borrows from both radio and optical technologies.

However, there are some solutions to these challenges. For ground-based telescopes, observation is possible in cool, dry, secluded areas. Popular areas include the Atacama Desert in Chile, where the *Atacama Large Millimeter/submillimeter Array* (*ALMA*) is located, currently the largest facility at that waveband, and is an interferometer making observations in star formation and astrochemistry. Mauna Kea, Hawaii, has also been a successful location for ground observatories. There are also a variety of near-space observatories, including the *PILOT* (*Pathfinder for an International Large Optical Telescope*), which is flown to Earth's stratosphere to measure the polarized dust emission in an effort to contribute to cosmological space and ground missions using a large balloon. And finally, many missions in this waveband are simply launched into space on satellites, such as the *Planck* cosmological mission. Space missions may seem like the obvious solution; however, the time it takes to design and launch a satellite, as well as the cost, make this option prohibitive.

To provide further context, I'd like to talk briefly about some of the applications of millimetre-wave astronomy, one of the major ones being the study of star formation. To illustrate the benefits of observation in this waveband, one can compare the observation of a star-forming region in the optical to that of the same in millimetre-waves. We can see that these regions of star-forming activity are obscured by dusty matter in the foreground in the optical waveband. However, at millimetre and sub-millimetre wavelengths, the radiation behind the dust causes the dust to re-emit, giving us an important window into the observation of those regions in this waveband, allowing us to see the light behind the curtain, so to speak. It is for this reason that millimetre-wave observations are vital for any astronomical object which is heavily obscured by dust, such as molecular clouds and galaxies. Using these techniques, it is possible to create density maps of star-forming activity in dusty regions, which is simply not possible using optical techniques.

This waveband is also an invaluable tool in cosmology, and an illuminating example of this is the *Planck* space mission. *Planck* observed the sky at nine different frequencies between 30 and 857 GHz, with the intention of measuring the cosmic microwave background (CMB), or relic radiation left over from just after the Big Bang. The CMB peaks at 1·06 mm and has a peak spectral radiance of 1·8 mm. However, the CMB is dominated by foregrounds. In front of the CMB relative to us is the entire galactic plane of the Milky Way, which is full of dust, as well as everything else in the Universe. The highest frequencies are mostly dominated by dust emission, which produces a thermal signal, whilst the observations at the lowest frequencies are dominated by synchrotron radiation and bremsstrahlung, while the CMB itself is most evident between 70 to 220 GHz. The *Planck* collaboration has a good explanation of this on their website, for those interested.

In order to resolve the relatively small CMB signal behind all of this dust and radiation, it is imperative to resolve all of those components separately in each particular waveband at which they are prevalent, and then remove them piecemeal from the all-sky maps observed directly, which is why observing in these frequency windows is so important.

If one does all of this correctly, it is then possible to resolve sky maps of various attributes of the CMB including temperature and, in future, polarization fluctuations. One of the principal accomplishments of *Planck* was to plot the angular power spectrum of the CMB temperature fluctuations, or anisotropies. These angular power-spectrum measurements were fitted using the current model taken as our understanding of cosmology. That fit was excellent for small angular scales, but at large angular scales there appears to be uncertainty. That could either be simply due to observational restrictions, but it could also be that our current understanding of cosmology needs revising. Future cosmological instruments seek to probe this further, as well as measure the polarization of the CMB in search of primordial signals which could confirm our present understanding of the cosmological model and the events which unfolded in the early Universe.

So, now that I've said all that, what is the common linkage between all of these things? To state it simply, these studies need large arrays of ultra-sensitive detectors in order to carry on their work (especially in cosmology!). Because they are looking for such a small signal, the detectors must have very low noise, very high sensitivity, and well-controlled systematic effects. Past and present technology in this waveband include spiderweb bolometers such as those used in *Planck*, which measure a signal as a change in heat, or transition-edge-sensor bolometers, which utilize the sensitivity of the temperature–resistance relationship in the superconducting phase transition. There are also many other detector types for these uses, each with its own advantages and potential issues.

The newest types of detector for such work are kinetic-inductance detectors (known as KIDs), which is the type of detector we studied in this work. KIDs are essentially just LRC resonator circuits made from a superconducting material, which are inductively coupled to a feedline. Photons incident on the inductor element change the kinetic inductance of the detector, which changes the frequency at which the resonator resonates. The value of the resonant frequency is dependent on the inductance and capacitance of the circuit. The usual type of capacitor used in KIDs is an interdigitated model, and the geometric size of the capacitor fingers is what determines the capacitance.

When multiple KIDs are coupled to the same feedline, provided that each has a different resonant frequency, the signal across the line will typically have a dip in signal magnitude which is centred about that frequency. When there is radiation incident upon the inductive element, it shifts the resonant frequency of the signal as well as changing the amplitude of the signal, which is how those detectors are used to observe radiation. The sharpness of the resonance peak is determined by the quality factor, or Q-factor, which is the ratio of the energy stored in the resonator *versus* the energy lost per cycle. A resonator with a high Q will have a very sharp peak and a small full-width at half-maximum (FWHM). As Q decreases, the sharpness decreases with it and the peak has a larger FWHM, which signifies higher levels of loss per cycle.

KIDs are useful for millimetre astronomy for a number of reasons. They are very easy and inexpensive to fabricate in large numbers, giving them advantages over technologies with many different layers or complex geometries. They are also very easy to multiplex, which means that large numbers of detectors can be read out using the same coaxial transmission line, whereas other models require complicated read-out circuits which take up space and come with their own complications. The next generation of the *BLAST* (*Balloon-borne Large-Aperture Submillimetre Telescope*) mission, for example, has 250 KID resonance peaks between 550 and 950 MHz, which is a large number of separately-resolved detectors, with only one feedline. Since detectors in this waveband usually need to be cryogenically cooled, either to be sensitive enough or to superconduct, they need to be able to withstand many cycles of heating and cooling, and KIDs have been shown to be resistant to damage from thermal cycling. They are also resistant to radiation impact, which is important in the case of space missions. The *Planck* mission, which used bolometric detectors, was quickly discovered to be very susceptible to false signals from cosmic rays, with about one impact per minute. Simulations and experiments with KIDs have shown that, while they are still very sensitive to cosmic-ray hits, it's easier to remove the spurious signal, or 'de-glitch', than it is for other detector types.

One limitation of such detectors is the capacitance, which determines the resonant frequency, and is itself determined by the geometric area of the capacitive element as I mentioned previously. In cases where large arrays are necessary, the real estate taken up by the capacitor can be prohibitive because it is desirable to have as much space as possible for the inductor, the part of the detector actually detecting radiation. The point of the work we have undertaken was to see whether it might be possible to replace the interdigitated-capacitor geometry with a parallel-plate capacitor, using a low-loss dielectric between the capacitor plates. We chose diamond as the dielectric because of its excellent electrical insulation and low loss, and also because Cardiff has a diamond group which specializes in growing thin layers of nanocrystalline diamond on films. So the idea of this project was to take the preliminary steps to see how diamond would interact with KIDs and see if it is a suitable candidate for a dielectric material in alternative capacitor types.

If this could be done, we could produce KID arrays with a greater fill factor, put more pixels within a given frequency band, and potentially increase the sensitivity of the detector. This would also carry a lower risk of resonance collision, or 'cross-talk', between two neighbouring resonators, due to the higher Q and the sharper peak in a very-low-loss resonator.

Since this was very much a first-step project, the aims were first to fabricate a KID with nanocrystalline diamond grown on top, to see if this can even be done, or whether the diamond would interfere with the behaviour of the circuit or the underlying material. Next, we would take some films of nanodiamond grown on the substrate of KIDs to see what effect a diamond layer has on the ability of those films to superconduct (such as the transition temperature and the resistance as a function of temperature). We then would use those temperatures and resistances by calculating the complex conductivity parameters using the Mattis–Bardeen theory of superconductivity, with the idea of using those parameters in a simulation to optimize a KID structure for the highest quality factor. Finally, we would fabricate a KID structure using the optimized KID geometry, and test the transmission properties of that KID with and without a nanodiamond layer to see the effects on the resonance and the losses. Once this is done, it is possible to move forward with the design and fabrication of KIDs containing parallel-plate capacitor elements.

First, it was necessary to test which substrates we could use for KIDs which would survive the process of diamond growth. To grow nanocrystalline diamond on the films, microwave plasma chemical vapour deposition (MPCVD) was used. For that process, the films were placed in a furnace of hot gas, including carbon in the gas mixture such that diamond would grow. Microwave photons in the reactor ionize the gas and generate plasma. We seeded the films with nucleation mixtures, which increase the likelihood of diamond growth on the films.

Diamond growth was tested on two substrate materials — niobium and aluminium. Two nucleation substances were used on each material type, one terminated with hydrogen and the other with oxygen. The growth on the films was inspected on images from a scanning electron microscope, allowing us to resolve the growth of diamond particles on the film's surface. Using H-terminated solutions on both materials resulted in uniform nucleation across both raised circuit elements as well as the ground plane, which was the effect we had been hoping for. By contrast, O-terminated seeds in both materials caused non-uniform growth on both materials, and induced impurities on the aluminium film. By further inspection it was also found that the aluminium film was mostly destroyed by the diamond-growth process. For those reasons we chose to work with H-terminated niobium for the remainder of this work.

Next, we wanted to measure the resistance of some sample films as a function of temperature, to see what effect a nanodiamond layer has on the superconducting properties of the materials. This was done with the intention of extracting various superconductivity parameters from each film and then calculating complex conductivity parameters using the Mattis–Bardeen theory of superconductivity. For the measurements, the samples were cooled to 77 K by liquid nitrogen and further cooled by liquid helium to 4 K in a wet cryostat. The cryostat was pumped to reduce the pressure, further decreasing the temperature of the test bed. A small resistor heater was then used to control the temperature in the immediate area of the sample between 1·7 and 11 Kelvin.

Several samples were used in order to probe various effects on the superconductivity. Four niobium films were used, each with a thickness of 200 nm. The first film was completely unmodified and was used as a control sample. The second was not seeded with a nucleation solution but was placed in the reactor environment with other samples to test the effect of the reactor itself. Another was also unseeded and not placed in the reactor but was heated to a comparable temperature for 27 minutes to test the effect of high temperatures on the film. Finally, another niobium film contained 30 nm of gold on the surface. Three films were used which were also made from 200-nm-thick niobium, upon which 100 nm of nanodiamond was grown. In these samples, small squares of nanodiamond needed to be removed so wire bonds could be made to measure the resistance. Two films had the bond-site diamond removed by photoresist techniques, and one of those had a manufacturing defect causing the photoresist squares to be offset by about 450 microns. The last film had diamond removed by a technique called inductively coupled plasma, with the intention of testing the effect that creates the least amount of interference with the superconducting properties or introduces the smallest level of systematic effects.

The niobium control film behaved as expected, with a superconducting transition temperature near the book value. By exposing the niobium to the plasma environment, the transition temperature increased by about 1 K and became slower in rate, implying that the reactor environment facilitated some kind of chemical change in the film. The Nb film which had been annealed at comparable temperatures showed very large changes, with a much lower transition temperature and a much higher normal-state resistance, for reasons which were unknown at that time but probably related to the annealing process. The films with nanodiamond grown on top showed several interesting superconducting features, including multiple temperature–resistance transitions. The film without the manufacturing defect had two transitions while the film with the defect had three, and fully superconducted at a much lower temperature of about 3 K. The upper transition at 7·4 K is most likely due to the niobium layer, while the lower transition likely relates to the diamond in some form. The last film, which had bond-site diamond removed by oxygen-inductively-coupled plasma, had a very slow transition and never actually superconducted down to 1·8 K. For that reason, that technique was ruled out for future experiments.

As stated previously, the superconducting properties of each of the films were extracted and then used to calculate the complex conductivity parameters by Mattis–Bardeen theory. Some of these parameters were then put into a simulation of three different KID types in SONNET in which we simulated their transmission as a function of frequency, with the idea of comparing the three types to find the one with the highest quality factor. All the simulated KIDs had Q-factors in the same order of magnitude, but the best, KID '1', was chosen.

The next stage was to fabricate this device and measure its transmission properties both before and after adding a layer of nanocrystalline diamond, to compare the quality factors as well as the noise parameters. Unfortunately, given the time restrictions involved in an MPhys project as well as the use of the equipment of another lab, the second stage could not be completed. Therefore what I am presenting now is an example of what we would have completed if we had the time to measure the new KIDs before and after the diamond growth.

We performed measurements of the scattering parameter 'S21', which arises when one treats the detector as a two-port system, with one port on each side of the transmission line. S21 is the ratio of the voltages on port 2 with the voltage on port 1, and it is a complex signal, with real and imaginary components. We measured five resonators each with a different resonant frequency, and we performed frequency sweeps across each of those frequency ranges, and at temperatures from 230 to 405 mK. Since the signal has both real and imaginary components, the signal has both a magnitude and a phase. The magnitude is shown [on the screen], where each of the dips is a resonance about each resonator in frequency space.

The signal phase as a function of frequency was also calculated and then fitted with an equation which describes its relationship to the quality factors, which can then be used to deconstruct the quality factors Q_i (the internal quality factor of the resonator), Q_r (the overall quality factor for the entire device), and Q_c (the quality factor relating to losses in the capacitive coupling to the feed line). As expected, the quality factors decrease with increasing temperature for the KID without any nanodiamond growth. The question of how much these would change, as one expects them to, after nanodiamond is grown on the films, remains an open question. The Cardiff Astronomy Instrumentation Group has plans to continue this work shortly.

To conclude this talk, I would like to reiterate that the work is currently incomplete owing to time restrictions, and so we can only make preliminary conclusions based on the measurements already performed. We will still need to grow nanodiamond on the KID and re-measure its transmission properties to make any larger conclusion about the effect of the diamond on the losses of the detector. However, the detector envisaged by this work is not simply a KID with nanocrystalline diamond grown on top. The idea is to fabricate a device with a parallel-plate capacitor which uses diamond as the dielectric substrate, which is the next step to take after verifying that the losses of a film with diamond grown on top are not too substantial (because some extra losses are expected at this early stage). This would not present a problem in further development, therefore, as the KID is only expected to contain diamond between the capacitor plates and not across the entire detector, as in this model. These are only preliminary measurements to see if this works. Based on the work performed so far, it would appear that the use of diamond in this manner is promising, and that my former colleagues at Cardiff can carry future work forward.

The President. Thank you very much; and just to repeat, this is work that you did as an undergraduate at Cardiff?

Ms. Stever. Yes.

The President. We have a few minutes for any comments or questions.

Dr. G. Q. G. Stanley. I know it's early days but do you see any fall-off with the capacitance over time at all with this technique?

Ms. Stever. Well, since we didn't actually get to fabricate a parallel-plate capacitor with this, I don't know to be quite honest with you. I'd be interested in seeing that but I'm not sure.

Mr. C. Taylor. I was interested in your diamond growing; you're doing this in the gas phase. Had you contemplated the method that was being explored about thirty years ago — I had a slight involvement in it — of photonic grain-growth diamond, where you take an existing diamond and basically try to bring carbon at it in a vacuum? You can dope the rings with whatever you like, you have complete control of it, the composition, the layering, you build up on the existing diamond. I have no idea where the project has gone in the past thirty years but it possibly might be useful.

Ms. Stever. That sounds useful. We hadn't considered that because we were only using the resources that were already available. Cardiff has a diamond lab: they have that machine specifically for doing studies on diamond so we decided to utilise that, but that sounds interesting.

Mr. Taylor. It was work that was going on at AERE Harwell in the very late 70s and early 80s. I was very thoroughly involved in the research team at Oxford at the time.

Ms. Stever. I'll have to look into that.

The President. Can I ask, are you continuing any of this work in your current position or have you moved to other fields?

Ms. Stever. No, I'm still working in instrumentation but I'm working with different types of detectors and I'm actually working on the effect of cosmic rays on bolometers for cosmological missions, but not on kinetic inductance detectors and not on this specific technology either.

The President. Thank you very much indeed, Samantha. [Applause.]

Our second talk this afternoon is associated with the Keith Runcorn Thesis Prize. It will be given by Dr. Matteo Ravasi, currently at Statoil in Norway, and before he gives the lecture, it's my duty to present him with his certificate. Many congratulations. [Applause.] He will now present his talk which is on

'New advances in seismic imaging: can we get the most out of our data?'.

Dr. M. Ravasi. Geophysics involves listening to the echoes of the Earth's interior, and understanding the structure and properties of rocks sitting thousands of metres below our feet. Some years ago, when I was still undertaking courses in telecommunication engineering with special focus on signal processing, I decided that this was a challenging and fascinating topic, and I wanted to learn more. Five years later, I am here at the RAS Ordinary Meeting in London to present some of the findings of my PhD work, which aimed at further improving our understanding of how waves propagate in the Earth and how we can create accurate images of the sub-surface by taking advantage of so-called multiply-scattered waves, also known as multiples (waves that bounce off sub-surface discontinuities more than just once).

I want to start by introducing the general concept of imaging by means of a simple analogy: imagine you are standing in front of a cliff and want to understand how far away is the cliff from you. By emitting a sound and listening to its echo, the time that such a wave took to reach the cliff and come back to you is twice the distance of interest divided by the speed of sound in the air (which is well known to be 343·2 metres per second). Seismic imaging (also sometimes referred to as migration) can be seen as an extension of this concept to a three dimensional Earth's sub-surface, allowing us to emit and record waves at the surface of the Earth and create images of sub-surface structures by implementing advanced mathematical and physical concepts into computer algorithms. The requirements of state-of-the-art seismic-imaging techniques limit our ability to take advantage of the additional information contained in multiples. As a consequence, seismic recordings are generally heavily processed before imaging.

The first finding of my PhD work is devoted to the handling of a special type of multiple events, which are created by the water–air interface (or free-surface) during offshore acquisition of seismic data. Since such events always follow primary sub-surface arrivals with some small time delays, the geophysical community refers to them as ghosts. It is well known that standard imaging algorithms that use only pressure recordings cannot distinguish whether an event is reaching the receivers directly from the sub-surface or from above, as is the case of a ghost arrival; such limitation is mostly due to the fact that pressure recordings are omnidirectional. By modifying our imaging algorithms to be able to handle also particle velocity (or acceleration) measurements, which are sensitive to the direction of arrival of waves, both primaries and ghosts can be imaged at their correct sub-surface locations. The advantage of this new approach which my co-authors and I named 'vector-acoustic migration' is two-fold: ghosts can be kept in the data to be used for migration, reducing the processing steps, and can help enhance the signal-to-noise ratio of the final image as their contribution is combined constructively with that of primaries. [A field-data example from a North Sea field was shown to the audience to show the applicability of the proposed method to real-life scenarios.]

Building upon the findings of the previous study, I would like to discuss how to extend this idea to elastic media: as the Earth is an elastic medium, we expect two wave modes (so-called P- and S-waves) to be excited any time an incident wave is interacting with our medium's discontinuities. Conventionally, seismic processing aims at separating such wave modes from the recorded seismic data to image them separately. Currently, state-of-the-art elastic-imaging techniques are not able to handle P- and S-waves simultaneously, leading to the creation of fake wave modes in the numerical simulation and artifacts in the resulting image. If multi-component measurements are available in the form of particle velocity and stress (or strains), the imaging process can naturally separate different wave modes and correctly position those in the sub-surface, leading to cleaner images and a reduction in the amount of data processing required prior to imaging. The proposed methodology, despite showing great promise in numerical simulations, has not yet been tested on field data since the stress (or strain) component of the elastic wave-field is not yet commonly recorded in industrial applications. Nevertheless, our research shows the value that such recordings could provide in terms of quality of the final sub-surface image even with a limited number of sources and shorter acquisition windows.

One of the hottest topics of exploration geophysics these days concerns internal multiples (waves that bounce three or more times, always within the sub-surface). These types of multiples have been studied by many geophysicists over the years, but methods for handling them accurately in imaging have only been very recently discovered. While sometimes very weak and not of great importance, internal multiples can be very prominent in some geological settings, such as sub-salt or sub-basalt, and create artificial structures in the sub-surface image if not properly removed from seismic data. Half-way through my PhD I started investigating those events and soon realized that active research had being carried out by two academic institutions (Colorado School of Mines and TU Delft) at the same time. Their research was investigating special types of equation, derived by Ukrainian mathematician Vladimir Alexandrovich Marchenko in the early 50s, in order to explain the inverse-scattering problem in 1-D media. It quickly turned out that such equations could be adapted to the geophysical context and expanded to two and three dimensions and could be used for accurate handling of internal multiples while imaging the full seismic wavefield. In this presentation, I have focussed on providing an intuitive explanation of how such equations provide an exact description of the propagation of waves in complex media, and showed the first successful field-data example on which I worked towards the end of my studies. This new area of research is just in its early days, but many other geophysical problems beyond imaging may benefit from the improved understanding of propagation of seismic waves in a complex medium provided by the Marchenko equations. It is exciting to have been working on this topic since its early days and I am positive that geophysics, as well as other disciplines, will benefit from such recent learnings and developments.

The President. Thank you very much indeed, Matteo. We have a few minutes for any comments or questions.

Dr. Sheila Peacock. I really appreciated your talk. I would be grateful to hear what are the effects of attenuation absorption on your method, in particular on the multiples — you are dependent on the frequency content of the multiples being similar to the primary, realizing this may be a problem in certain gas fields, and emanations of gas in the Norwegian continental-shelf area.

Dr. Ravasi. Thank you for your question — it's actually very interesting. The first two methods do not have any limitation with respect to absorption; I think they would work anyhow. With the last method, Marchenko imaging, the theory is actually quite clear that it requires lossless media. There has been recent research on trying to understand how they could be extended to media with absorption or at least how to mitigate the absorption in the data before we apply the technique. That's definitely something important, especially on the

Norwegian continental shelf, and we haven't come up with a solution yet, but there are directions in which people are looking to make it more robust, at least to absorption.

Dr. Lyndsay Fletcher. I guess to turn these lovely reflection diagrams into a physical depth, you need to know very well the propagation characteristics of the wave through the medium. How well is that generally known?

Dr. Ravasi. Generally, we spend a lot of time on making velocity models. I would say the first time you start making images of your sub-surface, that's probably the level of detail you have. In the field of geophysics, there has been a lot of attention to what we call full-waveform inversion, which is a technique that tries to make velocity models more and more accurate both to mimic the kinematics of the wave in a more accurate way and also add the details. We start from a very-low-frequency model and we then try to add higher frequencies, so more details.

Dr. Stanley. Do you find that with core models and resistivity measurements you can define these even better because this gives you various reference points on your reflections?

Dr. Ravasi. Yes, I think there are procedures where you combine seismic and resistivity and electromagnetic techniques, where you try to use all of them to make your velocity model because they are sensitive to different scales and can be complementary. So that's definitely something that people do to get better models, but then when you want to come up with something like this, you really need the seismic input because the elastic waves are the waves that are more sensitive to quick changes, so you can make images of the contrast more than an image of the property. When you want to make an image of the property you try to combine more methods, but when you want to end up with an image of the contrast then you use more seismic data.

The President. Matteo, thank you very much indeed for your presentation. [Applause.]

Our third talk today is the 2016 George Darwin Lecture, which will be given by Professor Michael Kramer of the Max Planck Institute for Radio Astronomy in Bonn, and jointly he's at Jodrell Bank, University of Manchester. The title of his talk is 'Probing Einstein's Universe and its physics — the joy of being curious'.

Professor M. Kramer. [A summary of this Lecture is expected to appear in a future issue of *Astronomy & Geophysics*.]

The President. Thank you, Michael, so much. We do have a few minutes — thank you for your precision in timing. [Laughter.] Of course we would expect nothing less. So, do we have any comments or questions?

Professor D. Lynden-Bell. Do you have a prediction for when the second of the two pulsars will come back?

Professor Kramer. That depends a little on the beam model. As we have seen from the other pulsars, we have completely misunderstood anything about pulsar beams so far because they are not a cone-like shape. There was a prediction that said it would come back last year. It didn't, I can tell you that. So the next prediction is for about 2020, but really that assumes we have an understanding of the pulsar beams and honestly, we don't. I think it's clear that we don't, so we keep looking.

Professor Lord Rees. Can you say a bit more about what you think the timing array will detect — will it be super-massive binaries, that have come close enough to coalesce?

Professor Kramer. That was the expectation so far, that we saw the signals and did the stochastic background of merging black-hole binaries, but I think we still don't understand a lot of the merging process of the black holes, so that's why, whenever we put out a new limit on our detection, the theoreticians lower their expectations. The thinking has changed: the best thing is really to identify an optical quasar and do a single-source search in our data because then we can dig deeper and find the best pulsars. It all depends on geometry: we have the beam pattern of our *Pulsar Timing Array* that is sensitive in some directions but not in others, but if you identify a candidate of a nice optical double quasar that is entrenched, and which has a known period, then we believe that would probably be the most promising candidate to look for.

Rev. G. Barber. Would the presence of dark matter in the Galactic centre affect the precision of these predictions?

Professor Kramer. Yes. I think that's the nice thing about combining these methods because the black-hole image will not be affected by the dark-matter distribution at the Galactic centre, but a binary pulsar orbit, if we find one, may indeed be affected by dark matter. If we find the deviation of things don't really cross at the same point, then there's some indication that something else must disturb the orbits, and if it's not visible it's probably dark matter. It would be a long shot and there may be other interpretations that could be likely, but we really have to see the data that they come up with. If everything fits, the pulsar orbits and the image, then dark matter may not be very close.

Dr. Stanley. What you have presented is enthralling, and knowing things to two attoseconds is beyond belief. Do you see the variations in those periods coming through and, as such, how well is that complementing *LIGO*?

Professor Kramer. The precision in our periods is so good on long time baselines. We're still relying on our atomic-clocks colleagues to provide us with accurate time. Pulsars are not very good clocks on short time-scales but on long time-scales the precision really gets better and supersedes many atomic clocks. So when you see the numbers, it's not instantaneous accuracy, it's an accuracy that we obtained by accumulating many more rotations of the pulsar as a function of time. However, that's also why we are sensitive to secular effects that occur in relativistic binaries, for instance, the decay of the orbit. We do not really measure the decay of the orbit every day by about 108 ns — that would be nice, but we see the cumulative effect of that orbital decay. In that respect, we know that pulsars have some slight rotational instabilities, but it depends very much on the pulsar. Millisecond pulsars are the smoothest ones because they rotate fastest and have the weakest magnetic fields, so the spin down is slower, but even then there are some pulsars that we know are better rotators than others. So what we want, one of the big things when we construct this timing array, is to identify first, painstakingly, the pulsars that are most accurate by comparing them to each other. The nice thing is that even if the pulsars have individual properties, what we do with the timing array is to observe many pulsars at the same time, so that gravitational-wave signals would affect all the pulsars in a similar way, so we get all of the signal across all of the sample but each individual pulsar would have its own noise. Each pulsar has different noise so we can separate the possible instability of the individual pulsar from the instability of the whole sample. It's really a combination of comparing the pulsars; *LIGO* is just unique in probing the highly dynamic régime of space–time and gravity. So we will not be able to compete with *LIGO* when it comes to the merger. What I've tried to demonstrate is that if you talk about at least some constraints on gravitational-wave emission, at least to low orders we can compete or be more precise than *LIGO*, and I think that's the beauty of combining these methods. By completely different methods, completely different régimes if the theory is correct, it has to fit all across the parameter space and that's where the power lies in the combination of the two methods.

Professor P. G. Murdin. How close are you to being in a position of not having accurate enough terrestrial clocks to do this?

Professor Kramer. Fortunately, we're still on the safe side. First of all, our clock colleagues are making superb progress: they now have precisions of down to 10^{-21}. But as those clocks are only stable for weeks to months, they hand over from clock to clock, while our pulsar time-scales are accurate over years and decades. So for the instantaneous measurement, we don't run into problems and that's the real measurement we do. When we do the instantaneous measurement, we refer it to an atomic clock in the observatory, do the GPS transfer, correct it to atomic time and international time. We can, however, — and this is a nice experiment — show by just looking at pulsars, that our colleagues in Paris at the BIPM tune their atomic clocks from time to time. We see this in our signal because suddenly, we see some deviation that is common to all the pulsars. Nothing is secret. [Laughter.] So I think again, we're feeding off each other and helping each other.

The President. Michael, thank you very much indeed, and thanks for a wonderful George Darwin Lecture. [Applause.] So that concludes today's programme. May I invite you to a seasonal drinks reception in the RAS library immediately following this meeting, and I give notice that the next Open Meeting of the Society will be on Friday, 13th of January 2017. Finally, a happy Christmas to Fellows and visitors. [Applause.]

POLARIMETRY NARROWS DOWN THE POSSIBILITIES FOR THE DUSTY S-CLUSTER OBJECT (DSO/G2) IN THE GALACTIC CENTRE

By Michal Zajaček, Andreas Eckart & Banafsheh Shahzamanian
University of Cologne

There have been many speculations about the character of the dusty object moving fast in the vicinity of the Galactic-centre black hole. The recent detection of polarized continuum emission provides new constraints for the models. The fact that the object is intrinsically polarized implies that it is non-spherical. The authors propose that a young star developing a bow shock can explain the main characteristics. However, more observations in the future are needed for the final confirmation of the nature of the source.

Discussion

The object known as the Dusty S-cluster Object (DSO; where S-cluster is the name of the innermost stellar cluster in the Galactic centre), often also denoted as G2, was considered shortly after its discovery[1] as a small gas and dust cloud of only three Earth masses. However, subsequent monitoring by the *Very Large Telescope* of the European Southern Observatory as well as the *Keck* telescopes has shown that the object does not tidally stretch in a way we would expect for a simple core-less gas cloud. Instead, the dusty source has stayed more compact than expected and survived intact the close passage to the black hole in the spring of 2014[2,3].

Despite the compactness, the dispute about the character of the object has continued, mainly because it has not been possible to resolve directly the internal structure of the enigmatic object, as is possible, for example, for nearby young stars in the Orion star-forming region. To make things more complicated, some experts claim[1,4] that they do detect the tidal stretching of the source. As a result, many scenarios for the nature of the DSO have been proposed. They can be mostly grouped into three categories: a core-less cloud[1] or streamer[4,5], a dust-enshrouded star[6,7], and a binary scenario — either binary merger[3,8] or disruption[7] of both components, where one of them can escape the Milky Way entirely as a so-called hypervelocity star.

However, there is a way to go partially around the angular-resolution problem. One can try to study the polarization properties of the incoming electromagnetic signal to see if the source as a whole is polarized or not. Polarized sources have a preferred plane in which the electric-field vectors are oscillating, which gives hints about their internal geometry as well as radiative processes.

It was quite a surprise when it was discovered[9] that the DSO is an intrinsically polarized source in the near-infrared *Ks*-band (2·2 micrometres). Whereas surrounding stars close to its position have a degree of polarization close to zero, the DSO exhibits a polarization degree of around 30 percent for four consecutive epochs (2008, 2009, 2011, and 2012). This implies that the source must deviate from spherical symmetry, otherwise the individual polarization contributions would cancel out.

The detection of polarized emission puts a new constraint on the character of the object. In general, the DSO is a very faint source in an extremely crowded stellar field: the number density of stars in the central few light years is about 10 million times that in the Sun's neighbourhood. Therefore disentangling the emission of the DSO from that of the surrounding sources is often challenging. In addition, it is not possible to resolve the brightness distribution as it is for nearby objects. As a consequence, it is necessary to combine carefully orbital dynamics, spectral properties, and, at last, the polarimetry, to see the full picture of the mosaic.

In the polarization-detection paper, the authors[9] also construct a numerical radiative-transfer model of the DSO. The model consists of typical ingredients of young stars: a star at the centre of the DSO is the source of thermal photons, and is surrounded by a dusty envelope and bipolar cavities due to outflows, which together re-process the emission of the star — UV and optical photons are absorbed by dust particles and re-emitted at longer wavelengths, mostly in the near- and mid-infrared domains. Furthermore, the photons emitted by the star and the dust are scattered by dust particles, which is the source of polarized emission in the model.

Moreover, since the DSO is expected to move supersonically close to the black hole, a bow shock is formed ahead of the star[10]. All of these components, which one would expect for a supersonic young star in the Galactic-centre region, lead to a significantly non-spherical nature of the source, which gives rise to the overall polarized near-infrared emission. Not only is the model successful in explaining the polarization properties, it can also match other observed characteristics of the DSO, namely a significant near-infrared excess or 'reddening' due to dust emission and broad hydrogen-emission lines, which arise due to the Doppler broadening either because of the material flowing towards the star (accretion) or by gas outflows or winds, which are both typical features of young stars[2].

It could be argued that the overall non-spherical shape is caused by the gradual prolongation of the gaseous component by tidal forces rather than the model described. However, the DSO/G2 source does not show convincing signs of tidal interaction in either line or continuum emission[2,3]. Tidal stretching would be expected for a core-less cloud or a star with an extended envelope with a length-scale of about 100 AU. In that case the source would be tidally stretched along the orbit by a factor of a few[2], which was not detected during the peribothron passage[2,3], when the effects of the orbital foreshortening are minimized. In fact, the DSO is fully consistent with being a point source[3].

Therefore, based on the compactness and a prominent IR excess, a pre-main-sequence star surrounded by a non-spherical dusty envelope (envelope with bipolar cavities) seems to be a more natural scheme to explain the continuum and line-emission characteristics. In the framework of this scenario, a bow shock forms due to an expected supersonic motion close to the pericentre, which further breaks the spherical symmetry.

Further monitoring of the source will help us to test the proposed model, mainly by the means of orbital dynamics. If the motion of the source does not deviate from a simple Keplerian ellipse, it must be a compact object, not a cloud. On the other hand, the core-less cloud would sooner or later start spiralling in towards the black hole because of the interaction with the surrounding ambient medium.

It remains a small puzzle, though, how such a young star as proposed to explain the DSO phenomenon can be formed and subsequently orbit so close to the black hole for such a long period of time — possibly several-hundred-thousand years, which is the estimated age of class 0 and class 1 protostellar objects[2]. Thanks to the computer modelling, this problem can be partially tested by means of numerical experiments. It was already confirmed[11] that *in-situ* star formation close to the black hole can take place when a cold molecular cloud of about 100 solar masses falls in towards the black hole from the region where there is a molecular circum-nuclear disc that contains clumps of a similar mass (approximately 1·5–6 parsecs from Sgr A*). In this model, the critical density for the onset of the collapse is reached by the tidal focussing because of the black hole's gravity — one can talk about so-called black-hole-assisted star formation. Another proposed scenario is the gravitational instability and the fragmentation of a massive accretion disc encircling the black hole[12], which is supported by the observed stellar disc containing massive young stars with an age of only a few million years. On-going star formation in the central 2 parsecs was also supported by recent radio and infrared observations[13] in terms of finding localized water and SiO masers and identifying infrared-excess sources whose spectral energy distribution is consistent with massive young stellar objects.

Since the star formation close to the massive black hole has many intricacies, several important details of how stars are formed at the Galactic centre remain still blurred. New, powerful instruments in the near future, such as the *James Webb Space Telescope* or *European Extremely Large Telescope*, will certainly shed new light on the problem. Regardless of some remaining theoretical problems, the observations seem to show that star formation can proceed in different environments throughout the Galaxy — from the close vicinity of the supermassive black hole at the Galactic centre all the way to the Galaxy outskirts.

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SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 254: HD 155878, HD 156613, HD 159027, AND HD 162054

By R. F. Griffin
Cambridge Observatories

The stars mainly discussed in this paper are all between about the eighth and ninth magnitudes and are located in the constellation Hercules. They came to attention as binaries in the course of the writer's 'Clube Selected Areas' programme[1] of radial-velocity observations (recent succinct descriptions of which may be found in the *Introduction*s to Papers 251 and 253[2,3]). HD 159027 and HD 162054 are in Area 1, and so is HD 155878 although it was not actually on the Clube programme, while HD 156613, which is at a somewhat higher declination, is in Area 2. All except for HD 162054 are *Hipparcos* stars, and they all have good magnitudes and colour indices determined by the satellite's *Tycho* programme. In no case has the companion star been apparent in the radial-velocity traces.

HD 155878 is brighter than most stars on the Clube programme, at $V = 8^{m}{\cdot}11$; the $(B - V)$ colour index is $1^{m}{\cdot}03$. Although the star is within Area 1, it was not eligible for the present writer's 'Clube' programme because its spectral type in the *Henry Draper Catalogue* is G5 and not K0. There is an MK classification of G8 II, but the *Hipparcos* parallax shows that the luminosity actually corresponds to class III. Eighty-two Cambridge radial velocities support an orbit that has a period of 4·4 years and an eccentricity of 0·6.

HD 156613 is another star that is shown by its *Hipparcos* parallax to have the luminosity of a giant, or nearly so; its *V* magnitude is $9^{m}{\cdot}01$. It has a circular orbit whose period is about 14 months.

HD 159027 is even brighter than HD 155878, at $V = 7^{m}{\cdot}99$. Again, the parallax shows it to be a giant, and it has been classified as K2 III. Its radial velocity was first measured by the writer in 1970, but it was not until the sixth observation was made, in 2005, that it was recognized as a binary, although its velocity amplitude of 7·8 km s^{-1} is the largest among the four stars treated here. The period is about 3·7 years and the orbital eccentricity about 0·38.

HD 162054, which at $8^{m}{\cdot}11$ is as bright as HD 155878 and nearly a magnitude brighter than HD 156613, was omitted from the *Hipparcos* programme because its brightness is considerably under-stated (at $8^{m}{\cdot}7$) in the *HD*, although photometry was nevertheless obtained for it by *Tycho*. It has proved to be a binary whose orbit has a period of a little over two years and a moderate eccentricity of 0·33.

Introduction

Certain recent papers[2,3] in this series have included brief introductory sections describing the 'Clube Selected Areas' radial-velocity programme[1] that has led to the discovery of numerous spectroscopic binaries, the orbits of a good many of which have already featured in this series of papers. Here the orbits of three more of the Clube stars are presented, together with the orbit of a star (HD 155878) that is within one of the relevant fields but is not eligible in its own right for the Clube programme because its *HD* spectral type is not K0 (one of the criteria for inclusion in the programme) but G5. The four stars are all quite close together in the sky, in the constellation Hercules, with right ascensions near 17½ hours. They are within Clube Area 1, having declinations near +28°, except for HD 156613, which is in Area 2 at nearly 46°.

It was explained in the second paragraph of the *Introduction* to the later[3] of the papers to which reference is made at the beginning of the paragraph above that the Clube programme in the northern hemisphere was undertaken in two phases, the results of the first of which were published[1] some thirty years ago. The observations were made in Cambridge, and so were unable to include Areas much south of the equator. Subsequently, the southern Areas were observed from ESO; the greater richness of the *Henry Draper Catalogue* in the southern hemisphere, and the writer's privilege in using there a larger and partly automated telescope, resulted in a reversal of the disparity between the hemispheres of the radial-velocity coverage of the Clube stars. That inequity was addressed by a renewed observational campaign at Cambridge (still not published), in which the population of stars eligible for the Clube programme in the northern sky was increased simply by deeming the several Areas to be considerably bigger than before and thereby bringing a lot of 'new' stars into the programme. The objects still had to match the original criteria of featuring in the *Henry Draper Catalogue* with 'photometric' magnitudes within half a magnitude of 9·0 and a spectral type of K0. Two of the four stars principally discussed below (HD 156613 and HD 162054) are 'new' in that sense, and did not feature in the original publication[1] on the Clube programme.

HD 155878

This star is really an interloper in the 'Clube Selected Areas' programme: although it is well within one of the designated fields (Area 1), it is classified in the *Henry Draper Catalogue* as type G5 rather than the K0 that is one of the selection criteria for the Clube programme. It is also 'too bright', having a 'photometric' magnitude in the *HD Catalogue* of 8·2, whereas for eligibility for the Clube programme it would need to be within half a magnitude of 9·0. The *HD* magnitude has been quite closely confirmed by the photoelectrically determined *V* magnitudes of 8·102 and 8·11 that have been published for it by Paunzen[4] and Hohle *et al.*[5], respectively. The former also gave a *B* magnitude that implies a $(B-V)$ of $1^{m}{\cdot}03$. HD 155878 was observed in the course of the *David Dunlap Observatory* (*DDO*) survey[6] of the +25° to +30° declination zone in the 1950s; the mean of four radial velocities was found to be +3·0 km s^{-1} with a 'probable error' of 1·1 km s^{-1}, and the spectrum was classified as G8 II. The star was observed by *Hipparcos*, which assigned it the number 84239 and determined its parallax as 2·72 ± 0·77 milliseconds of arc. That corresponds to a distance of 368 pc, with an uncertainty of the order of 100 pc; the distance modulus is therefore about 8 magnitudes and the M_V must be close to zero, suggesting that the luminosity is that of a normal giant rather than the Class II of the *DDO* classification. (The values of 367·650 pc for the distance and 83·88 $L_{\odot}$ for the luminosity are listed by McDonald, Zijlstra & Boyer[7] with a precision that is thousands of times greater than is warranted by the accuracy of the data.) No doubt it was on the basis of the same data that Hohle *et al.*[5] gave an L_{bol} of 84 $L_{\odot}$; they also listed the mass of the star as 2·49 ± 0·29 $M_{\odot}$. In addition to the *DDO* radial velocity, there is a mean of −2·00 ± 1·27 km s^{-1} that was given by de Medeiros & Mayor[8].

Radial velocities and orbit of HD 155878

The appreciable (though not exactly arresting) uncertainty of that radial velocity listed by de Medeiros & Mayor seemed to flag HD 155878 as having a variable velocity. On the basis of that understanding, in 2002 May the star was placed on the writer's radial-velocity programme and was observed with the Cambridge *Coravel* instrument every month or two. In the first year a small increase of velocity (less than 1 km s^{-1}) seemed to take place. No significant further change occurred during the second year, but there then ensued a definite decline, amounting by late 2004 to about 4 km s^{-1}. The star has continued under observation at Cambridge, often still at 1–2-month intervals, but somewhat more often during the comparatively rapid declines of velocity and rather sharp minima that occur as a result of the quite high eccentricity (~0·6) of the orbit and its ω in the second quadrant.

TABLE I

Radial-velocity observations of HD 155878

Except as noted, the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity km s⁻¹*	*Phase*	*(O–C) km s⁻¹*
1986 May 25·03*	46575·03	+0·9	0·796	−0·2
July 9·97*	620·97	+1·3	·825	+0·2
1987 May 7·04*	46922·04	−2·7	1·014	+0·1
1997 Aug. 30·91*	50690·91	−0·3	3·380	−0·3
2002 May 31·04	52425·04	+0·3	4·468	0·0
July 13·99	468·99	+0·6	·496	+0·2
Aug. 27·87	513·87	+0·4	·524	−0·1
Oct. 4·85	551·85	+0·7	·548	+0·2
Nov. 14·76	592·76	+0·4	·573	−0·2
2003 Feb. 18·23	52688·23	+1·0	4·633	+0·2
Apr. 16·14	745·14	+0·7	·669	−0·2
June 21·00	811·00	+1·0	·710	+0·1
Aug. 14·94	865·94	+1·2	·745	+0·2
Oct. 11·86	923·86	+0·6	·781	−0·5
2004 Mar. 1·23	53065·23	+1·3	4·870	+0·2
May 22·06	147·06	+0·9	·921	+0·2
Aug. 12·95	229·95	−0·7	·973	+0·1
Sept. 8·85	256·85	−1·6	·990	+0·2
13·84	261·84	−2·0	·993	0·0
Oct. 5·83	283·83	−3·0	5·007	−0·4
25·75	303·75	−3·2	·020	−0·2
Nov. 14·71	323·71	−2·6	·032	+0·4
2005 Jan. 11·24	53381·24	−2·6	5·068	−0·1
Mar. 23·20	452·20	−1·9	·113	−0·1
May 8·07	498·07	−1·0	·142	+0·5
June 11·01	532·01	−1·1	·163	+0·2
Aug. 6·92	588·92	−0·8	·199	+0·2
Sept. 16·84	629·84	−0·8	·224	0·0
Oct. 25·79	668·79	−0·7	·249	−0·1
2006 Mar. 23·18	53817·18	−0·2	5·342	0·0
May 11·08	866·08	+0·2	·373	+0·2
June 11·03	897·03	+0·1	·392	+0·1
July 12·96	928·96	+0·5	·412	+0·4
Aug. 7·96	954·96	0·0	·428	−0·2
Sept. 10·91	988·91	−0·2	·450	−0·5
Oct. 26·78	54034·78	+0·2	·478	−0·1
Nov. 29·71	068·71	+0·6	·500	+0·2
2007 Apr. 12·16	54202·16	+0·9	5·584	+0·3
May 8·10	228·10	+0·5	·600	−0·2
June 21·05	272·05	+1·0	·627	+0·2
July 18·98	299·98	+1·2	·645	+0·4
Aug. 30·94	342·94	+1·0	·672	+0·1
Sept. 22·86	365·86	+0·7	·686	−0·2
Oct. 17·82	390·82	+0·5	·702	−0·4
Nov. 21·73	425·73	+1·8	·724	+0·8

TABLE I (*concluded*)

Date (UT)			*MJD*	*Velocity* km s⁻¹	*Phase*	*(O–C)* km s⁻¹
2008	May	19·09	54605·09	+1·3	5·836	+0·2
	Aug.	30·91	708·91	+0·8	·902	−0·1
	Sept.	26·89	735·89	+0·7	·919	−0·1
	Oct.	21·80	760·80	+0·6	·934	+0·1
	Nov.	7·75	777·75	+0·4	·945	+0·1
		18·73	788·73	−0·2	·952	−0·3
	Dec.	2·71	802·71	−0·3	·960	−0·1
2009	Mar.	6·23	54896·23	−2·9	6·019	0·0
	Apr.	22·15	943·15	−2·9	·049	−0·1
	May	20·08	971·08	−2·3	·066	+0·3
	June	26·04	55008·04	−2·0	·089	+0·2
	Aug.	15·93	058·93	−1·9	·121	−0·2
	Sept.	25·87	099·87	−1·6	·147	−0·2
	Nov.	17·76	152·76	−1·3	·180	−0·2
2010	Apr.	8·17	55294·17	−0·7	6·269	−0·2
	May	12·11	328·11	−0·4	·290	0·0
	June	12·06	359·06	−0·4	·310	−0·1
	July	21·90	398·90	−0·2	·335	0·0
	Aug.	23·95	431·95	−0·3	·355	−0·2
2011	Oct.	14·79	55848·79	+0·6	6·617	−0·1
2012	May	12·09	56059·09	+0·8	6·749	−0·2
	June	29·02	107·02	+1·2	·779	+0·1
	Aug.	1·93	140·93	+1·0	·800	−0·1
	Sept.	3·88	173·88	+1·2	·821	+0·1
	Nov.	5·77	236·77	+0·8	·861	−0·3
	Dec.	1·70	262·70	+0·9	·877	−0·1
2013	Apr.	28·13	56410·13	−0·9	6·969	−0·3
	May	7·14	419·14	−0·9	·975	0·0
		9·11	421·11	−0·8	·976	+0·2
	June	4·10	447·10	−1·7	·993	+0·2
		14·04	457·04	−2·2	·999	+0·1
		21·97	464·97	−2·5	7·004	0·0
	July	10·03	483·03	−3·0	·015	−0·1
		29·97	502·97	−3·2	·028	−0·2
	Oct.	16·81	581·81	−2·5	·077	−0·1
	Nov.	12·73	608·73	−2·1	·094	0·0
2014	Feb.	16·23	56704·23	−1·7	7·154	−0·3
	May	15·11	792·11	−0·7	·209	+0·2
	Aug.	17·92	886·92	−0·4	·269	+0·1
2016	Aug.	7·92	57607·92	+0·8	7·721	−0·2
	Sept.	11·86	642·86	+1·0	·743	0·0

*Observed with OHP *Coravel* by de Medeiros & Mayor[8]; wt. 1

The Cambridge observations have been more or less maintained up to the time of writing, and there are now 82 of them. They are set out in Table I, and delineate an orbit with a period of about 4·4 years and an eccentricity, as already noted, of 0·6. The four OHP observations[8] are available individually, and are listed at the head of Table I after receiving an empirical zero-point

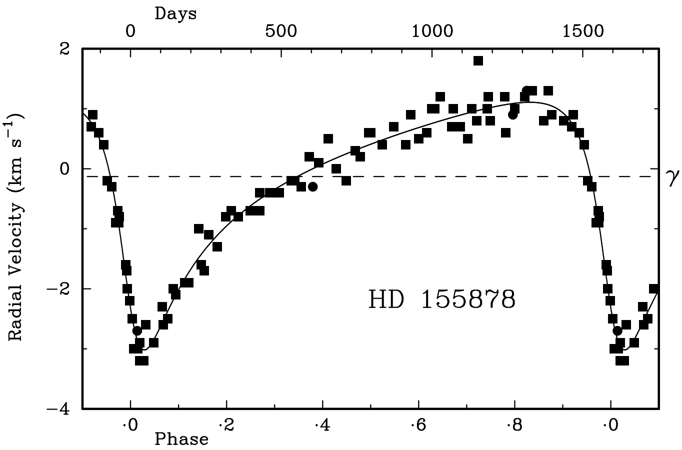

FIG. 1

The observed radial velocities of HD 155878 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The first four observations were made by de Medeiros & Mayor[8] at Haute-Provence and are plotted as filled circles; the remaining 82 were obtained by the writer with the Cambridge *Coravel* and are shown as filled squares. The two sources were weighted equally in the derivation of the orbit.

adjustment of +1·5 km s^{-1}; they give residuals similar to the Cambridge ones, and are included with the same weight in the solution of the orbit, although they are too few to make significant improvements to the orbital parameters or their standard errors. The orbit is illustrated in Fig. 1 and its complete elements appear in the first numerical column of Table V. The r.m.s. residual of 0·22 km s^{-1} is reasonably small for *Coravel* observations, although the residuals for HD 159027 and HD 162054 are seen from Table V to be smaller still (less than 0·2 km s^{-1}). The mass function is unusually small and must indicate that the secondary star is of low mass and/or that the orbit has a low inclination to the line of sight. The smallness of the mass function may also be due in part to the considerable mass of 2·5 $M_{\odot}$ attributed by Hohle *et al.*[5] (as noted above) to the primary star. If that figure for the mass of the primary is accepted, then the minimum mass of the companion (corresponding to the situation when the orbit is seen edge-on) would be about 0·17 $M_{\odot}$. That is about the mass of a main-sequence star with a type of M6 or M7. For orbital inclinations away from 90°, the deduced mass would rise approximately as the inverse of sin *i*, but the fact that no evidence of the companion star has been seen in the radial-velocity traces shows that that star must in any case be much fainter than the primary.

HD 156613

HD 156613 is at a somewhat higher declination (about 46°) than the other stars treated in this paper (they are all at about 28°), and is in Clube Area 2 whereas all the others are in Area 1. It is to be found about 50 minutes of arc south-preceding the 5^{m}·6 M-type star 74 Her. The V magnitude and $(B-V)$ colour index, inferred from the *Tycho 2* V_T and B_T measurements, are 9^{m}·01 and 1^{m}·03, respectively. The colour index is about that appropriate to a giant star with the *HD* type of K0, but no subsequent classification is available. There is disappointingly little other information about the star in the literature. Really, the only hard datum seems to be the parallax found by *Hipparcos*, of 3·43 ± 0·77 milliseconds of arc, corresponding to a distance modulus of $7^{m}\cdot 3$ that is good to about half a magnitude; it inverts to a distance of 292 pc with an uncertainty of the order of 60 pc. Comparison of the distance modulus with the apparent magnitude of HD 156613 indicates the absolute magnitude to be near +1·7, with the same half-magnitude uncertainty as the modulus. The figures just given for the distance modulus and colour index are not expected to be much affected by interstellar absorption and reddening, in view of the (astronomically) modest distance of the star and the fact that it is far (~35°) from the Galactic plane.

Radial velocities and orbit of HD 156613

The only radial velocities that are known to have been made of HD 156613 are those made by the writer with the Cambridge *Coravel*, starting in 2002. (It was in that year that systematic measurements were begun of the stars in Clube Area 2 that met the criteria for eligibility for that programme.) The normal policy, in dealing with a large batch of previously unobserved stars, is to observe them not more frequently than once a year unless there is a special interest in an individual case; too short an interval is liable to result in failure to discover a good proportion of the binary stars in a new programme. Accordingly, a second measurement of HD 156613 was made nearly a year after the first; it was somewhat discordant, a situation that prompted another observation to be made the very next night, confirming the later result. Rather surprisingly in retrospect, the matter was not pursued further until 2006, when the star was at last included in the writer's binary programme; systematic observations soon demonstrated a variation in excess of 10 km s^{-1}, and the orbital period of about 14 months became apparent.

The *Coravel* has remained the sole source of radial-velocity data, and 53 measurements, set out here in Table II, have been accumulated. The traces demonstrate significant rotation of the star, giving a mean $v \sin i$ of 7 km s^{-1}. They readily yield an orbit in which the eccentricity, if allowed as a free parameter, takes the value 0·014 ± 0·012, with $\omega = 0° \pm 54°$. The sum of squares of the residuals of the $n = 53$ data points (S_e for the eccentric solution and S_c for the circular one) rises only from $S_e = 6{\cdot}71$ to $S_c = 6{\cdot}89$ (km s^{-1})^2 when the fitted orbit is constrained to be circular. Lucy & Sweeney's statistical test[9] of significance, kindly set out clearly for me by Bassett[10] many years ago (after I made a mistake in my first effort to apply it!), utilizes the quantities S_e, S_c, and n, which here are numerically 6·71, 6·89, and 53; the product $((n - 6)/2)((S_c - S_e)/S_e)$, which in this case is about 0·63, is used in a derivative of the 'variance-ratio test'. The relevant criterion (the product just specified) is compared with values listed in tables of the F distribution, such as those set out in ref. 11 for various degrees of significance, and which for the present purpose have to be entered with 2 and $(n - 6)$ degrees of freedom. The 1% point of $F_{2,47}$ is as much as 7·20, the 20% point is about 1·67, and even the 50% point, at 0·70, is still above the actually observed value of 0·63, so we have to conclude that the evidence for non-circularity of the orbit of HD 156613 is very far from being significant, and we should adopt the circular solution. That is the one whose elements are included in Table V below. The orbit is illustrated in Fig. 2.

The mass function, though not as small as that of HD 155878, is still only a hundredth of a solar mass, so it is not surprising that no evidence of the companion star has been recognized in the radial-velocity traces.

TABLE II

Radial-velocity observations of HD 156613

All the observations were made with the Cambridge Coravel

Date (UT)	MJD	Velocity km s⁻¹	Phase	(O–C) km s⁻¹
2002 Sept. 10·94	52527·94	–28·8	0·965	–0·6
2003 Aug. 19·96	52870·96	–32·7	1·769	+0·7
20·86	871·86	–33·2	·771	+0·1
2006 July 29·01	53945·01	–35·3	4·286	+0·2
Aug. 28·90	975·90	–37·9	·358	+0·1
Sept. 10·92	988·92	–38·6	·389	+0·2
22·80	54000·80	–39·0	·416	+0·4
Oct. 4·89	012·89	–39·6	·445	+0·3
24·79	032·79	–40·1	·491	+0·1
Nov. 18·76	057·76	–38·9	·550	+1·0
29·72	068·72	–39·5	·576	0·0
Dec. 9·76	078·76	–39·7	·599	–0·6
2007 Feb. 15·23	54146·23	–34·1	4·757	–0·2
Apr. 2·17	192·17	–30·5	·865	–0·4
12·16	202·16	–29·6	·888	–0·1
30·15	220·15	–28·4	·930	+0·2
May 19·09	239·09	–27·4	·975	+0·7
June 1·05	252·05	–28·0	5·005	+0·1
21·05	272·05	–29·0	·052	–0·6
July 7·03	288·03	–29·2	·089	–0·2
18·98	299·98	–29·3	·117	+0·3
29·95	310·95	–30·0	·143	+0·4
Aug. 9·93	321·93	–31·0	·169	+0·2
30·96	342·96	–32·9	·218	0·0
Sept. 11·87	354·87	–34·9	·246	–0·9
22·87	365·87	–35·0	·272	0·0
Oct. 13·85	386·85	–36·8	·321	0·0
2008 Mar. 5·23	54530·23	–37·9	5·657	–0·4
May 19·09	605·09	–30·7	·832	+0·4
June 26·05	643·05	–29·4	·921	–0·6
July 9·04	656·04	–28·1	·952	+0·2
Aug. 10·95	688·95	–28·0	6·029	+0·2
Oct. 21·86	760·86	–31·9	·197	+0·3
Nov. 11·75	781·75	–34·2	·246	–0·2
Dec. 6·71	806·71	–36·4	·305	–0·2
2009 Apr. 29·14	54950·14	–37·9	6·641	+0·1
May 30·09	981·09	–35·7	·713	–0·2
June 12·01	994·01	–34·6	·743	–0·2
July 9·99	55021·99	–31·9	·809	0·0
2010 May 12·12	55328·12	–40·0	7·526	+0·1
22·09	338·09	–39·9	·550	0·0
June 23·00	370·00	–38·7	·624	–0·2
July 17·99	394·99	–37·0	·683	–0·4
23·95	400·95	–36·3	·697	–0·2
2012 June 29·01	56107·01	–38·4	9·351	–0·6
Aug. 19·97	158·97	–40·2	·473	–0·1
2013 May 3·10	56415·10	–28·6	10·073	+0·1
July 14·98	487·98	–34·0	·244	–0·1
Aug. 25·88	529·88	–37·3	·342	+0·2

TABLE II (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2014 Aug. 17·92	56886·92	−31·3	11·179	+0·2
Oct. 7·84	937·84	−36·1	·298	−0·2
2016 June 7·08	57546·08	−35·0	12·723	+0·2
Sept. 11·87	642·87	−28·1	·950	+0·3

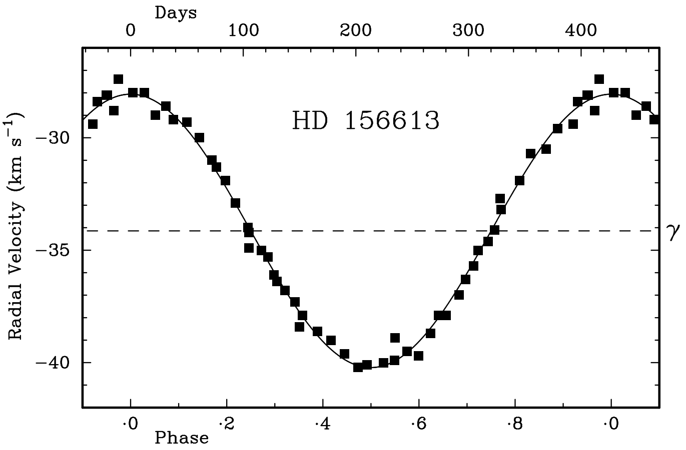

FIG. 2

Analogous to Fig. 1, but for HD 156613, and in this case all of the 53 observations were made by the writer at Cambridge.

HD 159027

This object is to be seen a little less than half a degree south-preceding the $5^{m}{\cdot}6$ A-type star 78 Her. Like the other objects treated in this paper, it is an *Hipparcos* star; its magnitude and colour index were measured in the *Tycho 2* programme, with results (when transformed onto the usual *UBV* system) of $V = 7^{m}{\cdot}99$, $(B - V) = 1^{m}{\cdot}24$. The *V* magnitude is unusually bright for a star on the 'Clube' programme. That is not through any mistake in its adoption as part of that programme, but is due either to variability or (perhaps more likely) to an unusually large error on the part of Miss Cannon[12], who (almost 100 years ago) judged the visual magnitude to be 8·6. (The Clube observing programme was compiled on the basis of the magnitudes and types listed in the *HD*, the only source that included all the stars of interest.) The spectral type of HD 159027 in that catalogue, like that of all 'Clube' stars, by definition, is K0. Yoss[13], however, gave the type as K2 III on the basis of an objective-prism spectrogram obtained with the Michigan 24/36-inch *Curtis Schmidt* (110 Å mm^{-1} at Hγ) when it was at the original site at Portage Lake, Michigan. (It was moved in 1967 to CTIO, where it still remains, albeit on the basis of what was nominally, at the outset, intended to be a 10-year loan.) Yoss also gave an intensity, estimated from the spectrogram, of the *CN* band that has its head at λ4216 Å. He put it at strength 3, meaning in effect normal strength, on a coarse numerical scale that ran from 0 to 4, where 4 represented unusually great strength and 2 to 0 represented increasing weakening.

The parallax of HD 159027 was measured by *Hipparcos* at 3·16 ± 0·80 arc milliseconds, which inverts to a distance modulus of $7^{m}\cdot5$ with an uncertainty of about half a magnitude, so the absolute magnitude probably lies between zero and +1.

Radial velocities and orbit of HD 159027

HD 159027 is the only one of the stars discussed in this paper to have featured previously in the original Cambridge 'Clube Selected Areas' programme[1], before the northern Areas were deemed to be increased in size in order to make the numbers of programme stars in them more comparable with those in the southern hemisphere where the *HD* (the source catalogue for the programme) is much richer. Three radial velocities were obtained of the star with the original radial-velocity spectrometer[14] in the 1970s. They showed a range of about 2 km s^{-1}, which was not then regarded as quite enough to demonstrate that the star is a binary. The mean value of +17·3 km s^{-1} was belatedly published by the present writer in the paper[1] giving radial velocities for 406 stars in the northern Clube Areas in 1986.

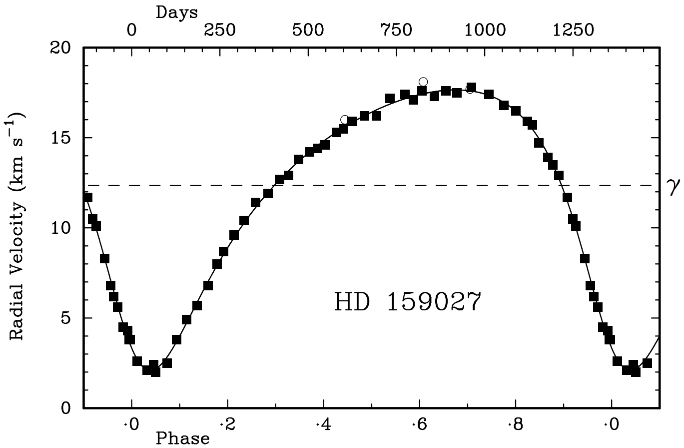

FIG. 3

Like Fig. 1, but for HD 159027. There are 58 measurements all told; the first three, represented by open circles (one of them almost hidden near phase 950 days), were made with the original photoelectric spectrometer[14] at Cambridge, and have been given weight ¼ in the solution of the orbit.

TABLE III

Radial-velocity observations of HD 159027

Except as noted, the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
1970 July 31·98*	40798·98	+18·1	0·608	+0·7
1974 Aug. 31·88*	42290·88	17·7	1·705	+0·1
1977 June 2·05*	43296·05	16·0	2·444	+0·4
2003 Sept. 19·87	52901·87	16·2	9·510	−0·3
2004 Sept. 14·91	53262·91	16·8	9·775	−0·2
2005 Sept. 16·91	53629·91	2·4	10·045	+0·3
17·87	630·87	2·1	·046	0·0
23·90	636·90	2·0	·050	−0·2
Oct. 25·80	668·80	2·5	·074	−0·3
2006 Apr. 4·15	53829·15	8·7	10·192	+0·2
May 3·10	858·10	9·6	·213	+0·2
June 1·07	887·07	10·4	·234	+0·1
July 3·99	919·99	11·4	·259	+0·3
Aug. 7·96	954·96	11·9	·284	−0·1
Sept. 8·93	986·93	12·7	·308	0·0
Oct. 4·89	54012·89	12·9	·327	−0·3
Nov. 1·80	040·80	13·8	·348	+0·1
Dec. 2·72	071·72	14·2	·370	0·0
2007 Apr. 2·17	54192·17	15·9	10·459	+0·1
May 8·11	228·11	16·2	·485	0·0
July 18·99	299·99	17·2	·538	+0·3
Aug. 30·95	342·95	17·4	·570	+0·2
Sept. 22·86	365·86	17·1	·587	−0·2
Oct. 17·82	390·82	17·6	·605	+0·2
Nov. 21·74	425·74	17·3	·631	−0·3
2008 Mar. 5·24	54530·24	17·8	10·708	+0·2
Apr. 24·13	580·13	17·4	·744	0·0
July 9·04	656·04	16·5	·800	0·0
Aug. 10·95	688·95	15·9	·824	+0·1
Sept. 12·91	721·91	14·7	·848	−0·3
Oct. 8·82	747·82	13·9	·868	−0·2
22·78	761·78	13·5	·878	0·0
Nov. 7·74	777·74	12·9	·890	+0·1
Dec. 2·72	802·72	11·7	·908	+0·2
2009 Mar. 27·20	54917·20	4·3	10·992	+0·4
Apr. 22·15	943·15	2·6	11·011	−0·1
May 20·09	971·09	2·1	·032	0·0
Aug. 11·90	55054·90	3·8	·093	+0·1
Sept. 9·90	083·90	4·9	·115	+0·2
Oct. 8·82	112·82	5·7	·136	−0·1
Nov. 9·77	144·77	6·8	·160	−0·2
2010 Oct. 6·82	55475·82	14·6	11·403	−0·3
Nov. 7·72	507·72	15·3	·426	0·0
2011 Sept. 13·89	55817·89	17·6	11·655	0·0
Oct. 14·79	848·79	+17·5	·677	−0·2

TABLE III (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2012 May 16·08	56063·08	+15·7	11·835	+0·2
Sept. 6·89	176·89	10·5	·919	–0·1
Nov. 5·77	236·77	6·2	·963	–0·3
Dec. 1·72	262·72	4·5	·982	–0·2
2013 Aug. 25·89	56529·89	8·0	12·178	+0·1
2014 June 6·10	56814·10	14·4	12·387	–0·2
Aug. 17·93	886·93	15·5	·441	–0·1
2016 June 7·09	57546·09	10·1	12·926	+0·1
July 2·01	571·01	8·3	·944	0·0
18·04	587·04	6·8	·956	–0·3
Aug. 7·94	607·94	5·6	·971	0·0
Sept. 8·87	639·87	3·8	·995	+0·1
11·87	642·87	+3·8	·997	+0·3

*Observed with original Cambridge spectrometer; wt. ¼

When the Clube stars were re-observed in a renewed effort, made with the new *Coravel* spectrometer in the enlarged northern fields, HD 159027 was again observed in 2003 and 2004; in those years it gave mutually accordant results that were within the spread of the 1970s ones. It was quite a surprise, therefore, to find in 2005 that there had been a change of about 14 km s^{-1} in just a year. Naturally that discovery led to the inscription of the star on the Cambridge binary programme, in the course of which 55 observations in total have been made with the *Coravel*. The measurements, plus the three much earlier ones which have merited weight ¼, are all set out in Table III and lead to an orbit with a period of about 3·7 years, which is plotted in Fig. 3 and whose elements are listed in the third numerical column of Table V.

The mass function is by far the largest of those found for the stars treated in this paper, but at about 0·05 $M_{\odot}$ it is still very modest. For primary masses of 1 and 2 $M_{\odot}$, the minimum masses required for the secondary would be about 0·5 and 0·7 $M_{\odot}$, respectively, corresponding to main-sequence companions of types near M0 and K5, whose luminosities would be negligible in comparison with the primary's. The lack of any evidence for the secondary star in the radial-velocity traces is therefore not at all surprising.

HD 162054

HD 162054 is to be found about 1° north of, and slightly following, the third-magnitude solar-type star μ Her. It is attributed a photo-visual magnitude of 8·7 in the *Henry Draper Catalogue*, but the *V* magnitude obtained by *Hipparcos* (on the *Tycho 2* programme; HD 162054 is not an actual *Hipparcos* star) is considerably brighter, $8^{m}·11$, while the corresponding *B* magnitude is $9^{m}·17$. The colour index of $1^{m}·06$ is that of a main-sequence star of type K3 or of a giant of type K0; the latter is more likely to correspond to the truth, in the light of the very small proper motion of only about 0″·007 annually.

The first radial-velocity measurement was made in 2003, and a year later the next one disagreed by nearly 10 km s^{-1}; the 55 observations now available are

TABLE IV

Radial-velocity observations of HD 162054

All the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2003 Sept. 19·88	52901·88	–18·6	0·498	+0·3
2004 Sept. 14·92	53262·92	–27·9	0·964	0·0
Oct. 26·81	304·81	–29·1	1·019	–0·4
Nov. 4·80	313·80	–28·5	·030	+0·1
2005 May 8·08	53498·08	–21·0	1·268	+0·2
June 1·05	522·05	–20·7	·299	–0·1
July 16·96	567·96	–19·6	·358	+0·2
Aug. 15·95	597·95	–19·2	·397	+0·3
Sept. 12·93	625·93	–19·5	·433	–0·3
Oct. 25·80	668·80	–19·1	·488	–0·1
Dec. 8·72	712·72	–18·3	·545	+0·6
2006 Mar. 23·18	53817·18	–19·6	1·680	–0·1
May 3·11	858·11	–20·3	·733	–0·1
June 1·08	887·08	–20·9	·770	–0·1
July 4·00	920·00	–21·7	·813	+0·2
Aug. 7·97	954·97	–23·4	·858	–0·1
29·95	976·95	–24·6	·886	–0·1
Sept. 10·93	988·93	–25·3	·901	–0·1
22·81	54000·81	–25·9	·917	0·0
Oct. 4·89	012·89	–26·3	·932	+0·3
24·78	032·78	–27·6	·958	+0·1
Nov. 23·71	062·71	–28·8	·997	–0·1
2007 Mar. 2·24	54161·24	–25·3	2·124	+0·1
Apr. 2·17	192·17	–23·9	·164	0·0
12·17	202·17	–23·6	·177	–0·1
30·15	220·15	–23·1	·200	–0·3
May 19·11	239·11	–22·1	·224	0·0
June 5·02	256·02	–21·4	·246	+0·2
Aug. 4·93	316·93	–20·3	·325	–0·1
Nov. 21·74	425·74	–19·0	·465	0·0
2008 Mar. 31·19	54556·19	–19·1	2·634	+0·1
Sept. 12·92	721·92	–22·9	·848	+0·1
Oct. 5·86	744·86	–24·0	·877	+0·1
Dec. 2·73	802·73	–27·5	·952	–0·1
2009 Mar. 30·19	54920·19	–25·9	3·103	+0·3
Apr. 29·14	950·14	–24·7	·142	0·0
2010 Mar. 23·21	55278·21	–19·1	3·566	–0·2
Apr. 13·14	299·14	–19·3	·593	–0·3
June 3·09	350·09	–19·2	·658	+0·1
July 17·99	394·99	–20·0	·716	–0·1
Sept. 11·86	450·86	–21·1	·788	+0·1
Oct. 10·85	479·85	–22·3	·826	–0·1
2013 June 4·10	56447·10	–27·3	5·074	0·0
14·04	457·04	–26·7	·087	+0·1
Sept. 14·91	549·91	–22·8	·207	–0·2
Oct. 5·83	570·83	–22·1	·234	–0·2
2014 May 15·13	56792·13	–18·8	5·519	+0·1
July 1·05	839·05	–19·1	·580	–0·2
Nov. 12·72	973·72	–20·6	·754	–0·1

TABLE IV (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2015 June 30·96	57203·96	–28·1	6·051	0·0
2016 July 19·01	57588·01	–19·1	6·547	–0·2
Sept. 8·87	639·87	–19·0	·614	+0·1
11·88	642·88	–19·1	·617	0·0

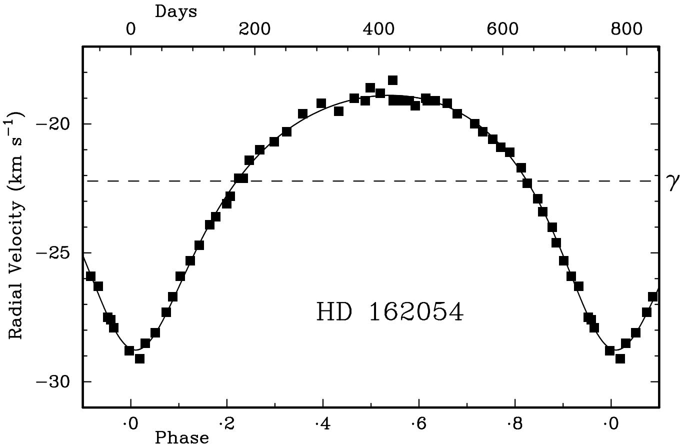

FIG. 4

Analogous to the preceding figures, but for HD 162054. All of the 55 radial velocities were obtained with the Cambridge *Coravel*.

set out in Table IV and yield an orbit with a moderate eccentricity of 0·33 and a period of 2·2 years. It is plotted in Fig. 4, and the complete elements are shown in the final column of Table V.

TABLE V

Orbital elements for HD 155878, HD 156613, HD 159027, and HD 162054

Element	*HD 155878*	*HD 156613*	*HD 159027*	*HD 162054*
P (days)	1593·2 ± 1·8	426·80 ± 0·30	1359·5 ± 1·0	774·8 ± 0·7
T or T_0 (MJD)	54866 ± 4	54676·7 ± 0·8	54927·9 ± 3·0	54840·1 ± 2·6
γ (km s^{-1})	–0·13 ± 0·03	–34·14 ± 0·05	+12·35 ± 0·03	–22·21 ± 0·03
K_1 (km s^{-1})	2·06 ± 0·04	6·08 ± 0·08	7·77 ± 0·04	4·94 ± 0·05
e	0·606 ± 0·012	0	0·378 ± 0·004	0·330 ± 0·007
ω (degrees)	131·4 ± 2·3	—	147·3 ± 0·9	172·3 ± 1·4
$a_1 \sin i$ (Gm)	36·0 ± 0·8	35·7 ± 0·4	134·6 ± 0·8	49·7 ± 0·5
$f(m)$ ($M_\odot$)	0·00073 ± 0·00005	0·00996 ± 0·00038	0·0527 ± 0·0009	0·00816 ± 0·00025
R.m.s. residual (wt. 1) (km s^{-1})	0·22	0·36	0·19	0·18

There is an obvious visual companion star a little over 2′ due south of HD 162054. The few mentions of it in the literature refer mostly to its position and not to its nature. It has, however, got *Tycho*-based magnitudes of $V = 9^{m}{\cdot}38$ and $(B - V) = 0^{m}{\cdot}50$, and *Simbad* lists a spectral type of G5 that does not appear to be in very good accord with the colour index. It has been observed for radial velocity four times, with the reasonably consistent results listed in Table VI; it gives a weak and rather wide dip in the traces, such as could be expected from a main-sequence star of about mid-F type with a projected rotational velocity of the order of 10 km s^{-1}. Its proper motion differs by a probably significant amount from that of HD 162054 itself, and the mean velocity of $-32{\cdot}1 \pm 0{\cdot}3$ km s^{-1} differs from the γ-velocity of the primary star by about 10 km s^{-1}, demonstrating with certainty that the two objects are not related to one another.

TABLE VI

Cambridge radial-velocity observations of BD +28° 2838 (HD 162054 B)

Date (UT)	*Velocity km s⁻¹*
2004 Sept. 14·92	−32·2
Oct. 26·81	−32·8
2005 May 8·08	−31·3
2006 Sept. 10·93	−32·2

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CORRESPONDENCE

To the Editors of 'The Observatory'

On the Velocity of Gravitational Waves

In 1905, when Einstein propounded his first theory of relativity, the only known means of remote observation of the physical world, dependent on neither transmitting medium nor transfer of material particles, was by electromagnetic waves, and that physical world was itself regarded, in the dominant Lorentzian view of the time, as an inherently and exclusively electromagnetic entity. It was therefore entirely natural for Einstein to identify the invariant fundamental signal-velocity required for the axiomatic construction of his new theory with the known 'velocity of light'. This choice, seemingly arbitrary to some, has long caused unease in some minds*. With the recent detections by *LIGO*, however, a new and fundamentally different era in physical science has dawned, for we now have a second, independent, such means of remote observation of the world. It may, therefore, be an apposite moment, with gravitational waves 'in the air', to take another look at this foundational issue, especially as there would appear to be a very simple thought-experiment argument which may settle the obvious question.

Two axioms, presumably uncontentious, are required. First, the macroscopic uniqueness axiom ('M.U.A.'), which simply says that physical reality on the macroscopic, classically-describable, scale is unique: in particular, that bodies possess uniquely-defined spatial positions referred to any given frame of reference. Without this there can evidently be no rational basis for classical mechanics, Newtonian or relativistic. Second, that gravitational waves could, in principle, be used to determine spatial positions, measure lengths and distances, and so forth, just as electromagnetic waves have been throughout the pre-*LIGO* era of physical science. There doesn't appear to be anything obviously contrary to the laws of Nature in this proposition, whose practical realization is therefore 'merely'(!) a technological challenge.

Now take a straight rigid rod, bearing at each of its two ends 'A' and 'B' a source of gravitational waves such as a massive rotating barbell, the rod in motion in the direction AB relative to a distant observer, to whom it is also optically resolvable. By Axiom 2 above, that observer can now make two completely independent measurements of the length AB relative to the observer's reference-frame, one by electromagnetic observation, the other by gravitational. For each such mode of observation and measurement, the usual argument for Special Relativity will, logically, apply with equal force, each therefore leading in exactly the same way to its own proper set of Lorentz transformations with the relevant signal-velocity, c for light and $c^\star$ for gravitational waves, inserted in the resulting equations. It is immediately evident that $c^\star \neq c$ leads to a direct contradiction of Axiom 1, by virtue of the Lorentz–Fitzgerald contraction. Therefore $c^\star = c$ — as simple as that! In a nutshell, the uniqueness of reality means that there can be only one invariant signal velocity, and it is purely historical accident that one particular physical manifestation of such signals was already familiar

* Einstein himself explicitly acknowledged this: A. Einstein, *The Meaning of Relativity, 6th Edn*. (Science Paperbacks reprint, 1967), p. 27. It is interesting that in such a short book, his only mathematical exposition of the theory in that format, Einstein was prepared to devote a paragraph to the issue, so often ignored in other texts.

long before Einstein came on the scene: the significance of the velocity of *light*, specifically, is merely historical, not logical.

Is this argument so obvious in general as to be trivial (in hindsight!)? One might be tempted to say so, were it not for two things. In the first place, it is not conspicuous in the literature of relativity, at least so far as the writer's acquaintance with that goes, despite its obvious relevance to answering precisely the kind of doubt about 'c' that any bright, critical-minded undergraduate ought to feel; many of the standard texts, indeed, seem to avoid any honest confrontation of *that* foundational issue entirely. And secondly, it appears from remarks at a recent RAS Specialist Discussion Meeting that the idea of a secularly-varying value of c — in itself not obviously in conflict with the argument above — has spawned a new generation of 'Bimetric' theories whose consistency with the uniqueness requirement is not self-evident. At the very least, *if* the argument given here is valid in this particular case, it is surely to be preferred either to asserting that $c^\star = c$ is solely a specific result of the mathematics of gravitational waves in GR — which doesn't exactly win any prizes as an *explanation* of this vital point! — or to the logical error of claiming, as is sometimes done, that it is a mere assumption†? Incidentally, it immediately follows from the thought-experiment just proposed that when the observed value of c varies, as indeed it does in GR in a localized gravitational field, $c^\star$ must likewise vary in exactly the same way — *ergo* the possibility of gravitational lensing of gravitational waves, something which would surely have delighted Einstein and which will presumably be implemented observationally one day?

The writer makes no claim to deep technical expertise in GR, despite having devoted much thought over the years to issues of physical foundations, so he would be very interested to hear the views of a real — and critical-minded — relativist on what has been said here. The matter is surely worth considering.

Yours faithfully,
CHRISTOPHER TAYLOR

Hanwell Community Observatory
Banbury
Oxon
OX17 1HN

2017 February 22

†The tangled tale of $c^\star$ for gravitational waves in GR is amply illustrated by, *e.g.*, the following: A. S. Eddington's *Mathematical Theory of Relativity* (1924), §57 and Note 7 — see especially his remarks in last paragraph p. 130 and the first on p. 131; see also F. A. E. Pirani, *Invariant formulation of gravitational radiation theory* in *Phys. Rev.*, **105**, 1089, 1957, an important paper in the development of the classical theory, in which Pirani adopts $c^\star = c$ as part of his *definition* of the particular waves he discusses (out of a potentially larger set of wave-solutions), a procedure plainly only logically possible and desirable because of the lack of clarity on this issue in the existing theory; and to judge by Chap. 20 of R. d'Inverno's popular textbook *Introducing Einstein's Relativity* (Oxford University Press, 1992 & 1999), the situation recently is no more logically- and mathematically-straightforward than it was either in 1924 or in 1957. In mathematics and mathematical physics, complexity often comes first, simplicity only later: *is* there any such simplicity to be had here?

REVIEWS

Amazing Stories of the Space Age, by R. Pyle (Prometheus, Amherst), 2017. Pp. 325, 20·5 × 13 cm. Price $18 (about £14) (paperback; ISBN 978 1 633 88221 8).

Back in the early 1960s a tea company in the UK sold packets of tea each containing a small collectable card illustrating the wonders of space travel, current and future. One of the highlights of that set of cards was a spacecraft with wings and a sharp-nosed streamlined shape — just like the jet fighters of the era. That vision of technological exuberance was called the *Dyna Soar*, and as the years went by I often wondered what became of that elegant craft; this book has finally told me. It morphed into the Air Force X-20 space plane which ultimately lost the funding battle to NASA's Mercury and Gemini 'spam in a can' approach to manned space flight when Robert McNamara became President Kennedy's Secretary of Defence. Those of you who have burned the midnight oil drafting and redrafting funding proposals for satellite and rocket instruments can only marvel at the resources available to both the successful and failed programmes during that period. By the time it was cancelled in 1963 over 400 million dollars had been spent on the *Dyna Soar* project.

There is much to admire in this book even though some of the 'amazing stories' have the aura of spoofs; for example, one of the initially classified documents consulted and illustrated carries the title "The meanderings of a weapon oriented mind when applied in a vacuum such as on the moon" (*Report number 18698·53* from the US Army Weapons Command). As Pyle notes, the author probably meant that the weapon was applied in a vacuum and not the mind. The report deals with the effect of extreme temperature variations on guns, and the potential for cold welding of clean metal moving parts. After elaborating on the various methods of making guns for space and the Moon, serious consideration was given to the possibility of a bullet fired on the Moon, if it missed its target, having sufficient velocity to make a complete lunar orbit and return to shoot the unfortunate marksman in the back — neglecting crashing into lunar crater rims, *etc.* In spite of the UN treaty on the non-militarization of outer space and the subsequent banning of weapons in space, we are told that there is one known exception; in a special emergency package in the *Soyuz* capsule used to carry crews of all nationalities to and from the *ISS*, there is a three-barrelled gun which according to the author is placed there because the Russian capsules return to Earth in the vast wastes of Siberia. The gun is for defence against any marauding bears that might find a space-suited astronaut a tasty gift-wrapped lunch. Guns in space are just one of the many surprises to be found in this book.

The cover (on the advance copy) shows Ed White during his iconic space walk from *Gemini 4* (in 1965) collaged with an artist's impression of another Gemini-era spacecraft, the proposed *Manned Orbiting Laboratory*. The image together with the comic-strip title seems designed to appeal to eight-year-old boys, and as such the book's cover belies the content. This is actually quite a serious and well-researched book that I would guess will appeal to exactly the demographic of *The Observatory* magazine — those who, in the current argot of the latte-drinking classes, are described as nerds or geeks and are also probably a few decades older than the publisher's seemingly anticipated readership. Those of us who grew up during the frenetic, cold-war-driven, space programmes of the 60s and early 70s will remember many of the spacecraft described, but probably at the time knew little of the other battle going on behind the scenes. Played out between the US Air Force and the civil programme of NASA was a struggle for control of manned space flight. As much as the technology, management personalities played a part in the final outcome. The antipathy of a couple of Air Force generals towards each other, the antipathy of the Air Force towards NASA, and the belief that, if it's got wings it needs a pilot and belonged to the Air Force, drove the largely futile attempts of the USAF to secure a role in manned space flight. Pyle does tell us, however, that the Air Force did have significant input into the design of the space shuttle — it did, after all, have wings.

The amazing stories are not just from the US space programme, but, as the *Soyuz* gun illustrates, the Soviet Union programme also gets significant mention. There are chapters dealing with the *Vostok* flights and the early ill-fated *Soyuz* (and there is one particularly insensitive image from a failed landing which I hope doesn't make it to the final published version of the book), and a significant exploration of the *Buran* space shuttle look-alike, which it turns out was spectacularly and ironically well named. Partly because of the time frame being covered, European space endeavours do not feature very highly, other than the German pioneers of rocketry. A story that could have been appended concerns one of the earliest USAF studies, awarded to Bell Aircraft in 1954 for the X-1 rocket plane. What Pyle fails to mention is that in this case the Brits had got there first — the Miles Aircraft Company in Woodley, Reading, had already developed a design for a supersonic aircraft (M-52), which along with some Rolls Royce aero engines was handed over to the US in 1944. The wind-tunnel models are still available to see at the Miles museum in Woodley (Berkshire Museum of Aviation http://museumofberkshireaviation.co.uk/html/gallery/m52.htm).

The *Dyna Soar*, orbiting laboratories, nuclear rockets, and many other futuristic plans are described in this quite dense book: 22 chapters, each a project, plus 24 pages of photographs, and numerous illustrations within the text detail the aims and ambitions of successful programmes as well as those which for various reasons remained as drawing-board sketches or even, just like the Moon gun, concepts to be illustrated in reports with whimsical titles.

There is a chance that if I had seen only the cover of this book I may not have picked it up, so it was an unanticipated pleasure to be asked to read it for review and be able to report that it is enlightening, fun, and a great read. — BARRY KENT.

The Future of Human Space Exploration, by G. Bignami & A. Sommariva (Palgrave Macmillan, London), 2016. Pp. 205, 22 × 15·5 cm. Price £66·99/$99·99 (hardbound; ISBN 978 1 137 52657 1).

As a child of the space age, growing up in the era of the race to the Moon, I have been rather disappointed by the much slower pace of progress since the heady days of the 1960s, when everything seemed possible. For example, a human mission to Mars, predicted for the 1980s at the time, still seems just as far in the future as it ever did. On the other hand, as my own 'space' career has developed, I have come to appreciate just how difficult it can be to drive things forward for a variety of political, economic, and technical reasons. This modest (in size) book offers a thoughtful and interesting perspective on the prospects for the future of human space exploration in the Solar System and beyond.

Giovanni Bignami is well known as a senior space scientist who has been active in ESA, COSPAR, and the Italian Space Agency, but Andrea Sommariva will probably be less familiar to a space-science readership. Nevertheless, his credentials are impeccable as an economist of international finance and monetary policy focussing on markets for oil, raw materials, and renewable energy, besides development of space. The combination of technical and economic expertise is what makes this book so interesting, bringing an important perspective on whether advanced technical solutions that might enable us to explore beyond the Earth–Moon system could actually be implemented.

The book is structured in a straightforward way related to the existing or required technical advances that deliver a particular capability. A brief review of the history of space exploration to-date is followed by chapters on working in deep space, to mine asteroids, visit Mars and the outer reaches of the Solar System, before examining the ultimate challenge of visiting extrasolar planetary systems and colonizing the Galaxy. While some of this may initially seem fanciful from the present-day perspective, it is all completely grounded in the known laws of physics and reasonable extrapolation of present-day technologies into the future. In particular, it is well informed by personal knowledge on just what it takes to translate basic research into viable technical solutions and high technology-readiness levels.

An important premise of much of the book is that this future will only happen if there is an economic imperative and, for me, as a professional space scientist, the question of how this will work is the most interesting. Even quite simple tables on the volume and terrestrial value of key materials that could be obtained from other bodies in the Solar System, when coupled with estimates of the costs of obtaining them, readily demonstrate which things will be worth the investment of entrepreneurs and which not.

This is a book that will be of interest to anyone who wants to understand the potential for the human race to move beyond its current confines. Most importantly, it is founded in reality rather than science fiction and, hence, provides a useful blue-print for space-policy makers to consult. Unfortunately, I suspect that its relatively high cover price for its size will restrict its circulation to the professional community, although the pain can be reduced a little by purchasing it on-line. — MARTIN BARSTOW.

Astronomy in the Ancient World: Early and Modern Views on Celestial Events, by Alexus McLeod (Springer, Heidelberg), 2016. Pp. 234, 24 × 16. Price £82/$129 (hardbound; ISBN 978 3 319 23599 8).

In today's modern multi-ethnic, multi-cultural, equality-minded society there seems to be a troubling problem with the history of astronomy. Looking back over the previous 4000 years or so, well over 95% of the key advances in our subject have been made by white male Europeans. And this has made folk from China, India, Arabia, Africa, and the Americas a tad miffed.

Alexus McLeod is an assistant professor of Philosophy and Asian and American Studies at the University of Connecticut in the USA, and I am not sure that he is a fan of modern astronomy. He worries about the fact that it has become "globalized, homogenized and professionalized". Even worse, he is convinced that, unlike the ancient astronomy of North America, Mesoamerica, Arabia, China, and India, the human aspect has been squeezed out of it. McLeod makes much of the possible influence of the great supernovae of

1006 and 1054 AD on the development of astronomy in the Americas. He is also convinced that early-Chinese astronomy was possibly dominated by the appearances of great comets. Unfortunately little hard evidence is produced to support these conjectures.

In reading this rather disappointing book, I became gradually convinced that there was an important underlying thesis struggling to emerge. Unfortunately again, the discursive text did not rise to the task of clarifying the enquiry. The question is simple: why did the ancient Maya, Mesoamericans, Arabians, Chinese and Indians make such a dog's breakfast of understanding the science of astronomy? They did not just come a noble second in the race, they were absolutely trounced. McLeod stresses the human aspect of the ancient enquiry and the supposed importance of the human relationship between the sky and happenings on planet Earth. Maybe the non-European ancients were mired in the cloak of astrology and did not throw off this hocus pocus soon enough. — DAVID W. HUGHES.

Annual Review of Earth and Planetary Sciences, Volume 44, 2016, edited by R. Jeanloz & K. H. Freeman (Annual Reviews Inc., Palo Alto), 2016. Pp. 813, 24 × 19·5 cm. Price $302 (institutions, about £230), $114 (individual, about £87) (hardbound; ISBN 978 0 8243 2044 7).

Annual Review reversed its slimming trend this year and has fattened up to over 800 excellent pages. This year's offering contains the usual diverse set of chapters on subjects of topical interest.

The book starts off with the life history of Stuart Ross Taylor, who was privileged to work on many cutting-edge subjects of the day including tektites and Moon rocks. It continues on this planetary theme with chapters on the Tunguska and Chelyabinsk meteorite impacts and the methane 'hydrology' of Titan (which has seas of liquid methane at its poles, and methane 'weather'). The past climate of Mars, we are told, was, in contrast, controlled by temperature and a paucity of water that prevented the entire surface from being glaciated. Although conditions made the surface inhospitable, they left conditions in the sub-surface favourable to life.

The relevance of Earth sciences to society is covered in chapters on forensic science and shale-gas hydro-fracturing. The latter provides a useful, balanced review of the subject, including explaining modern techniques. Not all 'fracking' is the same. This is topical and useful now, when there is increasing awareness of the widespread effect of industrial activities on earthquake occurrence and other environmental factors, alongside a desire in many countries for energy security.

The ever-present issue of climate change is well represented with papers on estimating changes in CO_2 in Earth's systems using boron in Foramanifera and permafrost. More bad news there! The latter chapter is interesting to compare with the chapter on the climate of Mars. Neat, interdisciplinary papers include one on ^{14}C dating, and the short-term climate fluctuations that limit its accuracy. The continued effort to understand the impact of climate change on the collapse of civilizations is presented in a case study of the Maya civilization.

Classical palaeontology is represented by a chapter on the evolution of Brachiopoda which includes an elegant overview of the basics of this important phylum as well as a broad summary of its evolution. Further introducing a new geological term, an unusual paper explores the evolution of body size during the 'Geozoic'. You won't find much with Google about this very new term, but it simply refers to the 3·6-Gyr period of Earth's history when life existed. Two chapters deal with biomarkers, one in the context of mass extinctions and the other looking at cellular and molecular biological approaches. The recent surge of interest in the development of life, highlighted in many recent papers on the Cambrian biological explosion, is represented by a chapter that looks at the evolution of what is arguably the most important founding process — photosynthesis.

As usual, this year's *Review* is beautifully produced on high-quality paper with summary boxes making for a clear and relaxing read, and the beautifully photogenic colour figures are ideal for teaching purposes. — GILLIAN R. FOULGER.

A History of the Solar System, by C. Vita-Finzi (Springer, Heidelberg), 2016. Pp. 100, 23·5 × 15·5 cm. Price £15/$19·99 (paperback; ISBN 978 3 319 33848 4).

This slim volume is not just a history of the Solar System but also a history of ideas about the Solar System's origin and evolution. To attempt so much in a hundred pages is a challenge that Claudio Vita-Finzi has tackled with aplomb, but also with a mixed degree of success. The cover blurb says that the book "is intended for a general readership", but it is patently at too advanced a level for beginners. I would not recommend it for anyone lacking a modest depth of background knowledge. Several specialist terms remain undefined until their second or third appearance, and are also missing from the index.

In terms of models of Solar System evolution, it is fairly up to date. The Nice Model is there, but I would have liked to read also about both pebble accretion and the Grand Tack hypothesis.

To get the best from this book, one needs to be able to see past the sometimes-convoluted sentences, and also avoid being misled by poorly-phrased statements. For example, the beginner could be forgiven for coming away from p. 28 with the impression that the *SOHO* Sun-watching satellite sits at a Jupiter–Sun Lagrange point among the Trojan asteroids (Jupiter's L4 and L5 points, 60 degrees ahead and behind Jupiter), whereas in fact it is in an unstable orbit about the Earth–Sun L1 point, between Earth and the Sun. The proof-reading leaves something to be desired too. There are a number of howlers, including the birth of the plausible neologism 'planetary palaerodynamics' thanks to a rogue 'r'.

I think this is a book that I will return to in future; for example, when a topic catches my attention, I may like to see what Vita-Finzi has to say about it. He provides plenty of references, many of which were unfamiliar to me, so the reader does not simply have to take his word for it. There are ten short, helpfully-titled, chapters so it is an easy book to dip into. — DAVID A. ROTHERY.

Rock Legends: The Asteroids and their Discoverers, by Paul Murdin (Springer, Heidelberg), 2016. Pp. 207, 28·5 × 21·5 cm. Price £16·50/$29·99 (hardbound; ISBN 978 3 319 31855 6).

Paul Murdin has been honoured by having an asteroid named after him. It is number 128562. This promotion to the celestial hall of fame has generated a fascination for asteroidal nomenclature the result of which is this gem of a book. In it he delves into the story of asteroidal discovery, and marvels at the dangers asteroids represent due to their propensity to be perturbed onto chaotic orbits which can result in them hitting planetary surfaces and producing dinosaur-eliminating craters. They also have the habit of littering those surfaces with meteoritic evidence of asteroidal crusts and interiors, making them unique amongst astronomical objects in as much as they come to see us, rather than relying on us going to see them.

It is an intriguing subject. We read of how Johannes Kepler, around 1600, first hinted that something seemed to be missing in our Solar System between the orbits of Mars and Jupiter. Then 200 years later the first asteroid was stumbled upon by the Sicilian astronomer Giuseppe Piazzi when correcting and extending a star catalogue. By the late 1880s the introduction of astrophotography had increased the discovery rate sevenfold and today we are adding new asteroids to our catalogues at the rate of between 20 000 and 30 000 per year.

We have gone a long way since the Austrian astronomer Edmund Weiss (1837–1917) dismissed asteroids as "those vermin of the sky". Some now suggest that asteroids brought water to the Earth (although what brought water to the asteroids is overlooked); others follow the Harvard geologist Reginal Aldworth Daly's 1946 suggestion that a large asteroidal impact was responsible for our Moon (although why other terrestrial planets were not similarly blessed is also overlooked). Many also think that the distinction between asteroids and comets is rather fuzzy (although there is a strong possibility that they were produced in different places and by different processes).

However you look at it, asteroids are prominent members of the Solar System's zoo of strange bodies. Murdin's insightful, well-written, and highly readable book will do much to encourage more astronomers to study them. — DAVID W. HUGHES (asteroid number 4205).

A Practical Guide to Lightcurve Photometry and Analysis, by Brian D. Warner (Springer, Heidelberg). 2016. Pp. 410, 23·5 × 15·5 cm. Price £29·99/$39·99 (paperback; ISBN 987 3 319 32749 5).

What an excellent book. And not just because it refreshed my mind on all those things you should do to get your CCD photometry right, but because I find I *have* got them right! The author is well known to the amateur fraternity and has a wealth of experience of using the equipment he describes and so is well qualified to write this book — especially this second edition. He's also produced some excellent software, should you need it, although you'd need to purchase that separately.

After an introductory couple of chapters he introduces 'Targets of Opportunity', or more specifically asteroids and variable stars, before describing CCDs and DSLRs. Magnitudes and their various types such as instrumental, apparent, exo-atmospheric, and standard come next. He then spends some time on signal-to-noise and the factors affecting it, before dealing with filters and the various standards, such as Johnson–Cousins and SDSS. I'm also delighted that the Henden Stars are mentioned — indeed, not just mentioned, as in Appendix H almost 80 finder charts are given together with their photometry tables — most useful. We then have reduction techniques including first- and second-order extinction with a worked example. Master frames are not overlooked either.

The following chapters deal with telescopes and cameras and then imaging and photometry software. This is all sound stuff, and even if you have some or all of this it is still well worth reading. Similarly, the next chapters on collecting photons and then measuring the images are not to be skipped, and I was pleased to see the author discussing the quality of the data and what you can and cannot omit without ever discarding the original data! Finally comes period analysis and publishing the results.

There are then eleven(!) appendices, giving some very useful examples, and a bibliography, a glossary, and an index to complete the book. I didn't spot any factual errors, although with any book of this type it would be easy for a couple to slip through. So, if you feel you need to improve the standard of your photometry, be it asteroids or variable stars, or indeed anything else, then this book comes highly recommended. — ROGER PICKARD.

Finding a Million-Star Hotel: An Astro-Tourist's Guide to Dark Sky Places, by Bob Mizon (Springer, Heidelberg), 2016. Pp. 322, 23·5 × 15·5 cm. Price £29·99/$39·99 (paperback; ISBN 978 3 319 33854 5).

Bob Mizon is the public face of the Commission for Dark Skies, and has been since its inception, championing the fight against light pollution and giving awards to anyone from individuals to local councils for installing star-quality lighting — lighting that is the correct brightness and correctly angled. In this, his latest book, he has sought out the darkest places in the UK, the United States, and selected European countries. Bob has adopted the Bortle-scale measure of sky darkness, recognized by the International Dark Sky Association, whose award scheme for dark-sky places he draws on extensively — as well as dark-sky maps and the experiences of other astronomers.

The book is written as though the author has visited all the places described, and the style is very readable. The text is peppered with useful web addresses for local campsites, hotels, park opening times, *etc.* A chapter of the book is devoted to the Sun, planets, and Solar System phenomena, with the usual warnings about looking at the Sun visually or with any optical aid. The four seasonal star charts reproduced in this chapter are on so small a scale as to be of limited use. The book goes on to show the circumstances of every type of solar eclipse for the next ten years, with particular emphasis on the 2017 American event.

A short chapter on 'Stargazing Etiquette' provides some useful tips for hosting star parties. The rest of the book is concerned with light pollution, its causes, the loss of the night sky and its remedies, of which Bob is an acknowledged expert.

If the reader is determined to seek out all the dark places in the UK and the United States, this book will be invaluable; however, the eclipse data will quickly become out of date. Lists of towns on or near the centre line are useful, but can be found in numerous other places and much of the general data can be found elsewhere. Unless you're an avid astro-tourist, at £30 this book is unlikely to find a place on your bookshelf. — MALCOLM GOUGH.

Observational Constraints on the Influence of Active Galactic Nuclei on the Evolution of Galaxies, by C. M. Harrison (Springer, Heidelberg), 2016. Pp. 192, 24 × 16 cm. Price £74·50/$129 (hardbound; ISBN 978 3 319 28453 8).

This book is from the *Springer Theses* series, which recognizes outstanding PhD research in topics within the physical sciences and engineering. It details the thesis research of Christopher M. Harrison, undertaken at Durham University under the supervision of David Alexander.

Harrison's research aims to increase our understanding of the ways in which accreting black holes can affect their host galaxies, and thus impact galaxy evolution. Galaxy-formation simulations make broad predictions about the physical mechanisms that may be at work, but conclusive observational evidence is currently lacking. This is where Harrison's work aims to contribute, providing new observational constraints that can help improve our understanding. He approaches his task in a variety of ways in this thesis, conducting both population studies and in-depth analyses of individual objects. Using integral-field spectrographs he is able to detect ionized-gas outflows from strong active galactic nuclei and determine their properties.

As in many of the titles in this series, the majority of the content is reproduced from his papers. An expert in the field will thus find little new here. However, Harrison's writing style is good enough that this does not detract overmuch from the narrative. To an interested party starting studies in this field, the book provides a good introduction to one approach that can shed light on this interesting topic. — Tim Davis.

The Shadow of Black Holes: An Analytic Description, by A. Grenzebach (Springer, Heidelberg), 2016. Pp. 94, 23·5 × 15·5 cm. Price £37·99/$54·99 (paperback; ISBN 978 3 319 30065 8).

Astrophysics of Black Holes: From Fundamental Aspects to Latest Developments, edited by C. Bambi (Springer, Heidelberg), 2016. Pp. 207, 24 × 16 cm. Price £82/$129 (hardbound; ISBN 978 3 662 52857 0).

These volumes share an educational connection as well as black holes (BH). Author Arne Grenzebach has published his PhD thesis, completed under Claus Lämmerzahl at Bremen, and editor Cosima Bambi has collected five of the six-lecture series given at a 2014 February winter school at Fudan University in Shanghai, directed at masters and PhD students. The topics of the lectures were accretion discs, transient BH X-ray binaries, BH spin, winds, and relativistic gravitational collapse; and the editor asserts in his preface that the volume has all the features to become a very useful reference book to researchers and students working on astrophysical black holes. An appendix provides a nine-page introduction to General Relativity, covering most of the topics needed for the chapters, which are largely focussed on simulations and observations rather than relativity *per se*. The absence of an index is particularly annoying, because one would like to be sure whether any chapter mentions things one might want to look up, particularly, for instance, the topic of Grenzebach's thesis, the shadow cast by a black hole on radiation coming from behind it.

Useful things in the winter-school book include a table of the relativistic spin parameters, *a*, for 22 black-hole X-ray binaries (a distribution fairly flat over 0·2 to 0·95), but no numbers for active galactic nuclei. Author Middleton, however, closes the loop by saying that we will be able to do a better job for Sgr A* (our own Milky Way black hole) when the *Event Horizon Telescope* becomes fully operational.

A spot check indicates good referencing. Author Malafarina, for instance, has a brief section on the Misner–Sharp Mass, and there is the Misner–Sharp (1964) paper, in case you want to know more than the definition provided as "the amount of matter enclosed within the radius *r* at the time *t*". Author Lasota claims to be "old enough to remember when even serious astronomers doubted the existence of accretion discs and scientists snorted with contempt at the suggestion that there might be such things as black holes". But neither he nor any of the other chapter authors mention that Zeldovich and Guseinov carried out the first search in 1965. I met Okhtay Guseinov only once, but he struck me as deeply serious. Yakov B. Zeldovich, on the other hand, definitely had a playful side.

Lasota is definitive on advection-dominated accretion flows, but I wish he had said whether he thinks this is why Sgr A* is so faint, because we are now returning to our own black hole and that in M 87.

What Grenzebach has done is analytic geometrical constructions of the shadows of black holes for all the metrics you have heard of, and some you (or at least I) might have to look up, like singularity C, Plebański–Demiański, and Kerr–Newman–NUT (but the N of NUT is also Newman, and there cannot possibly be two relativists that skilled and sharing a surname; U and T are Unti and Tamburino). The fundamental idea goes back at least to John L. Synge, who wrote on 'The escape of photons from gravitationally intense stars' in 1966, in *Monthly Notices*, no less!

The punch line from the thesis is that the dark region of sky, caused by photon paths being bent by the black holes, will have an angular diameter in the range 20–50 microarcseonds for both M 87 and Sgr A* for likely black-hole metrics. But Grenzebach has explored a full range of parameters, a (spin in geometrized units, so that $a = 1$ would give a naked singularity), charge β, the gravitomagnetic NUT-charge l, singularity parameter C, cosmological constant Λ, and acceleration α, all in units that give everything values of order unity. He also treats some cases with moving observers. Results are presented mostly as drawings, where dirty orange represents regions with unstable spherical light rays, internal anatomy is shown in dark blue with cross-hatching for the ergosphere, and so forth. All solutions have axial symmetry, so the drawings are meridional slices. They are rather fun to look at, though a feeling of being spied upon by the singularities eventually arises.

Several items in the 'Timetable' of discoveries and calculations leading up to his work raise my historian's (or anyhow aged) hackles. The 'no hair' theorem was the result of deep thinking by at least half a dozen people (including Werner Israel, Roger Penrose, Charles Misner, and partial anticipations by Doroshkevich, Zeldovich, and Novikov, Papapetriou, and probably others), but is simply credited to the monumental monograph of Misner, Thorne & Wheeler. Since Sgr A* will be one of the two prime targets of the *Event Horizon Telescope* and the European *BlackHoleCam*, its discovery probably also deserves more complete treatment than it gets here. — VIRGINIA TRIMBLE.

Galaxy: Mapping the Cosmos, by J. Geach (Reaktion, London), 2015. Pp. 270, 25 × 19 cm. Price £15 (paperback; ISBN 978 1 78023 516 5).

I'm not sure why this book is entitled *Galaxy* rather than *Galaxies*, since the latter better describes the contents — perhaps because there are fewer books with the former than with the latter title. The subtitle *Mapping the Cosmos* indicates one of the aims of the book, namely to provide an overview of how galaxies are distributed in the cosmos. Something of a cross between a typical popular-science book and a (small) coffee-table book (with corresponding copious colour illustrations), it is somewhat unusual in that more technical details regarding telescopes, instruments, data processing, *etc.* are included than is the case for similar books; these usually include such information only if they are written by and/or for amateur astronomers. In the same vein, Geach, a Royal Society University Research Fellow at the Centre for Astrophysics Research at the University of Hertfordshire, describes not only galaxies and the instruments used to observe them, but also astronomers' living quarters in Chile and so on, giving the reader a somewhat broader and more realistic impression of the day-to-day (or night-to-night) life of an astronomer.

The 243 pages of the main text are divided into only five chapters, though these have unnumbered sections (not listed in the table of contents). Those looking for a systematic exposition will not find it; the book is more like a long essay on a general theme, covering various related topics, many of which are visited more than once from different points of view. At times, it reminded me of Walt Whitman's "Song of Myself" (and I mean that as a compliment). As such, the content is somewhat difficult to summarize, but roughly the first chapter is a general introduction and discusses the Milky Way, the second moves to the extragalactic Universe, the third brings in more details, the fourth is concerned with galaxy evolution, and the fifth with cosmological simulations. A recurring theme is the multi-wavelength approach to astronomy, emphasizing the physical processes (gas dynamics, *etc.*) which this can reveal.

Almost half of the pages contain an image, often occupying the whole, and sometimes even more than one, page: (false-)colour images, usually of galaxies, groups, and clusters, but occasionally astronomical instruments or visualizations of simulations. All of the images are high-quality and reproduced very well (in spite of this, the price is very reasonable). There are no footnotes, endnotes, citations, or references. Again, this is less a textbook and more an epic poem. The main text is followed by a list of a couple of dozen important distances (separation between Earth and Moon, diameter of the Milky Way, distance to the Coma Cluster, *etc.*), a five-page glossary, and a bibliography of two dozen books (some reviewed in these pages) at a similar or somewhat higher level and well suited for further reading (though I note that in some cases newer editions than those listed are available). Extensive photo acknowledgements (though listed alphabetically by organization/person rather than by page number) and a three-page index round out the book.

Apart from my two standard complaints which many regular readers will recall, the book is written and edited well; there are only very few typos and other minor formatting mistakes. The book provides a good balance between pretty pictures and (non-mathematical) descriptions of the physics behind them, especially of galaxy evolution (not just in the chapter concentrating on that). It is light on the history of the subject (covered in many books) and heavy on current research, told by an insider but understandable to a non-expert readership. I recommend it to those looking for a modern introduction to observational extragalactic astronomy. — PHILLIP HELBIG.

Magnetoconvection, by N. O. Weiss & M. R. E. Proctor (Cambridge University Press), 2014. Pp. 397, 25 × 18 cm. Price £75/$120 (hardbound; ISBN 978 0 521 19055 8).

Magnetoconvection is a fundamental process in a plasma that is of key importance across astrophysics, from planets to the Sun, and to other stars and accretion discs. It concerns the process of turbulent convection in the presence of a magnetic field and is of crucial importance in its own right for explaining the nature and properties of convection and of magnetic fields in planetary, solar, and stellar interiors and surfaces, but it is also central for other related topics such as dynamo generation of magnetic fields, solar and stellar spots, and accretion discs.

Nigel Weiss is a towering figure in magnetohydrodynamics and the acknowledged world expert on magnetoconvection. His equally distinguished co-author, Mike Proctor, is a long-term colleague and a perfect foil with his tenacious and ultra-bright understanding of the necessary complex mathematical techniques. They have dedicated much of their careers to teaching and inspiring generations of researchers on magnetoconvection and dynamo theory. Together with their academic offspring, they have explored this field in great depth in an admirably systematic and thorough study of the various physical properties and effects of magnetoconvection under a wide range of parameter régimes.

Magnetoconvection has undergone a revolution in understanding over the past 30 years due to a combination of high-resolution observations of the solar photosphere, sophisticated computational advances, and clever mathematical analysis. This brilliant book gives a comprehensive and crystal-clear account of the current state of understanding and is heartily recommended as essential reading to applied mathematicians and fluid dynamicists as well as any astrophysicist, solar physicist, planetary physicist, or laboratory-plasma physicist interested in turbulence or magnetic fields.

The book is written from an applied mathematical and astrophysical fluid-dynamical viewpoint, with an emphasis on nonlinear dynamics and a series of model problems (governed by precisely formulated differential equations and boundary conditions) and well-designed, focussed, numerical experiments. This contrasts with a direct numerical-simulation approach that aims to reproduce observed behaviour by including as much of the relevant physics as possible, but is essential for making sense of such simulations and for extending the understanding to other parameter régimes.

Chapter 1 gives a historical background, including the original motivation, namely Biermann's (1941) suggestion that it is the inhibition of convection by a magnetic field that explains the coolness of a sunspot. This was taken up by Cowling (1957) and later by Chandrasekhar (1961) in an extensive treatment of linear stability theory, including the effect of inclined magnetic fields and both viscous and thermal diffusion. The process of magnetic-flux expulsion from convecting cells was then modelled in a pioneering numerical experiment by Weiss (1966), and the beginning of an understanding of nonlinear magnetoconvection was made possible in the 1980s with the development of nonlinear dynamics and bifurcation theory and of sophisticated computational experiments. Chapter 2 describes kinematic dynamos and the kinematic processes of flux concentration and flux expulsion by convecting eddies. The following chapter covers linear theory for the onset of incompressible (Boussinesq) convection in vertical and inclined magnetic fields. Chapter 4 begins a study of nonlinear theory by discussing weakly nonlinear behaviour for the onset of convection, starting with pitchfork and oscillatory bifurcations (as one parameter varies) and moving on to the Takens–Bogdanov bifurcation (as two parameters vary). It also describes a process of period-doubling and onset of chaos. The next two chapters deal in detail with 2D and 3D Boussinesq magnetoconvection, comparing numerical experiments and nonlinear theory, including transition to chaos, pattern formation, and the strong-field limit. Chapters 7 to 9 then give a review of dynamo theory, of the nature of compressible convection, and of solar and stellar magnetic fields, such as photospheric convection and magnetoconvection in sunspots, including Rempel's impressively realistic simulations.

The book is self-contained, with appendices on the Boussinesq and anelastic approximations, chaotic systems such as the logistic map and the Lorenz equations, double-diffusive convection, and magnetic buoyancy. It is a real pleasure to read and is a rich gold-mine that occupies a favourite place on my bookshelf. — ERIC PRIEST.

Physics of Partially Ionized Plasmas, by V. Krishan (Cambridge University Press), 2016. Pp. 261, 26 × 18 cm. Price £69·99/$110 (hardbound; ISBN 978 1 107 11739 6).

There are a number of fine textbooks and monographs that develop the mathematical theory of plasmas currently available to space-plasma physicists and astrophysicists. However, in the vast majority of cases they present a largely collisionless picture. If collisions are dealt with at all, then they tend to be Coulomb collisions between ions and electrons. The neutral component is largely absent from such books. This is understandable since, for many applications, such as in planetary magnetospheres, stellar winds, and in the dense inner regions of stars, neutral atoms do not play a significant role. However, as Vinod Krishan points out in her new book on partially ionized plasmas, there are situations where a neutral-gas component can be important, and even dominant, in determining plasma properties. What is also clear from this new book is that a further reason why it might be tempting to neglect the effects of neutrals is that they make the mathematical theory significantly more complicated than when their presence can be neglected. Professor Krishan is to be congratulated for such a mathematically detailed presentation of her material, which allows the reader to follow the developments step by step. Make no mistake, this is a challenging book, but it is also an extremely rewarding one for anyone who wants to acquire a thorough grounding in the theory of partially ionized plasmas.

The book begins with a brief descriptive overview of the types of plasma to which the subsequent theoretical material is applicable. This includes the evolving stages of ionization of the early Universe, the solar atmosphere, and laboratory plasmas. The second chapter covers the development of various aspects of multi-fluid descriptions of partially ionized plasmas. Beginning with kinetic theory and the Boltzmann equation, four different types of fluid approximation are developed. These are, respectively, three-fluid, two-fluid, and single-fluid approximations, with a further section devoted specifically to the weakly-ionized case. In some respects, that last situation leads to some of the most interesting results. The compromise here is that the moment equations obtained from the Boltzmann equation are not taken beyond the momentum-balance stage, so energy balance and thermal effects are largely neglected. This is a pity in some respects, but understandable in terms of managing the amount of material for a book of this kind. The third chapter examines the equilibria of partially ionized plasmas in each of the four types of fluid description from the previous chapter, primarily as a precursor to a major chapter on waves. In some ways this chapter on wave motion is the most interesting of all to anyone unfamiliar with the properties of partially ionized plasmas. In particular, wave processes in the weakly-ionized case, when ion–neutral collisions are strong enough to lock the dynamics of ions and neutrals together, have some rather surprising properties. For example, Alfvén-like waves exist that propagate with a speed in which the ion mass density of ordinary MHD Alfvén waves is replaced by the neutral mass density. Similarly there exists a *neutral* plasma frequency that is due to the same mass loading of the plasma by neutrals. These results are not that well known and may have important consequences in a variety of situations as, for example, in magnetosphere–ionosphere coupling and in the solar chromosphere.

The fifth chapter is devoted to some specific applications that the author describes as advanced topics. These include structures in the solar atmosphere, a variety of phenomena associated with the Hall effect, Kolmogorov dissipation, and the generation of magnetic fields. The final chapter is devoted to the author's views on some areas of partially-ionized-plasma research that need further work. There is a detailed mathematical appendix containing vector-calculus identities and the like. A list of definitions of symbols is unfortunately absent. In a book like this, which is densely packed with rapidly evolving sequences of equations, it would have been useful to have had symbols defined in one place, rather than having to search back through many pages. The book also contains a large number of exercises at the ends of each of the chapters, and is thus useful to research students who want to test their understanding of the material, as well as being of benefit to professional researchers.

This book is a good starting point for anyone wanting an up-to-date introduction to the mathematical theory of partially ionized plasmas. It is comprehensive within the boundaries that the author sets herself. There are necessarily limitations, but it certainly whets the appetite for a field that is of growing interest and importance as we further refine our understanding of the plasma Universe. I found things in this book that I did not know before, and that has sent me back to the research literature with renewed interest. One could not ask more of a book than that. — TERRY ROBINSON.

Physics: The Ultimate Adventure, by R. Barrett, P. P. Delsanto & A. Tartaglia (Springer, Heidelberg), 2016. Pp. 234, 24 × 16 cm. Price £33·99/$59·99 (hardbound; ISBN 978 3 319 31690 1).

This is an ambitious book which provides a general introduction to most of physics (though concentrating on pure, rather than applied) and some astronomy (in a single chapter on cosmology which, however, is the longest chapter in the book). Remarkably, it mostly succeeds. Written for non-physicists, it provides a good overview of almost the entire field and is surprisingly well balanced, with all topics described at about the same level. The standard topics (mechanics, thermodynamics, electromagnetism, relativity, quantum mechanics, atomic and nuclear physics, fields and particles) are covered, as well as complexity theory. In addition, three introductory chapters provide some context and background, and the final chapter addresses more philosophical and/or controversial topics such as the Anthropic Principle, variation of physical constants, determinism *versus* free will, entanglement, *etc.*

The above is the good. There is a bit of the bad too. The description of entanglement and superluminal correlations in the eponymous section is at best confused, as is the description of Einstein's static cosmological model (implying that Einstein added the cosmological constant to counteract the instability of a matter-only model, when in fact he added it to make the model static, producing an unstable model* in the process, as pointed out by Eddington[1]). There is also some of the ugly: while there are few typographical errors *per se*, there are many stylistic errors, not only many examples of things which I often notice which are (to some) arguably matters of taste, but also too much and/or inconsistent capitalization as well as typical errors made by non-native writers of English. Even though one of the authors is apparently a native speaker, it appears that the editor was not.

*Although the observed expansion of the Universe ruled out Einstein's static model, the instability was seen by many as a mark against it, and Einstein famously abandoned the cosmological constant since almost all models containing it are not static, later moving to the critical-density, matter-only Einstein–de Sitter model. Interestingly, although the latter is also an unstable fixed point and hence unstable in exactly the same sense as the former, that did not prevent its becoming the standard model and even remaining so in some quarters after observations had ruled it out as well.

Apart from the notorious lack of a full stop after a multi-sentence caption — long typical of Springer — and the variable lower margins typical of their more recent publications, the book is otherwise well produced, following the style of other books in this (*Undergraduate Lecture Notes in Physics*) and other similar (*e.g.*, *Astronomers' Universe*) series. Footnotes are fortunately in the main text and not realized as endnotes; some chapters contain a few references at the end; there are a handful of figures, in colour if necessary; an eight-page index rounds out the book. Most readers interested in physics have probably already encountered everything here, but in more detail, even at the popular-science level. Considering the range of topics covered by this book, that is to be expected. The target readership is presumably readers who want a good and balanced introduction to physics; the book might lead some to pursue some or all of the topics in more detail, but is also useful for those for whom this will be the only book on physics they read. — PHILLIP HELBIG.

Reference

(1) A. S. Eddington, *MNRAS*, **90**, 668, 1930.

Quantum Fuzz: The Strange True Makeup of Everything Around Us, by M. S. Walker (Prometheus, Amherst), 2017. Pp. 448, 23·5 × 14·5 cm. Price $28 (about £23) (hardbound; ISBN 978 1 63388 239 3).

Michael Walker is a member, though not a fellow, of the American Physical Society. He belongs to none of the sub-disciplinary units, but it is clear from his preface, back-cover blurbs, and choice of topics that his primary interest is in using devices describable by quantum mechanics to do useful things, like levitating trains, making lasers and magnets for fusion confinement, quantum computing, semiconductor devices, and so forth. His book title was suggested by a friend, who may not have had his best interests at heart, since it sounds more frivolous than his text.

Walker begins with the early-20th-Century development of quantum mechanics (and I'm grateful for his clear description of Compton scattering, which I shall quote at an editor for 'Another Publication' who said it was purely classical). There is a bit of early Universe, galaxy formation, and so forth in the middle, and then onward to explaining the periodic table (all of his are upside down, and most leave off the last row extending from element 104 to 118 — and where we find that lithium, beryllium, and boron seem to be produced in stars), and ending with a large assortment of applications. Controlled thermonuclear fusion can be expected around 2050 at the earliest.

The earlier chapters have a number of boxes with short descriptions of the physicists who did the work (my "aha!" moment is that by 1936 a quarter of the physicists and half the theoretical physicists had lost their positions in Germany, and Rutherford chaired the UK Academic Assistance Council that helped them find new jobs). An interesting tidbit for the history connoisseur is that not only Max Born but also the princely Louis de Broglie served in WWI, but not on the same side!

There are, as always in volumes that cover volumes, a good many "eh?", "NO!", and similar moments. "Temperatures in the neighborhood of two degrees Kelvin; that is three degrees above absolute zero." The expansion of the Universe begins with what he calls the "uniform" phase, before inflation, the need for which is never explained. Several subsections are taken straight from Wikipedia, and the references in general are a curious mix of standard textbooks, historical papers, and non-technical books. He gives Einstein's birthday as March 4th, rather than the 14th (pi day). And someone needs to tell him that the cat is the observer. — VIRGINIA TRIMBLE.

The Zeldovich Universe: Genesis and Growth of the Cosmic Web (IAU Symposium 308), edited by R. van de Weygaert, S. Shandarin, E. Saar & J. Einasto (Cambridge University Press), 2016. Pp. 641, 24·5 × 17 cm. Price £80/$120 (hardbound; ISBN 978 1 107 07860 4).

If you have been counting IAU Symposia since No. 1 (Co-ordination of Galactic Research, Groningen, 1953 June) then, first, you must have more fingers than I do, and, second, you might be surprised that the proceedings of No. 308 (Tallinn, 2014 June) reached its participants only in 2016 December. I suspect that the editors were waiting for the manuscript from a distinguished colleague, a former Zeldovich collaborator, who gave the first, very delightful, talk and who appears doing this among the conference photos that, as usual, occupy pages that might otherwise be blank. The usual conference photo is in colour, but the best image of the present reviewer appears on p. 384, where she has her back to the camera.

Yakov Borisovich Zeldovich (1914 Minsk–1987 Moscow) came to astrophysics and cosmology after a considerable career in combustion theory, nuclear physics, weapons development, and other topics, and then spearheaded a number of cosmic advances. The organizers of the present symposium chose to focus on large-scale structure, the cosmic web (and voids and large-scale streaming), frequently as calculated starting with the Zeldovich approximation. Thirty of the 120 presentations (reviews to posters) here have the phrase "cosmic web" in their titles. Many others mention voids or large-scale structure. The overarching theme was that simulations (normally ΛCDM) and observations (whether galaxies, QSOs, or gas) of the large-scale structure have come over the years to look more and more similar, suggesting to nearly everybody that the community is on the right track. Very roughly, the key 1970 idea was a model describing the non-linear evolution of structure in a co-expanding frame of reference; the ansatz is that a particle starting from initial position $x\ (t_0) = q$ would move ballistically according to $\mathbf{x} = \mathbf{q} - D(t)\mathbf{v}(q)$, with $\mathbf{v} = \delta\boldsymbol{\Phi}/\delta q_{\mathrm{f}}$ for some scalar velocity potential $\boldsymbol{\Phi}(q)$, according to the paper by B. J. T. Jones and R. van de Weygaert.

The other three editors all worked with Zeldovich at some point and include reminiscences in their contributions, as do several other authors (including yours truly). The 120 contributions present came from 243 authors (from the usual six continents) and 186 participants. Some interesting ones are off-topic (origins of large-scale magnetic fields, large-scale tests for $G(r)$ *versus* GR, black-hole searches, dark matter in the local Universe, *etc.*). Indeed nearly every contribution has something you might want to add to your semi-permanent files (semi-permanent, because Zeldovich's cosmology course evolved at a rate of about 5% per year as new ideas and discoveries crept into the inventory). But, of course, there is no index except of authors, and so no easy way to find topics you might want to relocate or find more about. This has become an IAU custom, and I wish I knew what to do about it!

The distribution of nationalities participating was noticeably different from what it would have been in Princeton or Paris or Patagonia, and there are other hints that we were not in Kansas any longer. The Bolshoi Simulation is just big, not balletic. The honouree has a diacritical mark in American papers (Zel'dovich) but not in Russian ones (Zeldovich). Andrei's last name is Sacharov in some figure captions, Sakharov in a contribution. Some financial support came from the Gambling Tax Council of Estonia! One of the structure simulations has a 'Matrioshka'-type structure (nested dolls, *etc.*). The Soviet system for producing outstanding theoretical physicists is described as analogous to the system that yielded many world-class chess players. But the description of the scientific stature of the Soviet delegation to GR10 in Padova in 1983 is, I think, a little unfair, given that E. M. Lifshitz was part of it. One tends to forget these days how difficult it was for our Russian/Soviet colleagues to get permission to travel. Zeldovich himself achieved what he called "the second cosmic velocity" only in 1982 (the Patras General Assembly of the IAU) and the third, to reach the US, only shortly before his death. — VIRGINIA TRIMBLE.

OBITUARY

Ann Savage (1946–2017)

We are sad to have to report the death of Ann Savage (née Coleman), in Coonabarabran hospital in NSW, Australia, on 2017 January 9. She died peacefully, after a long period of declining health. Her astronomical career covered three decades, split between the UK and Australia.

Ann began straight from high school in 1964 December as an assistant in the Nautical Almanac Office, part of the Royal Greenwich Observatory at Herstmonceux in Sussex. With the encouragement of the then NAO Superintendent, Donald Sadler, she seized opportunities to obtain a part-time degree in Applied Physics, followed by an MSc at the fledgling Astronomy Centre at the University of Sussex, where many of the early lecturers and students were also RGO employees. In 1969, Ann married Richard Savage, after a courtship that stretched back to their schooldays.

In 1972, Ann was accepted as a Sussex DPhil student and began to work on quasars with RGO Director Margaret Burbidge. Margaret resigned shortly afterwards, however, and returned to the USA. Needing a supervisor, Ann accepted an invitation to work with John Bolton, head of the Parkes radio telescope in New South Wales ("The Dish" in the movie). John wanted to have access to the deep Southern Sky Survey photographs which were starting to accumulate at the new *UK Schmidt Telescope* (*UKST*), also in NSW. These were ideal for identifying potential quasars that could be used to tie the radio- and optical-position reference frames together. Early in 1974, Ann and Richard arrived in Parkes, where they quickly adapted to life in country NSW.

The next decade or so was very much a case of Ann being in the right place at the right time: using the most powerful telescopes in the southern hemisphere (both radio and optical), studying quasars at the cutting edge of astronomical research, and working with many leading astronomers. She was among the first users of the *Anglo-Australian Telescope* (*AAT*), and her name was immortalized in the famous 'Ann plate', taken while the new telescope's control software was being tested in 1974 December. Never before had a large telescope been programmed to turn star images into recognizable words by making incremental offsets during the exposure. More significantly, Ann shared in the discovery of PKS 2000–330 in 1982, which remained the most-distant-known quasar for a decade.

Ann herself has given personal accounts of what her life was like then, in a talk entitled 'Wild, Woolley and Savage', at a symposium in honour of John Bolton (*Aust. J. Phys.*, **47**, 589, 1994) and another marking the 35th anniversary of the *AAT* in 2010 (*Celebrating the AAO*, eds. R. D. Cannon & D. F. Malin, 2011, Commonwealth of Australia, p. 311). A glance at her list of publications in the NASA/SAO ADS database shows the scope of her work, with 150 entries over 30 years, almost a third of them as first author.

Ann duly completed her DPhil in 1978 and was to spend the rest of her career working with the *UK Schmidt Telescope*. Sons Robert and Ross were born at Parkes in 1977 and 1979, respectively, and Richard became a 'house husband' — not such a common occupation at that time. Ann was a full-time member of the small *UKST* observing team in Coonabarabran (1979–82); worked at the Schmidt Plate Library at the Royal Observatory, Edinburgh (1982–86); and then moved back to Coonabarabran again in 1986. From 1988 to 1993 she took on administrative responsibilities as Astronomer-in-Charge of the *UKST*, which became part of the AAO in 1988.

The Savages enjoyed family holidays in Australia and elsewhere, especially swimming and snorkelling. Unfortunately, in the early 1980s Ann ruptured her right inner ear while scuba-diving in the Red Sea, and this eventually led to a complete loss of hearing on one side, together with serious balance problems. They severely limited how long she could cope with reading and working with computers, making it increasingly difficult for her to continue her work as an astronomer. By 1993, Ann was on long-term sick leave, and she eventually retired on ill-health grounds in 1995.

Ann and Richard had bought a small rural property near Coonabarabran, and chose to make it their retirement home. For many years, Ann had written articles for the local *Coonabarabran Times* newspaper, in which she managed to combine astronomical information with cookery recipes — both areas in which she excelled. After retiring she became much more involved in the local Coonabarabran community. Sadly, she was diagnosed with inoperable cancer in 2012.

Ann's funeral was held on Friday, 2017 January 13, in the Native Grove cemetery in Coonabarabran. It was essentially a family ceremony, attended by her many local friends and former observatory colleagues. Ann is much missed both in the world of astronomy and in the wider community. — RUSSELL CANNON AND FRED WATSON.

(We are grateful to Marg Mack, Margaret Penston, Richard and Ross Savage, Sue Tritton, Jasper Wall, George Wilkins, Roger Wood, and Alan Wright for additional information for this appreciation.)

Here and There

FEELS A PROPER CHARLIE

— resigned to take up a post of Chaplin and Senior Lecturer in Physics … . — *Institute of Astronomy Cambridge Annual Reports* 1976–1977, p. 15.