THE OBSERVATORY

Vol. 139 2019 JUNE No. 1270

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2018 October 12 at $16^{h}\ 00^{m}$
in the Geological Society Lecture Theatre, Burlington House

A. M. CRUISE, *President*
in the Chair

The President. Good evening everybody. Welcome to the new session of Ordinary Meetings of the Royal Astronomical Society. I have a few announcements, before we move to our two talks, and some of them sad, I am afraid. I have to announce the death of Eigil Friis-Christensen. He was Director of the Danish National Space Centre, and had a huge impact as a scientific leader in his field; he worked at the Danish Meteorological Office, and at the Niels Bohr Institute in Copenhagen. I think his quiet and kind personality, combined with a very profound dedication to science, and his ability to inspire young people and promote their individual careers will be remembered by many people, and certainly by all those who worked with him. I also have to announce the death of Allan Willis, who was a Fellow of the Society and known to many people here. Allan was an astronomer at University College London. He worked with Bob Wilson on *IUE* spectra, particularly of massive and hot stars, also the dust and the interstellar medium. He was a member of the Finance Committee for a number of terms with the Royal Astronomical Society. So can I ask you to stand please, for a few moments of silence. Thank you.

We come to our scientific programme now, and it is a great pleasure to invite Professor Stephen Smartt, from Queen's University Belfast, to give the George Darwin Lecture on 'Kilonovae and the birth of multi-messenger astronomy'.

Prof. S. J. Smartt. [It is expected that a summary of this talk will appear in a future issue of *Astronomy & Geophysics*.]

The President. Stephen, thank you very much indeed. That was an excellent talk. Open for questions.

Mr. H. Regnart. Is it possible, given the ultra-high temperature, pressure, and energy density of a kilonova event, that ultra-transuranic elements may be created with ultra-short lifetimes. And, if so, is there a chance we might be able to detect their fleeting presence?

Professor Smartt. The short answer is I don't know [laughter]. I think the answer to the first part is probably yes, but they would have such short lifetimes and their abundance would be subdominant in comparison with the elements we know are present. Though we do not know individual elements, the ones that are dominant in the neutrosynthetic trajectories, their abundances are large enough that they would always dominate, so I don't think they would affect that $T^{-1 \cdot 2}$, and we are not accurate to even 10% of that. I think the answer is, even if they were produced, we would find it extremely difficult to isolate them. We find it difficult even to isolate elements that we are almost certain are there.

Mr. Regnart. Of course, the key phrase would be 'islands of stability'.

Professor M. Cropper. Is it not possible to use every single gamma-ray burst as a marker by which we search for gravitational waves?

Professor Smartt. Yes, they have done that. Because both the gamma-rays and *LIGO–VIRGO* give very good temporal information, but poor sky-localization information, they have gone back to look for sub-threshold signals temporally coincident with any of the gamma-ray bursts, and there is no detection so far.

Professor Lyndsay Fletcher. You said that, at some point when you were doing the electromagnetic follow-up, if you look at the galaxies, the one you chose would have been near the top of the list anyway. Why is that? Is it just the mass or something to do with age?

Professor Smartt. Just the mass. They come from neutron stars, they come from massive stars, so pick the galaxies with the most stars.

Professor O. Lahav. Your third bullet point about the distances. It is obviously great that one can get the Hubble constant from that binary neutron star. But Nature is not kind enough to produce electromagnetic radiation for binary black holes, so we do not know the redshift. However, there are attempts to do it statistically, so I was just interested in your perspective on how competitive would the Hubble constant measurement be? Especially in light of tension from other measurements.

Professor Smartt. Ideally we would like neutron-star measurements, but I think we are going to be dominated by the black-hole detections, maybe by an order of magnitude, certainly at least five to one. I think that is a really interesting idea where, if you get a small enough sky-localization map, you measure all the redshifts of the visible galaxies. And because you have an estimate of the redshift from the black-hole merger, you probabilistically estimate which galaxy it came from. I think you need between 50 and 100 of those events, if I remember correctly, measured in that way to be competitive. I think it is extremely interesting and should be done. Measuring redshifts is actually quite cheap compared to doing this in terms of time and telescopes, and the pay-back is enormous. I think that both that aspect for binary black holes plus the individual neutron-star mergers should be done.

The President. And we know that the H_0 measurement for the signal event was between the supernovae and the *Planck* measurement.

Professor Lahav. And it agrees with both! [Laughter.]

The President. Stephen, thank you again for an excellent talk [applause].

Our next speaker is Dr. Alessandro Morbidelli from the Observatoire de Nice; he will give the RAS Harold Jeffreys Lecture on 'Combining dynamical and geochemical modelling: a powerful approach to understand the early history of the Earth and the Moon'. [It is expected that a summary of this talk will appear in a future issue of *Astronomy & Geophysics*.]

The President. Thank you very much indeed, Alessandro. Time for some questions.

Professor M. Rowan-Robinson. I don't understand in the last of your four scenarios, why there are no large craters between 3·9 and 4·5 billion years ago.

Dr. Morbidelli. It is not true that there are no craters older than 3·9 Gy. The point is that we don't know their ages for sure because of lack of precise sampling. So I can't report them in the diagram, because I know only the *y*-axis and not the *x*-axis. That is why there is a returning proposal to go sampling the South Pole–Aitken basin. According to crater-counting chronology that basin should have formed around 4·3/4·35 billion years ago.

Mr. M. Hepburn. There is surely a much simpler explanation for the highly-siderophile elements (HSEs) on the Moon. It is not the Moon but the Earth that is different. The Earth has got superheated water which is distributing things which have come from later impacts. The Moon is virtually devoid of water, therefore in any impacts containing those elements, they would remain precisely where they were. So, you don't need all these special things. Our exploration of the Moon has been very imperfect. We would never have found those bits and they wouldn't have been distributed in those areas where we carefully find things. It's like cosmic rays: big cosmic rays make a huge shower on the Earth because of the atmosphere. They don't make a huge shower on the Moon so it would be no good trying to make measurements there. You understand the point?

Dr. Morbidelli. I understand your point very well. The question is how homogeneous the lunar HSE record is. The highly-siderophile elements on the Moon are measured on rocks coming from the crust, but also from basalts coming from the mantle, sometimes the deep mantle. What is found is that the concentrations in the crust and in basalts from the mantle are different, but the concentrations in the various basalts from the mantle are quite similar. The experts (Richard Walker, James Day, and others) argue that the distribution of highly-siderophile elements in the lunar mantle is rather uniform. That is probably because of some past convection in the lunar mantle, probably during mantle overturn. Of course, if highly-siderophile elements just concentrated in pockets of the lunar mantle that have not been sampled, the deficit of HSEs in the lunar samples could be explained without invoking a late sequestration of lunar HSEs into the core, but there is no evidence for any strong heterogeneity so far.

The President. Last question, I am afraid.

Reverend G. Barber. What is the status of the hypothesis that the Earth, Moon, and Mars all formed by a giant impact on the Earth?

Dr. Morbidelli. I think that is not possible, because the formation of Mars is dated using radioactive chronometers that measure the time of the core–mantle differentiation. Mars formed extremely quickly. That is another anomaly of Mars compared to the Earth. Not only is Mars a tenth of Earth mass, but Mars formed in only a few million years, whereas the Earth took tens of millions of years, or a hundred million years, to form. So, Mars is a real planetary embryo. It formed in a few million years, in the lifetime of the disc, and then its growth stopped. The steep radial gradient of solid material that I spoke about, whatever its origin, explains why Mars is small and ended its growth quickly. That is because it was kicked out of the ring carrying most of the solid mass, so it stopped accreting. Because of the huge difference in age between the Moon and Mars, I think it is impossible to relate the Moon's formation with Mars' formation. And also the chemistry is not the same: Mars is much more oxidised than the Earth. Hence I don't think that forming the Moon and Mars in the same impact event is realistic.

The President. We should thank our speaker once again. May I remind you that there is a 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 the 9th of November.

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2018 November 9 at $16^{h}\ 00^{m}$
in the Geological Society Lecture Theatre, Burlington House

A. M. CRUISE, *President*
in the Chair

The President. Good evening everybody and welcome to the Ordinary Meeting of the Royal Astronomical Society. We come to the programme, and we have four excellent talks, I am sure, this evening on different subjects. That is a really unique characteristic of these meetings, and something very much to be valued. The first speaker is our Winton Prize winner, Dr. Kerri Donaldson Hanna from the University of Oxford, who is going to talk to us about '*OSIRIS–REx*: a sample-return mission to a primitive Solar System body'.

Dr. Kerri Donaldson Hanna. We are currently in an era of active asteroid exploration by space agencies around the world. Previous and current missions include NASA's *Dawn* mission to asteroids Vesta and Ceres and *OSIRIS–REx* to asteroid Bennu (the subject of today's talk), ESA's *Rosetta* mission to comet 67P/Churyumov–Gerasimenko, which flew by asteroids Lutetia and Steins, and JAXA's *Hayabusa* and *Hayabusa 2* missions to asteroids Itokawa and Ryugu. In addition there are future missions planned to asteroids including the recently selected NASA Discovery missions *Lucy* and *Psyche*. *Lucy*, which is expected to launch in 2021 and arrive in 2027, will be investigating the origin and evolution of Jupiter's Trojan asteroids, and *Psyche*, which is expected to launch in 2022 and arrive in 2026, will unlock important clues to metal-rich small bodies like asteroid Psyche. While the focus of this talk is *OSIRIS–REx* and asteroid Bennu, I would be remiss not to highlight briefly some of the recent and breath-taking results from the Japanese Space Agency's (JAXA) *Hayabusa 2* mission, which is currently in orbit around its target asteroid Ryugu. Ryugu is believed to be a primitive, carbon-rich asteroid and thus holds vital clues to the formation and evolution of early Solar System bodies. *Hayabusa 2* has now landed three rovers (*MASCOT*, *Minerva I*, and *Minerva II*) on the surface of the asteroid and is practising touching and sampling its surface. For those interested in the mission, further details can be explored on the mission's website.

Why are scientists so interested in asteroids? What makes asteroids so compelling? First, materials identified on asteroids and within meteorites are hypothesized to be the building blocks of the planets in our Solar System and provide vital clues to their formation. In addition, by making maps of asteroid compositions across the Solar System, these small bodies could also place constraints on dynamical models to understand better how planets and materials have migrated over the evolution of the Solar System. Second, carbon-rich asteroids contain volatiles, organics, amino acids, and other materials which provide insight into how water and other life-forming materials were delivered to the Earth–Moon system. Third, as we want to send humans and robots to explore further and further out into the Solar System we will need to find *in-situ* resources in space to make exploration cheaper and easier, and asteroids may contain some of those resources. Finally, some asteroids could threaten to come close to or impact Earth in the future, so understanding their physical properties and the evolution of their orbits could help in developing and testing mitigation strategies.

Today the focus of my talk is NASA's *OSIRIS–REx* mission, for which I have been selected as a participating scientist. The *OSIRIS–REx* acronym stands for *Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer*. *OSIRIS–REx* is a sample-return mission headed to the primitive, carbonaceous asteroid Bennu whose regolith likely contains evidence of the earliest history in our Solar System. The main goals of the mission include: (*i*) collect at least 60 grams of primitive, carbon-rich materials from Bennu's surface; (*ii*) use this sample to understand better the origin of life on Earth and the Earth's oceans by investigating carbon, water, amino acids, and other molecules found within the collected sample; (*iii*) determine the physical and chemical properties of a possibly hazardous near-Earth object for future scientists to plan strategies for keeping asteroids like Bennu from impacting Earth; and (*iv*) identify and quantify resources and materials that could be used in future robotic and manned missions.

Several criteria were used to select asteroid 101955 (better known as Bennu) as the *OSIRIS–REx* target asteroid. First, an asteroid's proximity to Earth was considered as a near-Earth object (NEO) would be the easiest to visit, particularly a NEO with an Earth-like orbit (meaning a fairly circular orbit) and a low inclination (meaning it is close to the plane of the Solar System). Out of 7000 known near-Earth objects only 192 asteroids meet this criterion. Next the size of the asteroid was considered. For a spacecraft to come safely into contact with the asteroid, an asteroid would ideally have a diameter greater than 200 metres, as asteroids with diameters less than 200 metres spin so rapidly that loose material can be ejected from its surface. This reduced the number of candidate asteroids from 192 to 26. Last, the composition of the asteroid was considered as scientists wanted to collect a sample from a primitive asteroid that is rich in carbon and which has not been significantly altered since the asteroid formed approximately four billion years ago. Primitive, carbonaceous asteroids contain organic molecules, volatiles like water, and amino acids that may be precursors to life and the Earth's oceans. We know that primitive carbonaceous asteroids are made of those materials because we can compare spectra of meteorites collected on Earth with telescopic spectra of asteroids. Using composition as a criterion reduced the number of candidate asteroids from 26 to 5. Bennu, a B-type asteroid with telescopic spectra similar to laboratory spectra of CM and CI carbonaceous chondrites, was chosen from those five.

The *OSIRIS–REx* mission officially began on 2016 September 8 at 7:05 pm EDT when the spacecraft was launched from Cape Canaveral Air Force Station on board an Atlas V rocket and began its journey to Bennu. After a year into the mission, the spacecraft's orbit needed to be changed to match asteroid Bennu's orbit around the Sun, which is tilted at a six-degree angle from Earth's orbit. So on 2017 September 22 the *OSIRIS–REx* spacecraft successfully used Earth's gravity to boost itself onto Bennu's orbital plane. During the Earth fly-by, some of the instruments, including the *MapCam, Visible and InfraRed Spectrometer* (*OVIRS*), and *Thermal Emission Spectrometer* (*OTES*) were turned on and tested by observing the Earth and Moon. The approach phase of the mission began on 2018 August 17, when the spacecraft was approximately 1·2-million miles (two-million km) away from Bennu, and this part of the mission will continue until the spacecraft arrives at the asteroid on 2018 December 3. The primary goals of approach are to locate Bennu visually for the first time, survey the surrounding area for potential hazards, and collect enough imagery of Bennu for scientists to generate a detailed shape model of the asteroid, assign a coordinate system, and understand its spin state.

To achieve the scientific goals of the mission a suite of instruments has been added to the *OSIRIS–REx* spacecraft. First, the *OSIRIS–REx Laser Altimeter*, or *OLA*, will send laser pulses to the asteroid's surface and measure its return signal to map Bennu's topography or surface elevation. The map of Bennu's topography will be used to create the shape model, determine the surface geology, and select the safest places for sample collection. *OSIRIS–REx* has two spectrometers on-board, one that measures the sunlight reflected off Bennu's surface (*OVIRS*) and one that measures the heat emitted from the surface (*OTES*). Both will be used to map the minerals on Bennu's surface and to pick the ideal location for collecting a primitive, carbon-rich sample. The spacecraft has a suite of cameras to map the surface visibly at all scales, in particular smooth areas and areas covered in boulders. These maps will be used to understand the surface geology and to make sure the sampling site is not covered by large boulders, which would prevent a successful sampling. After months of completely mapping Bennu's surface, all of the maps collected of the surface will be used to pick the best sampling site. The criteria used to select a sampling site include areas that are relatively flat, as these will be the safest for the spacecraft to interact with, areas that are relatively boulder-free and are covered in loose material, as the most sample material will be returned from these types of regions, and areas that contain primitive materials that have had the least amount of aqueous and thermal alteration.

Once the sampling site has been selected, sampling rehearsal begins in 2020 January with the sample collection in 2020 July. To collect a sample the *TAGSAM*, or the *Touch-and-Go Sample Acquisition Mechanism*, will be used to perform a touch-and-go manoeuvre with Bennu's surface. The *TAGSAM* head will be in contact with the surface of Bennu for a total of five seconds. During those five seconds the *TAGSAM* will release a burst of nitrogen gas, causing loose rocks and surface soil to be stirred up and directed into a collector on the sampler head. With enough nitrogen for three attempts, *TAGSAM* will obtain at least 60 grams and up to 2 kilograms of sample. As a safeguard to ensure some amount of material will be collected, especially of the finest materials, velcro-like material made of metal has been placed around the edges of the sample head to collect material during the brief surface interaction. The *OSIRIS–REx* spacecraft can depart for Earth as early as 2021 March and begin its nearly-two-year journey to bring the sample back home. Four hours before atmospheric entry, the *OSIRIS–REx* spacecraft will jettison the *Sample–Return Capsule* (*SRC*) and then perform a deflection manoeuvre that places the spacecraft on a stable orbit around the Sun. After atmospheric entry the *SRC* will free-fall until it reaches an altitude of approximately 3 km, at which point its parachute will deploy, bringing the capsule in for a soft landing in the Utah desert in 2023 September, a seven-year journey to Bennu and back.

In preparation for the spacecraft's arrival at Bennu and the interpretation of the remote-sensing observations of its surface, at Oxford we have been characterizing Bennu analogues (meteorites, minerals, and mineral mixtures) in the laboratory. Our lab measurements will be compared against *OTES* observations to make maps of Bennu's surface composition. These composition maps will then be used to help in the selection of a sampling site and in placing the sampling site into geological and spectral context with the rest of the asteroid. At the University of Oxford we have two environment chambers which reside in the Planetary Spectroscopy Facility within the Atmospheric, Oceanic, and Planetary Physics sub-department, which are capable of simulating the near-surface conditions of airless bodies like asteroids and the Moon. We simulate the near-surface environment of Bennu by removing all of the atmospheric gasses from the chambers using vacuum pumps to pressures less than 10^{-4} mbar, cooling the interior of the chamber to less than 125 K using liquid nitrogen, and heating the samples from below using a sample-cup heater and from above using a halogen lamp that simulates the solar irradiation of the Sun. Thus, we can place Bennu analogues in our chambers, heat the samples under Bennu-like conditions, and then measure the emitted radiation using a spectrometer. Our laboratory spectra will be placed in a library of spectra and then compared against spacecraft observations to try and identify materials across Bennu's surface.

The UK has other *OSIRIS–REx* team members who will be involved in various stages of the mission including Sara Russell, Ashley King, and their group at the Natural History Museum, who will be investigating the composition and origin of materials on Bennu using laboratory facilities at the museum; Ian Franchi, who will be investigating the origins of the organic and volatile materials by making isotopic measurements using facilities at the Open University; and Ben Rozitis at the Open University, who will be running detailed thermal models of Bennu's surface to enable the selection of the sampling site and understanding better the physical properties of the asteroid's surface.

Thank you for allowing me to talk today, and I would encourage you all to check out the mission's official website — www.asteroidmission.org — where much of the slide materials in today's talk originated.

The President. What a fantastic mission. There must be some questions.

Reverend G. Barber. What is Bennu's rotation rate?

Dr. Donaldson Hanna. It is approximately eight hours.

Mr. C. Taylor. A fabulous story. I had no idea that there was a mission planned to a carbonaceous asteroid. My question is: to what extent do you expect material on the surface of this object to differ from the C-type asteroids, which I think are mostly in the outer main belt, in view of the much greater flux of solar ultra-violet and solar plasma in the solar wind? With organics there, surely that's likely to do some interesting things to the chemistry?

Dr. Donaldson Hanna. Bennu is actually a B-type asteroid, which is a class of the C-type asteroid, which essentially means that in the near-infrared spectra they look similar. They are slightly different in the way their spectra slope. That would indicate that their compositions are similar — at least initially they should have started out different. But, as you said, as things get closer to the Sun, they heat up and become altered. Certainly that is one thing we are really interested in tracking, and something that students have been working on at the Natural History Museum is to make measurements in the lab so that we can try and identify things that have been thermally altered, based on their spectroscopic signature. That is something that we are really intrigued to determine.

Mr. Taylor. Is the presumption that it has been in that orbit for most of the age of the Solar System?

Dr. Donaldson Hanna. That, I am not sure.

Professor S. Green. Just to answer that last question, it can only have been in that orbit for a few million years. The dynamical lifetimes are only a few million years.

My question actually relates to the close-up images of at least a subset of the surface of Itokawa. It seems to show a complete dearth of small particles. If you discover on Bennu, which looks very similar at least superficially from a distance, that this is the case, what is the efficiency of your collecting mechanism actually to be able to pick anything up?

Dr. Donaldson Hanna. I think the *TAGSAM* sample head was efficient at sizes of centimetres and smaller, which when we were looking at disc-integrated observations of Bennu suggested that it was a reasonable assumption, or working number. Obviously, when *Hayabusa2* got to Ryugu, they found a lot more boulders than they were expecting, and they've had to delay the sampling because of that, and come up with different strategies, think about practising, and better targetting. If we get to Bennu and there are similar issues, I am assuming that we have a long period of time when we can reconnoitre the surface and we have all that time built in for doing the rehearsals, and to make sure that we get as much sample as possible.

Dr. P. Daniel. If your touch-and-go is going to touch and go three times, do you have a mechanism in place to keep the sample collected from each of the three locations separate?

Dr. Donaldson Hanna. We are hoping to do only one sample and get it from one location, because, to my knowledge, there is no way of separating samples if we had to do multiple touch downs, which would mean mixing materials.

The President. Thank you very much for that. Our next speaker is the winner of the Patricia Tomkins Thesis Prize, and this is a prize given for people working in instrumentation science relevant to astronomy. We should all remember that all these lovely results we see are the result of somebody building a superb instrument somewhere, and we must thank them very carefully and sincerely for all the work they do. The Patricia Tomkins Thesis Prize winner is Dr. David Cuadrado from the UKRI Rutherford Appleton Laboratory, who is going to talk about 'Millimetre-wave low-noise amplifiers for the *ALMA* telescope'.

Dr. D. Cuadrado Calle. Today is a day of great happiness for me. I am truly honoured that the Royal Astronomical Society (RAS) has selected me for the prestigious Patricia Tomkins Thesis Prize of 2017. Hence, I would like to start my presentation by thanking both the RAS and the Patricia Tomkins Foundation for the prize and also for offering me the opportunity to present my work here today.

ALMA is the largest mm- and sub-mm-wave telescope currently in existence. It is an interferometric array located in the Chilean Desert of Atacama at an elevation of 5000 metres, and it is being developed by an international partnership between Europe, North America, and East Asia, in cooperation with the Republic of Chile.

The telescope itself consists of 66 high-precision antennae. Fifty of those antennae form the main array and operate together as a unified science machine, performing observations with very high angular resolution. The maximum baseline of the main array can vary between 150 m and 16 km. In its most extended configuration the angular resolution of the telescope is as high as 0·04 arc second at 100 GHz. The rest of the antennae form what is known as the

ACA. The *ACA* consists of four 12-metre antennae, which operate individually to measure properties that cannot be measured with interferometry, and twelve 7-metre antennae which operate as a smaller interferometer to observe the big picture.

Apart from the interferometer and the large dishes, the other crucial element for the detection of the astronomical signal is the front end. The *ALMA* front end is far superior to any existing system and it is prepared for receiving signals in ten different frequency bands ranging from 31 GHz to 950 GHz. In particular, *ALMA* band 2 operates from 67 to 90 GHz and *ALMA* band 3 operates from 84 to 116 GHz. The maximum receiver noise over 80% of *ALMA* band 2 is 30 K and the maximum receiver noise over 80% of *ALMA* band 3 is 37 K.

The research that I am presenting today falls within an international collaboration, led by the European Southern Observatory (ESO), which is working on the development of an ultra-broadband front-end receiver that simultaneously covers the bands 2 and 3 of *ALMA*, *i.e.*, the so-called *ALMA* band 2+3 (67-116 GHz). During my PhD and postdoc at the Jodrell Bank Centre for Astrophysics of the University of Manchester I designed, developed, and characterized the low-noise amplifiers (*LNA*) for the *ALMA* band-2+3 receiver. My PhD advisors and postdoctoral line managers were Prof. Danielle George and Prof. Gary Fuller.

Once the development of the *ALMA* band-2+3 receiver prototype is completed, the *ALMA* board will decide if the new band-2+3 receiver is to be incorporated into the telescope. A receiver for *ALMA* band-2+3 would be very beneficial to the astronomical community for three main reasons: (*i*) it would increase the telescope's observational capacity by releasing an otherwise occupied front-end slot; (*ii*) it would allow astronomers to observe more spectral lines simultaneously, thereby enhancing the science that they can do with the telescope; and (*iii*) this LNA-based receiver would achieve excellent performance when operating at 15 K ambient temperature, whereas the current band-3 receiver uses SIS mixer technology and can only operate at an ambient temperature of 4 K or less.

I designed the LNAs using monolithic microwave integrated circuit (MMIC) technology. More specifically, I used the non-commercial 35-nm indium phosphide pseudomorphic high-electron-mobility transistor (pHEMT) process of NGC, to which we had access thanks to an excellent collaboration with the California Institute of Technology (Caltech) and NASA's Jet Propulsion Laboratory (JPL), where I actually did part of my PhD as a visiting PhD researcher. My first MMIC designs had two transistor stages in common-source configuration.

Once the fabrication of the circuits was completed, and given the relatively high chip-to-chip performance variability between MMICs fabricated in the same wafer run, it was necessary to screen them with a non-destructive cryogenic probing process that allowed the best samples to be identified. For that reason, I tested most of the available MMICs with the Cryogenic Probe Station at Caltech's CRAL.

The next part of this work consisted of selecting the best MMIC samples, as identified from the tests with the cryogenic probe station, and packaging them in highly-integrated modules with waveguide interfaces, which were also designed by me as part of this work.

The design of the highly integrated modules included not only the LNA housing but also a waveguide-to-microstrip transition and an off-chip protection circuit. The off-chip protection circuit is necessary to protect the MMICs against damage from improper biassing and RFI.

In order to couple the EM fields propagating along the waveguide channels to the microstrip input and output pads of the MMIC, it was necessary to use a waveguide-to-microstrip transition. I designed these transitions with quartz, a material which has a low dielectric constant and is transparent, allowing for an easy removal of the excess epoxy during the LNA assembly process. The simulated transmission losses of the waveguide-to-microstrip transition are less than 0·25 dB across the 67–116 GHz range. The fabrication of the LNA housings was performed at the Rutherford Appleton Laboratory and the University of Manchester. The assembly of the blocks was done at JPL.

I tested the LNAs at room temperature, for S-parameters, 1 dB compression point and noise temperature, and at cryogenic ambient temperature, for noise temperature and gain. The best LNAs that I developed during my PhD feature a gain of 14 dB with noise temperature less than 28 K from 70 to 110 GHz, setting a new record for broadband noise performance.

I successfully completed my PhD in 2017 June and right away after that I started a 1-year contract as a postdoctoral researcher at the University of Manchester, to continue working on the development of the LNAs for *ALMA* band 2+3, improving the performance of the LNAs that I had produced during my PhD. I designed three new types of MMICs for *ALMA* band 2+3 with an improved noise performance on the band-2 region and higher gain. I improved the mechanical design of the LNA bodies, and ensured that the fabrication of all the new units was performed with the highest possible quality at the state-of-the-art precision development facility of the Rutherford Appleton Laboratory (RAL). By machining the waveguides with excellent quality, we guarantee that the LNA blocks achieve a satisfactory performance up to 118 GHz. Lastly, I also produced a new and improved waveguide-to-microstrip transition design.

By the end of my postdoc, I had produced a cascaded *ALMA* band-2+3 LNA with 27 dB gain and average noise temperature of 26·3 K over the 67–116-GHz frequency range. The integration of this cascaded LNA into the ALMA band-2+3 prototype receiver, together with other state-of-the-art components developed by the groups in the *ALMA* band-2+3 consortium, resulted in a receiver with unprecedented average noise temperature of 36·9 K across the 67–116-GHz frequency range.

The President. Questions for David?

Professor Lyndsay Fletcher. This is wonderful work — congratulations. Is there one property in particular of the MMICs that makes it a record-breaking device to recognize temperature?

Dr. Cuadrado. The process that I am using is quite novel. It has transistors fabricated with high-quality semiconductor materials and a very short gate length. This is critical towards getting high-frequency devices with excellent performance. Then if your question is more related to the way I designed the MMICs, I don't really know. Some people have asked me how did I get such good results, and I don't think I have a key ingredient that I really can say "it is because of this". I designed the LNAs very carefully. I also got support from some colleagues. It is really difficult to give you the key ingredient of the recipe.

Dr. G. Q. G. Stanley. Obviously with the small batches you chose, you showed there is a variation in the noise. You'd be better making more of these. Do you see the process getting so the noise variation is reduced, or will you have to characterize each one very carefully?

Dr. Cuadrado. You have to characterize each chip very carefully. Every time there is a wafer run, we learn from it. This is a non-commercial process. It is a process that does not provide you with a design library — you have to draw everything manually. The simulations do not always match the measurements, so you need to learn about the process. And every wafer run that we participate in, we keep learning about it and we can apply the new knowledge in our next designs. But still, in each wafer, there is a relatively high chip-to-chip performance variability. This means that we get lots of MMICs, but they do not have exactly the same performance. There is always a standard deviation in the noise temperature and also in the gain, so you need to fabricate multiple chips to get some good ones.

The President. David, thank you very much indeed. [Applause.] Just to focus everybody's attention, that talk was about objects that were 1 mm by 1 mm in size. I find that absolutely extraordinary.

We have another extraordinary talk coming now. It is for the Group 'G' Award, by Professor Tim Wright from the University of Leeds, who is going to talk about 'COMET: The Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics'.

Professor T. Wright. COMET is the UK Natural Environmental Research Council's Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics, and it was a great honour for me to accept the RAS Group Achievement Award this year on behalf of COMET.

In this talk, I am going to try to summarize some of the things we do within COMET. COMET was founded in 2002 as an Earth Observation Centre of Excellence, funded by NERC, and at that point just focussed only on earthquakes and tectonics. In 2008 we became part of the National Centre for Earth Observation (NCEO) and expanded our remit to include volcanic hazard. In 2014 we were split out of NCEO and now we work to deliver 'National Capability' science in partnership with the British Geological Survey. During this time we have expanded from three universities and now have 21 scientists in nine UK universities. We employ eight staff scientists, co-funded by COMET, and have 50 PhD students who are associated with COMET, although most do not receive their funding from COMET.

COMET's remit is different from many organizations as it is not pure science. We do carry out pure scientific research on Earth observations and on tectonic and volcanic processes and hazards. But we also deliver data to the community. We are a community of researchers and we also aim to have broader impacts. Those aspects of our work link to each other. For example, we have for many years conducted research that has developed state-of-the-art methods for measuring ground deformation, topography, and concentrations of volcanic emissions. We have been developing data portals that enable members of the community to access these new data streams in near real time and use them in their own research. Our community has a wide range of expertise both within the UK and also in partnership with scientists in countries at risk from natural disasters. So when there is an event, such as an eruption or earthquake, we are extremely well placed to respond very quickly. By carrying out that response, we generate new scientific knowledge, so there are highly beneficial synergies between all of our activities.

I will explore each of these facets of COMET's activities in turn, and then discuss some examples at the end of the talk. In terms of the scientific output, we are highly productive, having produced around 260 papers since 2014. In earthquakes and tectonics, we use satellite geodesy to measure ground deformation that occurs during earthquakes, and we use satellite observations in conjunction with ground-based and seismological observations to build models of what happens in earthquakes and what the on-going hazard might be. We also look at how the ground deforms between earthquakes, as stresses build up in the crust. And on a smaller scale we look at high-resolution optical imagery to measure topography to map scarps that are associated with individual earthquake faults, and try to understand the history of activity on individual faults. We combine this information to build models that aim to improve our understanding of how the tectonic systems work. We also work on volcanoes and we have a similar set of observables. One that is different is that we use satellites to make measurements of volcanic gas and ash. We also measure deformation and topography and we combine all of those data sets again to build models of volcanic processes and hazard. For both earthquakes and volcanoes, the aim is to link the fundamental science to questions that decision-makers care about — what is the likelihood of an eruption? what is the seismic hazard associated with a particular fault?

COMET's key observations are from satellites. We use satellite radars to measure ground deformation. For example, the EU Commission's *Sentinel-1* satellites are providing vast volumes of data that we are using to measure ground movements in tectonic and voclanic areas. We use infrared and ultraviolet spectrometers to measure concentrations of volcanic emissions such as SO_2 and ash. And we use images acquired by very-high-resolution optical satellites, such as the French satellite *Pleiades*, to build high-resolution digital topographic models of the Earth's surface. But COMET's unique strength is in combining our expertise in Earth observation with expertise in tectonic and volcanic processes.

One of our aims is to make using the data sets easier. From the COMET website (http://comet.nerc.ac.uk) you can download various data sets. For example, through a project called LiCS you can download radar interferograms, which measure ground movement, for the entire Alpine–Himalayan tectonic belt and for global volcanoes, without needing to be an expert in how to produce those data. Volcanic-gas information is also provided through an interactive portal, and this information is used for real-time response to volcanic events.

A really important part of COMET's activity is the community building. We have two annual meetings that are well attended by the UK community. We also provide training in the various technologies, both to the UK community but also to international partners, often in developing countries. Over the 15 years that COMET has been in existence, it has helped embed EO technologies within most UK Earth-science departments. We have trained hundreds of students and scientists in the latest EO methods and their application. COMET also provides a focus for the tectonic/volcanic EO community in the UK, which gives us a strong voice at the European Space Agency.

COMET aims to make a broader impact beyond our scientific achievements. One of these is in the area of civil protection. For example, after the Nepal earthquake COMET scientists in Cambridge had a close partnership with the Department for International Development, and local Nepalese scientists, to help understand what had happened in the earthquake. Partners in BGS were involved in landslide mapping, which was one of the most significant issues caused by the event. Another example is the Bardabunga eruption in Iceland, one of the largest eruptions on the planet in the last 200 years. In that case, COMET's real-time processing was used to provide information on the on-going hazard to the civil-protection organization in Iceland. We also work on providing information to help with preparedness. For example, Professor Jurgen Neuberg at Leeds is the chair of the Montserrat Volcano Science Advisory Committee, reporting to the Foreign and Commonwealth Office and local authorities on the on-going eruption and hazard. We also have close collaboration with earthquake scientists and civil protection authorities throughout the Alpine–Himalayan seismic belt and with volcano observatories and monitoring organizations in the Caribbean, Latin America, and East Africa.

COMET also does a lot of work with the media and COMET scientists conduct outreach work on a number of levels. For example, Clive Oppenheimer, a COMET scientist at Cambridge, was involved in an excellent Werner Herzog movie, *Into the Inferno*. David Pyle at Oxford curated a recent exhibition on volcanoes at the Bodleian Library. Ruth Amey at Leeds has been involved in producing educational materials for schools and colleges, and we do a lot of direct outreach work in individual schools to pupils of all ages. There are also some economic benefits to our activity. At Leeds, we have recently formed a spinout company, SatSense Ltd, which is using *Sentinel-1* to measure deformation at a very high spatial resolution in the UK. This deformation is often caused by man-made activities such as tunnelling, for example, due to Crossrail and the Northern Line extension in London. COMET also works with a number of organizations around the world to broaden our impact.

I want to end with a couple of case studies. The first is at Chiles/Cerro Negro volcanoes on the Ecuador–Columbia border where there was an intense seismic swarm in 2014 October and considerable concern that there might be an eruption. Susi Ebmeier, a former COMET student and now faculty at Leeds, was able to work directly with local scientists to analyse satellite data. By combining the satellite data with local information, the alert level was lowered for that event. A second example is for the M7·8 Kaikoura earthquake, a big earthquake that happened in 2016 November in the South Island of New Zealand, which caused 10 m of ground offsets and intense shaking over a region more than 200 km wide. COMET was rapidly able to analyse *Sentinel-1* data within a few hours of the satellite overpass. We shared these results with collaborators at GNS New Zealand, including a former COMET PhD student, Ian Hamling. The results were really surprising, showing the Earth had behaved in a surprisingly complex way. The paper we wrote about that event is now influencing seismic hazard codes around the world.

I want to end by thanking my brilliant colleagues within COMET. It is a splendid organization to lead and a great honour for us to have received the RAS Group Achievement Award. Thank you.

The President. Well, that was a fascinating talk.

A Fellow. Apologies if I missed it, but could you say what scale of deformation you are actually measuring in London with the underground tunnelling?

Professor Wright. The motion colour bar saturates at about ±2 mm/year. So the Crossrail total subsidence is about 2 or 3 cm in most places. A bit higher in some places, but very small signals in general.

Professor Fletcher. In the case of earthquakes, can you translate that definition into a kind of magnitude of earthquakes that you can detect the effects of?

Professor Wright. Yes. There are two aspects to that. Let's look at a picture of an earthquake. The really big earthquakes are very easy to see; there are metres of motion in an individual event. But of course being a logarithmic scale, as you go down to something like a magnitude-5 earthquake, it depends on how deep the earthquake is. A shallow magnitude-5 earthquake you can detect might give you a few centimetres of ground motion. The more challenging part is we really want to measure the slow build-up of ground movement between earthquakes, as well as the movement in earthquakes, and there we can be talking about millimetres per year spread over distances sometimes of hundreds of kilometres (certainly tens of kilometres). And that is one of the reasons for processing this vast amount of data automatically — to throw all of those computational resources at this and try and measure those really small signals.

The President. And perhaps I could ask the dreaded question. If Brexit doesn't go terribly well, are you going to be in difficulty in getting some of these data from the Copernicus programme and things like that?

Professor Wright. Yes, well I hope Brexit doesn't happen at all ... [applause]. I apologise to any Brexiteers in the audience. There are two answers to that. The European Commission has a free and open data policy, so the data are available to anyone around the world, but for the Copernicus programme, the UK pays something like 13 per cent of the overall budget. So, withdrawing from that will make a major impact on the programme and will also reduce our impact to influence the mission. It was COMET that actually set the tectonic footprint mask for the *Sentinel-1* mission.

The President. Let's thank Tim again. [Applause.]

Our last talk this evening is the RAS Diary Talk by Mahesh Anand from the Open University; he is going to talk to us on the 'Dark side of the Moon'.

Dr. M. Anand. Sixty years ago we were familiar only with the near side of the Moon, yet the Moon remains a continual source of attraction to many people. I work with lunar samples, in particular those that were collected during the Apollo missions, but I have no sample from the far side as yet. We have additional Moon rocks in terms of meteorites, and today, I have brought along one such lunar meteorite which might be from the far side, but we don't know for sure. We would need to sample the far side to confirm this!

The first glimpse of the far side was obtained by *Luna 3* in 1959 October. Next month sees the 50th anniversary of *Apollo 8* and next year is the 50th anniversary of the first Moon landing (*Apollo 11*). Three men on *Apollo 8* were the first humans to have seen the far side, and when they saw the blue Earth emerging from behind the lunar terminator it made them realize how fragile the Earth is.

After *Apollo 8*, our knowledge of the far side really started growing in 1994 when the *Clementine* mission made an albedo map. That showed significant differences between the far side and near side, but no-one has yet been able to explain why that should be so.

The far side has much more contrasting relief and differences in topography than the near side. Amongst the most notable features are giant impact basins such as the South Pole–Aitken basin which is 2500 km in diameter and which likely formed between 4·3 and 4·5 billion years ago. Specialists want to study the composition of this basin. About ten years ago we collected data from the *GRAIL* (*Gravity Recovery and Interior Laboratory*) mission, to construct a map of the thickness of the lunar crust, which is quite ancient except in those places where it has been resurfaced by volcanism, but this is still quite old compared with what we see now, as volcanism ceased about 1 billion years ago. A recent Japanese mission called *Kaguya* reportedly found areas of exposed mantle. Unfortunately we have no confirmed samples of the lunar mantle but if you combined the spectral-imaging data with the crustal-thickness data then you would find olivine at locations where mantle exposures are expected.

Titanium is a key element in helping to classify lunar rocks and is locked up in a mineral called ilmenite which is found in the maria. Ti hotspots (correlated with iron) on the near side correspond to maria from where we have samples, but there are few hotspots of Ti on the far side. For the Moon, the Ti content of rocks is a key indicator of the magmatic activity, which tells us about the geological evolution of the Moon. Interestingly, the titanium and iron correlation in the South Pole–Aitken Basin is distinct from those elsewhere.

Before the Apollo missions we had no idea of the global geology of the Moon, especially the distribution of the radioactive element thorium. The Apollo landers all went to areas with high levels of thorium so all of our understanding of the Moon is derived from samples from those unique but anomalous regions. We now have an opportunity to visit other areas and one of those target areas is the South Pole–Aitken Basin. No mission has soft-landed on the far side but this will change in about a month.

The Apollo and Soviet sample-return missions brought back samples from nine areas on the near side and those specimens allowed us to make some key findings. Firstly, pre-Apollo we did not know how the Moon formed; was it a primordial body, was it captured, or formed from fission of the proto-Earth? The data from the samples told us that that it was none of those. The most unexpected discovery was the closeness of the isotopic composition of the Earth and Moon, but we could not reconcile the geochemical data with the dynamical data. It took a few years to come up with other formation scenarios. One of the problems was that the Moon was expected to form from the impactor material, so if the Moon and Earth are found to be so similar geochemically, then the Earth and the impactor would have had the same geochemical make-up. However, no other object in the Solar System as far as we know has the same geochemistry as the Earth. We think the Moon resulted from the impact of a giant planet with the Earth and the resulting debris was flung out into a disc which subsequently coalesced to form the Moon. The Earth was rotating rapidly, the impact was violent, and mixing was so complete that the Moon was formed of the same material as the Earth, but we still have no good constraint on the size of the impactor.

Another key theory is based on knowledge of the lunar magma ocean. The Moon coalesced from hot material which became molten and then solidified, and this is confirmed by the lunar samples. However, we need to know the composition of far-side material to verify further the lunar magma-ocean concept.

The last ten years have been the most exciting. In 2008 a paper by Alberto Saal and colleagues found water on the Moon to the level of parts per million in lunar pyroclastic glasses, whereas it had previously been thought that water formed no more than one part per billion. We think that the interior of the Moon contains water at the level of 100 parts per million. We need to relate what is going on between what is inside and what is on the surface. The Indian mission *Chandrayaan-1*, carrying an instrument called the *Moon Mineralogy Mapper*, went to high northern and southern latitudes and found enhanced water signatures which may be associated with the solar wind. Water at the poles seems to have come as a result of impacts: the low temperatures, close to –150 C, allow water ice to be trapped there. It could be that the water ice lies within one metre of the surface. This is of great importance to future human missions — a supply of water and thus liquid oxygen and hydrogen which are rocket propellants.

The Chinese National Space Agency has sent a mission called *Chang'e 4* to the far side. It already has a relay satellite at the L2 Earth–Moon Lagrangian point which allows *Chang'e 4* to pass on its findings back to Earth. The spacecraft has a lander and a number of European missions in its payload. Next year *Chang'e 5* will go to the far side and return with material. Recently ESA and NASA signed a memorandum of understanding for a human-tended lunar orbital platform which will involve regular access to the surface which will help reduce future costs, and this will also allow us to explore Mars and beyond. I encourage you to visit the website called OpenLearn (https://www.open.edu/openlearn/) and just type in 'Moon'. There are also the Twitter sources #moonmatters and #livingonthemoon.

The President. Questions, please?

Professor S. Sarjeant. Thanks — that was a really interesting talk. I liked your point about it being an important anniversary next year, not just of the Moon landings, but of other things. The International Astronomical Union (IAU) celebrate their hundredth anniversary next year.

A Fellow. The IAU is going to run one hundred hours of astronomy; this is continuous observing in lots of public places. The Moon will be at first quarter then, so it will be a great time for the public to get involved, so the Society for Popular Astronomy will be putting out lots of advice to get involved.

Mr H. Regnart. What do you think we can learn, or have learned, from lunar-water sampling about the origin of water on the Moon and on Earth? I am thinking about the comet hypothesis, isotope ratios, *et cetera*.

Dr. Anand. Thank you very much for the question. I think right now the jury is out. The more and more we study these samples, we are finding that there are probably multiple sources. Now, on balance what we have at hand seems like what we call asteroids. Mark my words: "what we call" asteroids. There appears to be the type of material that could have been the source of water on the Earth and the Moon. Tomorrow, if you decide to call the asteroids comets, comets asteroids, or something else, I don't know. But from the isotopic ratios, currently it seems like the majority of the water on the Earth and Moon is very similar to what we see in the asteroidal material.

Rev. Barber. Thank you for a very fascinating talk. What are the best bets as to the explanation of why there are mare on this side but very few on the far side — what could cause that asymmetry?

Dr. Anand. There have been a couple of ideas for quite some time. One is the crustal thickness. The crust is much thicker on the far side as you saw. The mare regions are expressions of volcanic activity in low-lying areas. So one theory is that if you don't have low-lying areas, you are overburdened, you are not allowing any volcanic material to come up.

Rev. Barber. They have had impacts?

Dr. Anand. Both sides would have had impacts that would have created craters, but because the crustal thickness is much more on the far side, those craters were not deep enough to allow the material to come onto the surface. That's one hypothesis. The second hypothesis is that there is an anomaly, as I showed you, with regards to thorium on the near side. And that is a heat-producing element. There has been, somehow, concentration of a lot of thorium on the near side that caused the melting of the lunar mantle, which then expresses itself on the surface. That is why we need a global sampling of the Moon to confirm if thorium did play a role or didn't play a role. There are a few other ideas out there, but to me at the moment, those two are probably the main reasons.

The President. Thank you very much for a most interesting talk. Shall we thank Mahesh again? [Applause.] Can I remind you that there is the usual drinks party in the library. I give notice that the next Ordinary Meeting will be on Friday the 14th of December.

LOOKING FOR KEPLER'S IDEAL POLYGON LAW IN *KEPLER*-MISSION DATA

By Martin Beech

Campion College, University of Regina

Johannes Kepler has been described, in contrast to his near contemporaries Tycho Brahe and Galileo Galilei, as a mystic, or visionary prepared to dream. Such works as his *Mysterium Cosmographicum* (published in 1596) and the posthumously published *Somnium* (1634) speaking loudly to that epithet. Obsessed throughout much of his life with *explaining* the planets, especially their number and orbital distribution, Kepler favoured some form of underlying geometrical framework, and indeed he suggested that planetary orbits might be spaced according to the circumscribed and inscribed circles associated with an ordered sequence of two-dimensional polygons. This sequence began with a triangle and then proceeded successively through the square, pentagram, hexagon, and so on. This idea was doomed to disappointment, however, since it failed to account correctly for the deduced orbital ratios between successive planets. While Kepler's polygon sequence fails as a framework for describing the classical Solar System (from Mercury out to Saturn), we now know of many more planetary systems[1], and it does not seem unreasonable to ask if the ideal polygon rule is satisfied, somewhere, amongst the many exoplanetary architectures that have been described[2] — a large number of these architectures having been discovered with NASA's *Kepler* transit-survey spacecraft.

At issue, of course, with any planetary system are the circumstances leading to stability and this is determined by a large number of non-trivial physical mechanisms. Remarkably, as is well known, while the equations describing the mutual gravitational interaction between multiple planets can be written down exactly, the solution to those equations can only be found through numerical integration. Not only are there no analytic solutions to the general N-body problem once $N > 2$ but the solutions that are found are liberally spiced with resonances and the reek of deterministic chaos. For all this, however, there is additionally, for so the statistics indicate, an underlying sense of harmony within deduced planetary spacings[3]. It is typical at this point, when discussing planetary orbits, that the Janus-face of the Titius–Bode rule raises its head[4,5] — the smiling and/or frowning face of Janus, in this case corresponding to the expression of the reader. When it comes to the Titius–Bode rule, two mutually exclusive camps seem to exist. One camp accepts the rule's existence as a physical principle (in whatever mathematical form it might take) and, with open arms and gleeful-face, point to its successful predictions both within the Solar System (accounting for the asteroid belt and the accommodation of Uranus and Neptune — but not Pluto) and within various exoplanetary systems. The second camp contains all those frowning-faced researchers not in the first camp — and it is a non-empty set. How, the second-camp occupiers argue, can the random smash-and-grab processes of planet formation result in the generation of bodies that are spaced according to some simple arithmetic progression[4,6]. It is as if one dropped a tin of a thousand beads on the floor and they miraculously fell into an arrangement of ten perfectly circular necklaces. Indeed, such a result would either be a miracle (as seen by Camp-2 followers), or predestined (according to Camp-1 followers) because of the fact that there were a convenient set of previously un-seen circular grooves that had been cut into the floor for the beads to roll into. To this author, placing his cards on the table, the Titius–Bode rule cannot possibly be a fundamental law upon which planetary spacing is predicated; rather it is an end-result summary of the hidden (much more fundamental) laws and processes that have combined to assemble a stable planetary system. It is by analogy the final picture derived from the myriad pieces of a fiendishly complex jigsaw puzzle that has been assembled without any afore knowledge of what the puzzle will eventually show. This being said, some hint as to the origins of Titius–Bode-like rules are seemingly encoded within the Principle of Least Interaction Action as developed by Hills[7], Ovenden[8], and Ovenden, Feagin & Graf[9] during the 1970s. In short, however, the Titius–Bode rule does not tell us how stable planetary systems come about, it is merely an expression of the regularity found in the end result, which is not to say that such knowledge isn't useful[5].

While not all random combinations of orbital spacings will result in stable planetary systems[6], there are none-the-less a vast number of orbital configurations that can result in long-term stability and yet not satisfy any specific Titius–Bode-like rule. One such configuration is exactly that proposed by Kepler in his *Mysterium Cosmographicum*. In that remarkable tome, Kepler outlined two geometrical sequences for arranging the orbital radii of the (then known) planets Saturn through to Mercury[10]. The first geometrical sequence was based upon the inscribed and circumscribed circles to 2-D polygons. This sequence started with a triangle (the simplest polygon) within which the orbits of Saturn and Jupiter are determined. A square is the next generating polygon for the orbit of Mars, and the other planets follow by the use of a pentagon, hexagon, and heptagon (Fig. 1). The ratio of orbital radii between adjacent planets is given according to the polygonal sequence as $r_{\text{circ}}/r_{\text{insc}} = 1/\cos(\pi/N)$, where $N = 3, 4, 5, \ldots$ is the number of sides to the polygon. Kepler's plan for arranging planetary orbits is beautifully simple, but does not provide a good match with the observations — at least for our Solar System (Table I). If, for example, within the geometrical scheme the Earth's orbital radius is normalized to 1 AU, then the location and spacing for Mars and Venus are found to be about 20% smaller and larger, respectively, of their actual values; Saturn and Jupiter, however, have orbital radii that are about a factor of 3 too small, while the orbit for Mercury is a factor of 2 too big. An additional problem (if one wishes to think of it that way) with the nested-polygon sequence is that the more one extends the sequence inward ($N \to \infty$) so $r_{\text{circ}}/r_{\text{insc}} \to 1$, and the associated orbital radii become essentially degenerate — which is not good for orbital stability. Indeed, as $N \to \infty$ the radius of the inscribed circle radius approaches the so-called Kepler–Bouwkamp limit, with $r_{N \to \infty} = 0{\cdot}11494$ (see Fig. 1), this being the limiting, that is final, inscribed circle radius that results

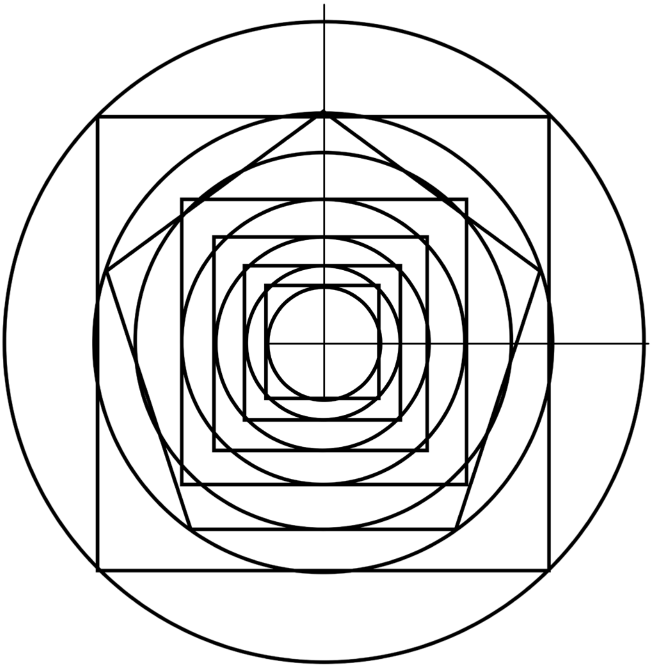

FIG. 1

The polygonal sequence for planetary spacing as originally proposed by Kepler in 1596. The outer two orbits are the circumscribed and inscribed circles to a triangle, and the subsequent orbits are deduced from the inscribed circles to a square, pentagram, hexagon, and so on. The central small circle has a radius corresponding to the Kepler–Bouwkamp limit — that is, it corresponds to the radius of the inscribed circle associated with the *infinitely* regressed polygon interior to the starting triangle.

TABLE I

Comparison between orbital ratios for Kepler's polygonal sequence (R_N), the classical Solar System planets, and the planets in the Kepler 11 exoplanetary system.

N	R_N	*Solar System*	R_{obs}	*Kepler 11*	R_{obs}
3	2·00	Saturn – Jupiter	1·83	f – g	1·86
4	1·41	Jupiter – Mars	3·41	g – e	1·28
5	1·23	Mars – Earth	1·52	e – d	1·26
6	1·15	Earth – Venus	1·38	d – c	1·45
7	1·11	Venus – Mercury	1·87	c – b	1·18

from the sequence of infinitely regressed polygons working inwards from the outermost triangle.

The current haul of exoplanetary data[1] indicates that there are only two known systems containing eight planets (the Solar System and Kepler 90); there are three systems containing seven planets (HD 10180, HR 8832 & Trappist-1) — of these, however, only the Trappist-1 system contains seven actually confirmed planets (rather than a total of seven including several suspected, but unconfirmed, planets). The number of known six- and five-exoplanetary systems comes in at four and 15, respectively. The comparison to be made in this study is the closeness with which the ratio of observed orbital radii (working inward from the outermost planet to the innermost one) agree with expectation when compared to the polygonal sequence given by $R_N = r_{\mathrm{circ}}/r_{\mathrm{insc}} = 1/\cos(\pi/N)$, where $N = 3, 4, 5, \ldots$. Here we use the circumscribed and inscribed circles for a triangle ($N = 3$) for the outermost two planets, and then move inwards with subsequent inscribed circles being generated by a square ($N = 4$), pentagram ($N = 5$), and so on (Fig. 1). In contrast to the typical construction of Titius–Bode-like rules we make no allowance for gaps (that is *missing* planets) within the observed (that is, published) orbital data. An error term is evaluated at each step with $E(N) = (R - R_N)/R_N$, where R is the actual orbital ratio between successive planets. Accordingly, the error term is zero if a perfect match is obtained — the larger (positive or negative) the error term so the poorer the comparison is deemed to be. A total error is then evaluated as $E_T = \Sigma \sqrt{E(N)^2}$ where the sum extends over the total number of steps (that is planet pairs) in the particular sequence. Systematically working through the list of 24 known systems with five or more exoplanets it is found that only one system, Kepler 11, provides a relatively good fit to Kepler's ideal polygon sequence (see Table I).

As Kepler found (and deeply pondered), the polygonal sequence fails to provide a good match to the Solar System because of the large (apparent) gap between Jupiter and Mars, and the total error for the classical Solar System is accordingly an unimpressive 1·61. If Ceres is included in the planetary/polygon progression the total error is slightly reduced and comes in as 1·03. If the full planetary complement of the Solar System, Neptune to Mercury, is considered then the total error is a very poor 2·27. The total error for the Kepler 11 exoplanetary system, however, is a relatively impressive 0·32, with the orbital-ratio fit between Kepler 11d and Kepler 11c being the least well described — *i.e.*, that between the inscribed circles to a pentagram and a hexagon. Kepler 11 is not especially notable among exoplanetary systems[11], although all six of its planets are closely packed and occupy a region just a little larger than the orbit with which Mercury orbits about our Sun. After Kepler 11 the next best comparison to the polygon sequence is that displayed by Kepler 90, with a total error of 1·73 — a similar total error to that deduced for the classical Solar System. The Kepler 90 system, however, has the same number (eight) of planets as our Solar System, although they are all compressed into a region just a little larger than Earth's orbit about our Sun.

There is, of course, no profound physical significance to the observation that the orbital spacings within the Kepler 11 system follow that predicted by Kepler's nested-polygon sequence. It is merely the continuation of an interesting historical indulgence[12,13] — or, as Christiaan Huygens was to write[14], less generously, of Kepler's ideas in 1698 that they were, "a mere fancy without any shadow of reason". For all of Huygens' bewilderment, however, in the modern era it is amply justified to reason[5] that sampling enough systems, and allowing for the large spectrum of exoplanetary system architectures that have been observed[1–3], one system, or another, must sooner or later satisfy almost any reasonable distribution rule or specified orbital sequence[6]. That being said, we additionally find that in terms of the four known six-planet systems, the classical Solar System continues to provide (in terms of a total error of 0·29) the best fit to Kepler's more often described 3-D nested-polyhedron sequence[15] — only Kepler 62 (a five-planet system) provides an otherwise reasonably good fit to the polyhedron sequence (omitting in this case the inscribed sphere to the octahedron), with a total error of 0·39. Living according to the dictates of Pascal's wager, however, and not giving-up the chance to make a prediction (in spite of my earlier dismissal of such possibilities), if another, inner-most planet exists within the Kepler 62 system, then its orbit, predicated on the radius of the inscribed sphere to an octahedron, will be 0·032 AU (with a period of 2·5 days). We note here, however, that based upon their analysis of Titius–Bode-like rules for exoplanetary systems, Bovaird & Lineweaver[5] place an additional six planets within the Kepler 62 system, all of which, however, have orbital radii exterior to the innermost known planet Kepler 62b.

In terms of nested 2-D polygon sequences, the Trappist-1 (T1) system provides an interesting case study since its various planets are distributed in-step with a near constant 3:2 orbital-resonance scheme[16]. Indeed, the orbital semi-major-axis ratios for T1c/T1b, T1d/T1c, T1e/T1d, T1f/T1e, and T1h/T1g average-out to 1·36 ± 0·04, with only T1g/T1f showing a slightly smaller value than this average, coming in at 1·22. These ratios are very close to those expected for the inscribed to circumscribed circles of a square (R_4 = 1·41 — see column 2 of Table I) and the inscribed to circumscribed circles of a pentagram (R_5 = 1·23). Accordingly, the orbital spacing of the T1 exoplanets (from b to h) is well described (see Fig. 2) by the inscribed and circumscribed circles to a polygon sequence consisting of four nested squares followed by a pentagram (between the orbits of T1f and T1g) and finally the circumscribed circle to a square for the orbit of planet T1h (with an impressive total sequence error of just 0·015). The sequence for the Trappist-1 system would presumably not have appealed to Kepler's aesthetic outlook, however, in spite of it providing a very good framework for the orbital spacings — that would be so since it is not an ordered or even constant sequence of nested polygons. Rather, it provides a nice example of Wittgenstein's rule-following paradox, which argues that it is impossible to establish an unambiguous rule to describe the next outcome (or action) in response to a given finite sequence of past outcomes[17,18]. In our case, what this boils down to is that there is no possibility of predicting what the ith circumscribed polygon should be, even though we know the profiles of all the previous (i – 1) inscribed polygons within the sequence.

In summary, we have revisited Kepler's ideas concerning the geometrical arrangement of planetary spacing in terms of either a nested sequence of 2-D polygons or as a nested sequence of 3-D polyhedra. It has been found that of the presently known exoplanetary systems, Kepler 11 provides as good a match (with a total error of 0·32) to Kepler's nested-polygon sequence as the nested-polyhedra sequence provides to the classical Solar System (total error 0·29).

Acknowledgments

Many thanks are extended to the referee (D. W. Hughes) for various suggestions that improved upon the original version of this paper — and for pointing out a number of my inadvertent rabbits.

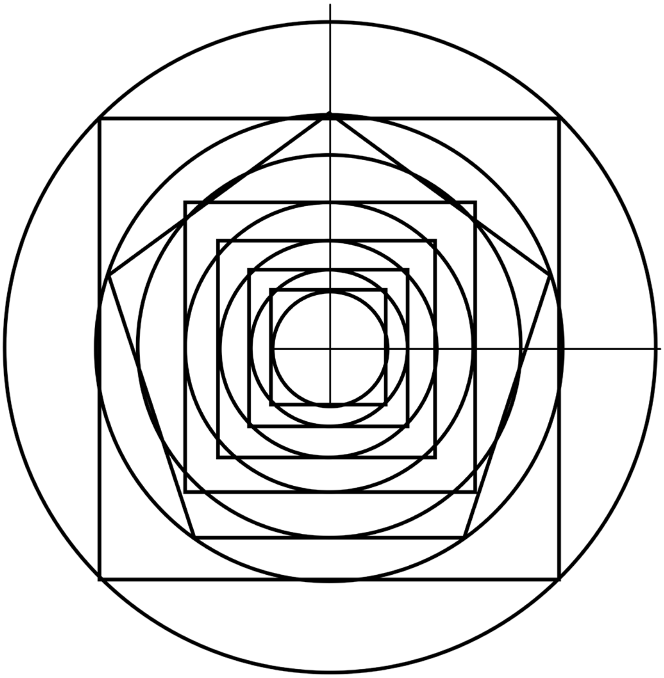

FIG. 2

The polygonal sequence for describing the orbital radii of the exoplanets within the Trappist-1 system.

References

(1) See the exoplanet catalog: http://exoplanet.eu/
(2) J. N. Winn & D. C. Fabrycky, *Ann. Rev. Astron. Astrophys*, **53**, 49, 2015.
(3) L. M. Weiss *et al.*, *AJ*, **155**, 48, 2018.
(4) M. M. Nieto, *The Titius–Bode Law of Planetary Distances: its History and Theory* (Pergamon Press), 1972.
(5) T. Bovaird & C. H. Lineweaver, *MNRAS*, **435**, 1126, 2013.
(6) W. Hayes & S. Tremaine, *Icarus*, **135**, 549, 1998.
(7) J. G. Hills, *Nature*, **225**, 840, 1970.
(8) M. W. Ovenden, *Nature*, **239**, 508, 1972.
(9) M. W. Ovenden, T. Feagin & O. Graf, *Celestial Mech.*, **8**, 455, 1974.
(10) S. Hollingdale, *Bull. Inst. Math. App.*, **22**, 34, 1986.
(11) J. J. Lissauer *et al.*, *Nature*, **470**, 53, 2011.
(12) M. Beech, *J. Rec. Math.*, **29**, 114, 1998.
(13) M. Beech & L. Peltier, *Am. J. Astron. Astrophys.*, **5**(3), 28, 2017.
(14) D. R. Danielson, *The Book of the Cosmos — Imagining the Universe from Heraclitus to Hawking* (Helix Books), 2000, p. 238.
(15) M. Beech, *The Large Hadron Collider — Unraveling the Mysteries of the Universe* (Springer), 2010, pp. 9–11.
(16) M. Gillon *et al.*, *Nature*, **542**, 456, 2017.
(17) S. A. Kripke, *Wittgenstein on Rules and Private Language* (Harvard University Press), 1982.
(18) A. M. Croom, *Dialogue: Jour. Canadian Phil. Soc.*, **52**, 103, 2010.

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 265: HD 200031

By R. F. Griffin
Cambridge Observatories

HD 200031 is a seventh-magnitude star in a Milky-Way field in Cygnus, about 2° south of ν Cyg. Its *HD* type[1] is G5. Nassau & Morgan included it in a listing[2] of high-luminosity stars, with a type of 'G2Ib:', but Bidelman[3] recognized it as having a composite spectrum, giving the types as G5III+A. Harlan[4], however, did not see it as composite, and assigned a type of G2III. Unanimity has been lacking also regarding its magnitudes, particularly in U: whereas Guetter[5] listed it as having $V = 6^{\mathrm{m}}\cdot76$, $(B-V) = 0^{\mathrm{m}}\cdot79$, $(U-B) = 0^{\mathrm{m}}\cdot45$, and very similar figures were given by Parsons & Montemayor[6], Fernie[7] found $V = 6^{\mathrm{m}}\cdot59$, $(B-V) = 0^{\mathrm{m}}\cdot83$, $(U-B) = 0^{\mathrm{m}}\cdot74$. The discrepancies are beyond normal photometric uncertainties, but in the absence of additional (and preferably systematic) measures of the star the reality of the apparent variation cannot be assessed.

Radial-velocity observations of HD 200031 were begun in Cambridge by the writer as long ago as 1978, with the original radial-velocity spectrometer[8], and were subsequently maintained, first with the Haute-Provence *Coravel*[9], whose use was kindly granted to the writer by Dr. M. Mayor, and then with the

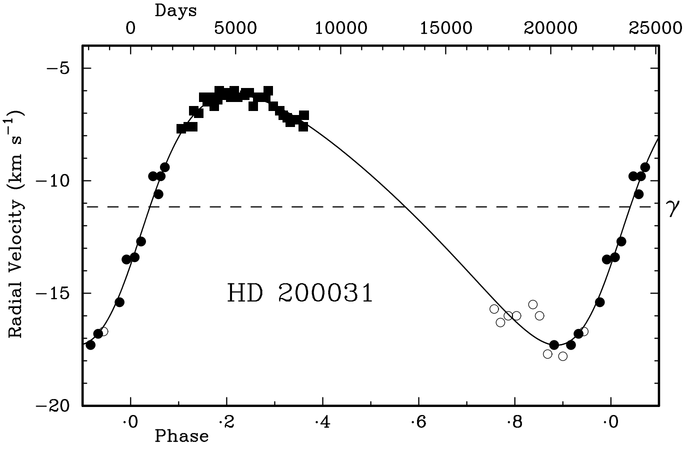

FIG. 1

The observed radial velocities of HD 200031 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The open circles plot the velocities (weighted ⅛ in the solution of the orbit) obtained with the original Cambridge spectrometer; filled symbols represent measurements made with the *Coravel* spectrometers at Haute-Provence (circles; weight ½) and Cambridge (squares; weight 1), respectively.

TABLE I

Radial-velocity observations of HD 200031

Date (UT)	*MJD*	*Velocity* *km s^{-1}*	*Phase*	*(O – C)* *km s^{-1}*
1978 Nov. 6·91★	43818·91	−15·7	0·757	−0·4
1979 Aug. 28·95★	44113·95	−16·3	0·770	−0·7
1980 Sept. 5·95★	44487·95	−16·0	0·786	−0·1
1981 Oct. 2·91★	44879·91	−16·0	0·803	+0·3
1983 Nov. 23·75★	45661·75	−15·5	0·838	+1·4
1984 Oct. 2·85★	45975·85	−16·0	0·851	+1·1
1985 Oct. 24·81★	46362·81	−17·7	0·868	−0·5
1986 Aug. 28·99†	46670·99	−17·3	0·882	0·0
1987 Oct. 21·82★	47089·82	−17·8	0·900	−0·5
1988 Nov. 6·87†	47471·87	−17·3	0·917	−0·2
1989 Oct. 31·87†	47830·87	−16·8	0·932	0·0
1990 July 15·04★	48087·04	−16·7	0·944	−0·2
1992 Aug. 14·87†	48848·87	−15·4	0·977	−0·3
1993 July 11·07†	49179·07	−13·5	0·991	+0·8
1994 Aug. 5·03†	49569·03	−13·4	1·008	−0·2
1995 June 6·10†	49874·10	−12·7	1·022	−0·4
1996 Dec. 25·77†	50442·77	−9·8	1·047	+1·0
1997 Sept. 10·90†	50701·90	−10·6	1·058	−0·5
Dec. 24·73†	806·73	−9·8	·063	0·0
1998 July 12·06†	51006·06	−9·4	1·071	0·0
2000 Sept. 4·01	51791·01	−7·7	1·106	+0·1
2001 July 26·07	52116·07	−7·6	1·120	−0·2
2002 Feb. 27·24	52332·24	−7·6	1·129	−0·5
Apr. 27·13	391·13	−6·9	·132	+0·2
Dec. 19·80	627·80	−7·0	·142	−0·2
2003 Aug. 4·04	52855·04	−6·3	1·152	+0·3
2004 Jan. 16·75	53020·75	−6·5	1·159	0·0
July 7·09	193·09	−6·3	·167	+0·1
Dec. 11·77	350·77	−6·7	·174	−0·3
2005 May 28·11	53518·11	−6·4	1·181	−0·1
Aug. 8·11	590·11	−6·0	·184	+0·3
Dec. 11·73	715·73	−6·2	·190	0·0
2006 July 19·09	53935·09	−6·1	1·199	+0·1

TABLE I (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s^{-1}*	*Phase*	*(O – C)* *km s^{-1}*
2007 Jan. 31·74	54131·74	−6·3	1·208	−0·1
Aug. 3·09	315·09	−6·0	·216	+0·2
2008 Jan. 7·75	54472·75	−6·3	1·223	−0·1
Dec. 6·78	806·78	−6·2	·238	0·0
2009 Jan. 29·73	54860·73	−6·1	1·240	+0·1
July 6·11	55018·11	−6·1	·247	+0·1
2010 Jan. 5·74	55201·74	−6·7	1·255	−0·4
Aug. 30·08	438·08	−6·3	·265	+0·1
2011 Jan. 14·76	55575·76	−6·3	1·271	+0·1
Sept. 14·00	818·00	−6·3	·282	+0·2
2012 Jan. 13·77	55939·77	−6·0	1·287	+0·5
Aug. 21·01	56160·01	−6·7	·297	−0·1
2013 July 10·12	56483·12	−6·9	1·311	−0·1
Dec. 9·82	635·82	−7·1	·318	−0·2
2014 July 1·11	56839·11	−7·2	1·326	−0·2
Nov. 12·83	973·83	−7·4	·332	−0·4
2015 Sept. 11·03	57276·03	−7·3	1·346	−0·1
2016 July 20·05	57589·05	−7·6	1·359	−0·2
Aug. 18·00	618·00	−7·1	·360	+0·3
Sept. 11·94	642·94	−7·1	·362	+0·3

*Observed with original Cambridge spectrometer; wt. ⅛
† Observed with Haute-Provence *Coravel*; weight ½
From 2000: Observed with Cambridge *Coravel*; wt. 1

analogous instrument in Cambridge that replaced the original spectrometer. All the observations are set out in Table I, and although they are far from encompassing a complete circuit of the ~63-year orbit they offer a tolerable solution for it, which is illustrated in Fig. 1 and whose elements are as follows:

P = 23164 ± 2915 days T = MJD 49386 ± 261
γ = −11·15 ± 0·11 km s^{-1} $a_1 \sin i$ = 1691 ± 152 Gm
K = 5·56 ± 0·18 km s^{-1} $f(m_1)$ = 0·36 ± 0·04 $M_\odot$
e = 0·30 ± 0·05
ω = 249 ± 6 degrees R.m.s. residual (wt. 1) = 0·31 km s^{-1}

References

(1) A. J. Cannon & E. C. Pickering, *Ann. HCO*, **98**, 241, 1923.
(2) J. J. Nassau & W. W. Morgan, *ApJ*, **115**, 475, 1952.
(3) W. P. Bidelman, *PASP*, **69**, 147, 1957.
(4) E. A. Harlan, *AJ*, **86**, 1896, 1981.
(5) H. H. Guetter, *PASP*, **92**, 215, 1980.
(6) S. B. Parsons & T. J. Montemayor, *ApJS*, **49**, 175, 1982.
(7) J. D. Fernie, *ApJS*, **52**, 7, 1984.
(8) R. F. Griffin, *ApJ*, **148**, 465, 1867.
(9) A. Baranne, M. Mayor & J. L. Poncet, *Vistas Astr.*, **23**, 279, 1979.

CORRESPONDENCE

To the Editors of 'The Observatory'

A. Vibert Douglas and A. S. Eddington

I was pleased to learn from the 2018 December issue of this *Magazine* that a new edition of A. Vibert Douglas's biography of Eddington[1] has appeared, even if, judging by Ian Howarth's account[2], the presentation of this new edition leaves much to be desired. I purchased a copy of the original edition early in 1957, a few months after publication, while I was still a graduate student at the University of Manchester. I have read and re-read it many times in the ensuing sixty years. When, nearly three years after that purchase, I came to Canada, I found that Dr. Douglas (as I always addressed her) was a respected member of the then rather small Canadian professional astronomical community, although, by that time, her published work was mainly confined to the history of astronomy. In 1979, during the Montreal General Assembly of the International Astronomical Union, I asked Dr. Douglas to sign my copy of her book, which she graciously did. She was a frail old lady then, and that shows in her signature, but she was to live for nearly another decade.

There is some confusion about Douglas's first name and I have to admit that I am at least partly responsible for it. When *The Canadian Encyclopaedia* first appeared, I was asked to contribute a very brief biography of A. Vibert Douglas and discovered that I did not know her first name. She nearly always published under the by-line of "A. Vibert Douglas". I had heard those more nearly contemporary with her than I was address her as "Allie" and (wrongly, as I now know) supposed that this was an abbreviation for some more usual name, such as "Alice" or "Alison". I alerted the editors of the *Encyclopedia* to my uncertainty, hoping that they would have the resources to find the correct name. The choice of "Alice" in that brief biography was theirs, not mine, although the article appears over my name[3]. I have since been reliably informed that her first name was indeed "Allie" and this is confirmed by a Queen's University web site[4].

In a review elsewhere[5] of Matthew Stanley's excellent and magisterial account of Eddington's life and work[6], I suggested that he had been a little too critical of both Douglas's biography of Eddington and David Evans' much later account[7]. Both books, after all, were written by people who actually knew Eddington. Nevertheless, it is undeniable that Douglas's account does at times verge on hagiography. For example, she gives very little space to the controversy with Chandrasekhar, in which we now know that Eddington was definitely in the wrong, and rather downplays Chandrasekhar's role. Perhaps she can be forgiven her reverential attitude. Eddington seldom collaborated with other authors in his papers. My own count, based on the compilation of Eddington's publications that Douglas herself gave, is that only nine papers out of 170 were written with co-authors, two of them with two co-authors. In all, only nine people wrote with Eddington and, of these, the only woman was A. Vibert Douglas. Clearly, Eddington was a major influence on her early scientific career. She may well have felt overwhelmed, when she came to write the biography, by the realization of the privilege that had been hers, as one of the few who had collaborated with the great man.

Much of Douglas's career was spent at Queen's University in Kingston, Ontario, one of Canada's older and more respected universities, where she was still based when I knew her. In addition to her teaching duties there, she held for twenty years the post of 'Dean of Women'. I have known people who encountered her in that capacity during their own student years and they speak warmly of the encouragement she gave them at a time when women in Academia were definitely in the minority. Most astronomers and historians of science will remember her only as the author of the first biography of Eddington. It would be unfortunate if an admittedly imperfect biography eclipsed her many contributions to Canadian academic life.

Yours faithfully,
ALAN H. BATTEN

2594 Sinclair Rd
Victoria B. C.
Canada, V8N 1B9

email: ahbatten@telus.net

2019 January 4

References

(1) A. V. Douglas, *The Life of Arthur Stanley Eddington* (Thomas Nelson and Sons Ltd), 1956.
(2) I. D. Howarth, *The Observatory*, **138**, 313, 2018.
(3) A. H. Batten, in *The Canadian Encyclopedia* (Hurtig Publishers), **1**, 506 1985. A revised version of the *Encyclopedia* is now freely available on line at: www.thecanadianencyclopedia.ca
(4) www.queensu.ca/encyclopedia/d/douglas-allie-vibert
(5) A. H. Batten, *J. British Studies*, **47**, No. 4, 980, 2008.
(6) M. Stanley, *Practical Mystic: Religion, Science, and A. S. Eddington* (Univ. of Chicago Press), 2007.
(7) D. S. Evans, *The Eddington Enigma* (Xlibris), 1998.

REVIEWS

Annual Review of Astronomy and Astrophysics, Volume 56, 2018, edited by S. M. Faber & E. van Dishoeck (Annual Reviews), 2018. Pp. 724, 24 × 19·5 cm. Price from $419 (print and on-line for institutions; about £327), $112 (print and on-line for individuals; about £87) (hardbound; ISBN 978 0 8243 0956 5).

Jaan Einasto begins the current volume with an autobiography played out in Estonia, where the social history, encompassing the Second World War and the rise of the Soviet Union, is every bit as fascinating as his important contributions to galactic structure and eventually the role of dark matter and the 'cosmic web'.

Although relatively parochial, for me the most interesting review this year is that by Stern *et al.* showing the amazing results of the *New Horizons* mission to the Pluto system, although of course readers of this *Magazine* will have had an idea of what was to come following Alan Stern's talk at the RAS in 2017 (see **139**, 90, 2018). Another fascinating 'local' topic is that of rubble-pile asteroids, discussed by Walsh; would they cause more or less damage should they strike Earth than a solid body? A further question of 'local' interest is: why doesn't the Solar System have any 'Hot Jupiters'? See Dawson & Johnson's review for possible answers. But you'll also need to look at how the Solar System evolved dynamically, in the review by Nesvorný. And if exoplanets are your 'cup of tea' then the enhancements to adaptive optics described in two chapters, by Guyon and by Rigaut & Neichel will be of considerable encouragement.

Interstellar material of one form or another gets a good airing this year. The final chapter, by Galliano *et al.*, considers the make-up of dust in nearby galaxies; so it's still a problem I recall from 40 years ago when a hot topic was the universality — or not — of the 2200Å feature in all those *IUE* spectra. Clearly the ISM still hides many secrets, and the paper by Stanimirović & Zweibel shows the fine spatial detail that will be required for a full understanding of our multi-wavelength observations; it's certainly the kind of information needed to identify the obscured AGN examined by Hickox & Alexander. Debris discs around stars are, of course, another source of complication, as shown by Hughes *et al.*

With all this matter around, perhaps it's time to look at star formation, and for high-mass stars and massive clusters the chapter by Motte *et al.* outlines evolutionary scenarios in the Milky Way. Even in our Galaxy, however, things were never simple, and the formation of the Galactic Bulge (Barbuy *et al.*) and globular clusters (Bastian & Lardo) is far from straightforward.

Finally, on the cosmological scale, Mandelbaum cautions against over-naïve use of weak lensing for high-precision cosmology, while Wechsler & Tinker's study of galaxy-halo growth brings us back to Jaan Einasto's concern about the influence of dark matter on large-scale evolution. — DAVID STICKLAND.

Annual Review of Earth and Planetary Sciences, Volume 46, 2018, edited by R. Jeanloz & K. H. Freeman (Annual Reviews), 2018. Pp. 580, 24 × 19·5 cm. Price from \$419 (print and on-line for institutions; about £318), \$112 (print and on-line for individuals; about £85) (hardbound; ISBN 978 0 8243 2046 1).

On Christmas Day, a somewhat slimmed-down issue of *Annual Review* provides me with ample food for thought to balance the traditional food for body. The first two chapters take us on a heady ride from the sea floor straight to Earth's core. Following on from this, the breadth of topics covered defy categorization and the table of contents is a lesson in the breadth of Earth science today. Topics covered include the crust, the study of life past and present, earthquake seismology, tectonics, and the hydrosphere. The other planets are represented by a lonely chapter only on the extreme super-rotation of Venus and Titan. Winds on Venus blow at up to 350 km/hour, 50 times the planetary rotation rate of the surface, and there is still considerable progress to be made in understanding why.

Earthquake seismology is represented by chapters on the physics of earthquake disaster and human-induced earthquakes. The latter subject has consumed seismologists in recent years in the wake of an enormous surge in earthquakes, some of them large enough to be life-threatening, in the hydrocarbon fields of Oklahoma. The good news is that they are beginning to come under control. The sobering news is that this has been achieved by reining in the activities that caused them, which are central to production of the hydrocarbons which we all consume in spades. More impetus for alternative energy.

Several chapters deal with biology, covering subjects ranging from elephants to bacteria. They include the evolution of pinnipeds (seals, sea lions, and walruses), proboscideans (elephants and their relatives), amniote vertebrates (mammals, reptiles, and birds), and cyanobacterial mats. The latter chapter focusses on the contribution of cyanobacterial mats to evolution of the atmosphere, particularly its oxygen content. Why are we not surprised that development of the oxygen content of the atmosphere defies simple models and a number of puzzling observations remain to be explained? This concise, well-written, nicely illustrated chapter brings us up to speed on our understanding of this fundamental process.

In the realm of tectonics, chapters are contributed on subduction orogenies, the tectonics of Eastern Australia (yes, it apparently does have some), and the Altaids, an enormous region of Asia north of the Himalaya, and one of the largest and long-lived accretionary orogens in the world, that developed from *ca.* 600 Myr to 250 Myr. This chapter focusses on crustal growth and nicely complements an earlier, broader review by Caroline Wilhem and colleagues in *Earth-Science Reviews*. The waning of this, one of the largest orogens, coincided with the eruption of the largest terrestrial flood basalt, the Siberian Traps, an interesting correlation.

The bottom line — a varied collection of reviews of current and, in some cases, unusual subjects, and a good read for those with broad interests and critical curiosity. — GILLIAN FOULGER.

Granite Skyscrapers: How Rock Shaped Earth and Other Worlds, by David S. Stevenson (Springer), 2018. Pp. 374, 24 × 16·5 cm. Price £24·99/$37·99 (paperback; ISBN 978 3 319 91502 9).

This highly imaginative planetary-science book held my attention throughout two transatlantic flights from Europe to North America and back. The North Atlantic Ocean separating those two continents opened up only 80 million years ago, in the final phase of the shattering of the supercontinent Pangaea. The map on the in-flight entertainment screen showed named features on the ocean floor, such as the Mid-Atlantic Ridge, a fracture zone, and some seamounts. In the 1960s, geophysical investigation of those features became one of the lines of enquiry that led to plate-tectonic theory. Having the features pointed out as I was reading the book greatly increased my engagement with it. David Stevenson offers a delightfully modern take on Earth-system science: the evolution of the continents, the role of plate tectonics, the orogeny of the Alps and Himalayas, life and the long-term habitability of Earth, and planetary magnetism.

The author believes that granite deserves a book all of its own because “it is the bedrock that made complex, intelligent life possible on our world”. Granite forms from the slow crystallization of magma below Earth’s surface. Its name derives from its granular appearance due to crystals of quartz, feldspar, and mica. Most of Earth’s surface is ocean floor, from which the continents — the “skyscrapers” in the title — rise sheer from the abyss to stand 3–4 km tall. They are unique structures in the Solar System. Granite is the basement rock underlying the sedimentary veneer of the continents. It becomes exposed at the surface during orogeny resulting from collisions of continental plates. The sheer abundance of granite in the continental crust belies the fact that it is probably a rare material in the Solar System: we do not see granite skyscrapers soaring above other planetary landscapes, nor is it present on their surfaces. This is a consequence of the lively tectonic history of Earth.

This book is great reading for anybody seeking a broad introduction to recent research on our planet's geological past and that of other bodies in the Solar System. I liked the comprehensive references at the end of each chapter. The style of referencing is admirable: full names and affiliations are given for most researchers, along with full titles of the cited papers, and full names of journals, together with page numbers. This is essential when reporting interdisciplinary research to people unfamiliar with the field. — SIMON MITTON.

Exoplanets: Hidden Worlds and the Quest for Extraterrestrial Life, by Donald Goldsmith (Harvard University Press), 2018. Pp. 254, 21·5 × 14·5 cm. Price £17·95 (hardbound; ISBN 978 0 674 97690 0).

Exoplanets are those planets found orbiting other stars — now numbering in their thousands. Since the mid-1990s this field of research has expanded enormously, both in terms of capability and the number of people engaged, both amateurs and academics. Goldsmith's book aims to provide an account of how we got to this point, the implications of the discoveries, and where the field is heading.

Most of the book is dedicated to how we actually find planets and what these searches have discovered. After a description of the basic concepts, such as a basic feel for the distances involved and orbital dynamics, the radial-velocity, transit, direct-imaging, and microlensing techniques each merit a chapter. The conceptual descriptions are accompanied by illustrative cartoons, and the techniques by plots that show real data. The latter will certainly be valuable to readers who want to see what planet hunters actually measure. A selection of 'interesting' systems are described; these descriptions are valuable and provide some concrete illustrations. Listing 'Tabby's star' first does the exoplaneteers something of a disservice, given that this system is currently better classed as unexplained by-catch rather than a true part of the exoplanet haul.

Later chapters move on to describe what the current exoplanet yield has taught us and where the field is heading in the near and distant future. These begin with the unfortunately-titled chapter 'What have we learned?' — which barely fills eight pages — but much of the knowledge is of course in the discoveries themselves, and then covered by a description of our current understanding of planet formation. The description of future interstellar travel, and the associated discussion of near-light-speed travel, is enjoyable and encourages the reader to think big (and not to worry about the generations that will pass as we make those journeys).

Overall this book is tailored to a wide readership, but does not shy away from explaining concepts in most of their gory detail. Those without a scientific bent, but an interest in our search for context and life, should come away with an appreciation for the work of many researchers over many decades, what this work has revealed, and a picture of where the Solar System fits. Those with a willingness or predisposition to understanding concepts such as parallax and barycentric orbits, and who get value from scientific plots, will find descriptions of how we did this, presented in a clear and scientific way that does not overstate our capabilities. I appreciated the latter in various places; for example, Goldsmith emphasizes that all search methods have biasses, and that while hot-Jupiters dominated the first exoplanet discoveries, we now know that they are in fact rather rare. — GRANT KENNEDY.

One of Ten Billion Earths: How we Learn about our Planet's Past and Future from Distant Exoplanets, by Karel Schrijver (Oxford University Press), 2018. Pp. 460, 22·5 × 14·5 cm. Price £25 (hardbound; ISBN 978 0 19 879989 4).

The exoplanet field is a dynamic, fast-moving topic with a huge amount of general interest. As such, there is no surprise that several popular-science books exist covering the field. This volume is the latest addition to that collection, and gives a wide-ranging, broad overview of the topic. I would recommend reading specific chapters for anyone who wants to get a quick picture of an area they are not familiar with before delving into the scientific literature. Many interesting facts are presented and much effort has gone to make technical terms comprehensible.

My main concern is the writing style, given the target readership. Clearly the book is aimed at the general public, but the writing is simultaneously 'breezy' yet not very engaging. I gave chapters to some non-astronomer friends to test, and all reported moments of excited interest mixed in with a struggle actually to finish the chapter. Many asides appear in disparate chapters talking about the details of the scientific method, funding, and telescope-time-allocation processes, which become repetitive and a bit much for the general reader. However, mixed in with those I found the occasional insightful and engaging comment expressed — the section managing to link the philosopher Popper and Buddha was especially fun.

There could have been better editing. A few typos and grammatical issues come up every so often, and some chapters could have been more concise. I spotted a few minor errors in the areas I am most familiar with (estimates of the triple-star fraction and circumbinary planet population do exist, for example, and there was a misunderstanding in the details of statistical planet validation), but these are forgivable in a book this broad. Flipping to the middle of a book to see the colour images is annoying, especially in the context of a popular-science book where the images are an important part of engaging the readership.

The overall sentiment, of the quiet revolution that has taken Earth from a single planet to potentially one of billions, is well highlighted and in my opinion one of the great changes in our collective perspective of recent decades and perhaps even centuries. Anyone who undertakes reading this volume will benefit from this and some other excellent ideas, as well as a comprehensive tour through a broad field. However, I strongly suggest taking the book chapter by chapter rather than aiming to read it in one go. — DAVID ARMSTRONG.

Mercury: The View after MESSENGER, edited by Sean C. Solomon, Larry R. Nitter & Brian J. Anderson (Cambridge University Press), 2018. Pp. 583, 28·5 × 22·5 cm. Price £42·99/$59·99 (hardbound; ISBN 978 1 107 15445 2).

Mercury has always been a challenging object to study telescopically from Earth, and until the three spacecraft fly-bys of 1974–5 we had been limited to knowing its diameter, rotation period, its approximate mass, and (as gleaned from polarimetry) that its surface must be broadly like the Moon's. *Mariner 10* mapped only 45% of the surface, including the intriguing Caloris basin, bisected upon the terminator. The *MESSENGER* mission to Mercury (2008–) has been a spectacular success, and this weighty book (to which dozens of authors have contributed) provides an excellent and authoritative summary of what we have learnt from it, in advance of *BepiColombo*.

This book has been attractively produced, and well illustrated, while the endpapers usefully offer location maps for the major Mercurian features. After an overview of the *MESSENGER* project, successive multi-authored chapters deal with Mercury's chemical composition, crust and lithosphere, internal structure, magnetic field, geology, mineralogy, cratering, tectonics, and volcanic character. I was especially interested in the account of Mercury's polar deposits (mostly water ice and located above latitude 80°), acquired over millennia from impacting comets (or perhaps from outgassing, followed by migration to the polar cold traps), and the constraints currently placed upon their thickness and purity. It is believed that these deposits, located in areas of permanent shadow, may persist for billions of years. Following the surface survey, further chapters summarize what we have learnt about Mercury's exosphere and magnetosphere, and of the little world's origin and evolution. Finally, there is an account of future Mercury missions, incorporating good short summaries of most areas of *MESSENGER* findings, and a detailed account of the instruments carried onboard *BepiColombo*. There have even been plans drawn up for a Mercury lander and a sample-return mission.

An excellent Index and a list of Mercurian place names complete this volume. The editors and Cambridge University Press are to be congratulated upon bringing this huge publication to successful completion. — RICHARD MCKIM.

Your Place in the Universe: Understanding our Big, Messy Existence, by Paul M. Sutter (Prometheus), 2018. Pp. 280, 23·5 × 16 cm. Price $24 (about £19) (hardbound; ISBN 978 1 63399 472 4).

The author begins by assuring the reader that "being curious and learning stuff is kind of fun, if learning stuff is your kind of fun. And it's my kind of fun, so that's why this book exists." The customary unit of fun is the barrel of monkeys★, and on that scale, *Your Place in the Universe* scores roughly a pot of pottos or gallon of gibbons. Early on, he also warns devotees of history and physics that his "choices to ignore/simplify/disregard certain aspects" of each are deliberate, but not meant to offend. Astrology also gets very short shrift. He starts with the Greeks, very wrongly puts inflation after the Big Bang, for which helium and the cosmic microwave background are evidence, and lets it solve the usual problems (including monopoles), tramples through fields of quarks and leptons, and ends with life in the Universe and the Fermi question. His version of the answer is a "very fine tuning" sort that requires a planet to have a magnetic field, plate tectonics, and so forth.

My list of certain aspects ignored/simplified/disregarded reached a full page a third of the way through the book and includes some of the classics, like dragging in the Doppler effect and crediting Jules Janssen for the discovery of helium, but also some of his very own, including "one arc second ($\frac{1}{360}$th of a degree)". Here and elsewhere a few drawings and graphs would have helped (there are none, except for the usual colour plates — most egregious, the *Planck* CMB data in a Mercator projection!). The trouble is that one then isn't quite sure whether to trust what might be a neat, new factoid, or not. Is it true that Kepler long delayed trying ellipses for his planetary orbits because he assumed "someone in the past millennium would have tried it already", instead of, he claims, piling up sequential epicycles?

★The SI unit is the cubic metre of comedians, with smaller units including the litre of lorises, bushel of bushbabies, and peck of possums. To save you looking them up, the potto is one of the cuter lorises.

We are currently in a gender-scary epoch, so I end with one seeming political incorrectness from a discussion of the early development of relativistic cosmology: "Willem de Sitter (a Dutchman with a pointy beard), Alexander Friedmann (a Russian with a caterpillar moustache), Georges Lemaître (a clean-shaven Belgian Catholic priest), Bob Robertson (an American with the tiniest moustache you've ever seen), and Arthur Walker (an Englishman with no beard) … . The most important point is that it demonstrates that no matter your choice of facial hair arrangement, you too can be a theoretical physicist." I find I have very little choice in that matter. — VIRGINIA TRIMBLE.

Limiting Outer Space: Astroculture after Apollo, edited by Alexander C. T. Geppert (Palgrave Macmillan), 2018. Pp. 367, 24 × 16·5 cm. Price £88 (hardbound; ISBN 978 1 137 36915 4).

This surprising book is the second in a series by a group of scholars associated with a German research group called The Future in the Stars which is described as dealing with Astroculture — a term introduced in their first volume, *Imagining Outer Space*. This second book is an excellent collection of essays which encompasses a wide sweep of the impact of space research and space dreams on the cultural landscape of society as a whole, beyond the limiting technological confines within which the enterprise is usually examined. Why is the book surprising? Firstly as a physical object it is surprisingly well made; the cover design subtly sets the agenda with a monochrome foreground image of the Moon and in the background a barely bluish Earth on a cool black material that is soft and tactile. The pages are clear and bright and the font is well sized and legible. The second surprise is the title: what can it mean to talk about limiting something so obviously limitless as outer space? Finally the content, in which space research is described as being limited by a sort of self-imposed lack of ambition, is surprising. To be confronted with information from one's working life but viewed not from a technological, functional stand point but from the different, but equally valid, perspective of the effect on human society is enlightening and rather unsettling.

The main discussion of the book is about the effect of space research on society at large and the effect of society's interests and aims on the pursuit of space science, especially during the years following the Apollo Moon landings but before the beginnings of the recent low-Earth-orbit industrialized space programmes of the present day. The contributors are addressing what they see to be a massive de-scope in the aims of space research from the original ambitions of the 1950s in which the message of "our future lies in the stars" was changed to the more mundane pragmatic view of the 1980s in which space becomes simply a platform for commercial interest and the quest for abstract knowledge is replaced by a relentless search for profit. This topic is discussed in a series of brilliantly researched essays referencing movies, novels, architecture, international treaties, and even LEGO figures, and with the possible exception of those egalitarian smiling toy characters, every human endeavour involves politicians making deals somewhere in the background.

The time-scale of the cultural arc from star-based fantasy to factory-floor reality is nicely bracketed by movies which illustrate those two concepts — from the Utopian evolution of humanity to become children of the stars in the film *2001 A Space Odyssey*, released in 1968, to the bleakly despairing *Alien*, released in 1979, in which the action takes place on a squalid industrialized factory spaceship. There is nothing new in observing that art references technology. But it is a mistake to see art only as a mirror. By reflecting the interests of, but also giving voice to the feelings of society at large, art also helps to set the context and agenda in which science operates — and can limit its more high-flown ambitions.

According to the editor, as far as society is concerned the two greatest achievements of the Apollo programme are not the kilos of Moon rock brought back for detailed study, or Neil Armstrong's footprints in the dust of the Sea of Tranquillity, but two photographs. Earthrise, taken by the astronauts on *Apollo 8* as it came out from behind the shadow of the Moon to witness the Earth rising above the lunar landscape in its viewports just before Christmas 1968, and the 'Blue Marble' — a view of the entire Earth seen by the last people to set foot on the Moon in 1972. The authors contend that those two images taken by humans with hand-held cameras on rolls of film encapsulate an essential human element not present in images from robotic spacecraft and their electronic eyes; and that that human vision was instrumental in progressing the nascent environmental movement — it now had powerful visual symbols of what it means to live on a fragile planet in the dark isolation of space. The authors argue that the very term 'globalization' could be seen to be a direct consequence of the view of the Earth provided by Apollo and that that new view at least contributed to the subsequent change in direction and overarching message of space research. So the bleak decade following Apollo involved a reigning in of space ambition and a greater focus on problems associated with living on a planet with decreasing resources and increasing human population. It could also be argued that without the global perspective provided by those images of the Earth in space, and the obvious lack of visible country borders on the surface of the globe, there would be no world wide web.

What did novelists think? Generally writing after they had time to digest the significance of both the reaching-for-the-stars type of space hype and the navel-gazing pondering of the whole-Earth images, at least as far as the Anglophone novels were concerned it was generally felt that "the process by which a mere visual image is charged with much more significance than it would appear to merit is less than wholesome". And that the novel is a much better medium for understanding humanity than any amount of space-image-inspired navel-gazing. But then they are wordsmiths and do not deal in emotive visuals.

In 1968 we could watch the film *2001* and believe that far enough into the future the events described would be at least technically plausible, and a few years later the follow-up novel *2010* occupied the same credibility space. Yet here in 2019 space travel is carried out in pretty much the same way as in the 1970s — often with the same technology: chemical rockets still 'Guy Fawkes' astronauts to the space station — which is not an elegant rotating wheel creating its own gravity but a kludged together mishmash of what looks like the contents of a second-hand space-hardware store. This clash between the 1970s dreams and 1980s and 90s realities is the core of this book. The shiny streamlined dreams of the 1950s were confronted with the realities of space travel in the Apollo era and the "mind's eye was now constrained by what the physical eye was seeing" and reality was found wanting — people looked elsewhere for excitement and visions of the future.

The early dreams of space were not just American or Soviet. An early chapter discusses in detail the UK's entry into space science and technology, dealing with the development of the UK launcher and the influence of the British

Interplanetary Society. It was under those influences that many space scientists and engineers were inspired to chart a course to space-based careers. The excitement was maintained with the daring activities of *Sputnik*, Gagarin, and the Mercury and Gemini programmes; but after Apollo the dreams faded — perhaps best illustrated in the popular context by the decline of the comic-strip hero Dan Dare.

In the last chapter, 'Final Frontiers?', we are given a necessary uplifting view of the future as the author reviews and places in context the previous 11 chapters, if not with the early technology-led visions and fantasies of the 1950s Astroculture, at least with a more hopeful stance. The entire book is a thoroughly worthwhile thought-provoking read. — BARRY KENT.

Low Frequency Radio Astronomy and the LOFAR Observatory: Lectures from the Third LOFAR Data Processing School, edited by George Heald, John McKean & Roberto Pizzo (Springer), 2018. Pp. 251, 24 × 16 cm. Price £96·50/$139 (hardbound; ISBN 978 3 319 23433 5).

LOFAR is the *LOw Frequency ARray* radio interferometer centred in the northern part of The Netherlands. As with any many-antennaed interferometer, its use is computationally intensive, and this volume is the proceedings of a 2014 November school for future users. The editors explain, in a 2018 March preface, that the system is rapidly changing and that they have tried hard to update the material in the lecture chapters from the school year to their present. They encourage readers to consult the *LOFAR* web pages for current information, and urge the use of proceedings from a 1998 June Summer School in Socorro, New Mexico, as a source of complementary and more stable information.

Chapter 1 is a very brief history of radio astronomy and of the low-frequency sky; Chapter 14 addresses high-time-resolution data from *LOFAR* — mentioning the PulP Standard Pulsar Pipeline is irresistible, though the process has been folded into the MoM/Scheduler. The other chapters are portions of an instructional manual rather than results from its use. Is something of the sort necessary? Undoubtedly! Should it be a £100 hardcover? Probably not. Loose-leaf with replaceable pages or even a downloadable 'App' might suit the purpose better.

Still, there are tidbits worth retaining: (*i*) a.u. is not always astronomical units, but sometimes (I think) arbitrary amplitude units (Fig. 9.2); (*ii*) sometimes the Crab Nebula is a noise source that has to be "demixed" even when it is outside the field of view (ditto for the A's of Cas, Cyg, Vir, Hyd, and Her (erroneously Hera in Fig. 4.3), though poor old Sgr A isn't even a dot on their map); (*iii*) there are two types of antennas, leaving 100 MHz undetectable in between because FM radio is also a noise source; (*iv*) Reber's 1960s array in Tasmania was the first radio *Square Kilometer Array*; and (*v*) extensive air showers due to very-high-energy cosmic rays are low-frequency radio sources, and this has been known since 1965–66. Not synchrotron or Bremstrahlung, but electrons and positrons accelerated into an electric current by the Earth's magnetic field and a build-up of negative charge excess in the shower front, made of electrons knocked out from atmospheric molecules. The data can be used to reconstruct the depth into Earth's atmosphere where the shower has its maximum development, and so is complementary to studies from the *Auger* CR array — not for the same showers, though, since *Auger* is in South America and, based on times of sunrise on December and June 21st, northern Netherlands must be quite far north. — VIRGINIA TRIMBLE.

Astronomical Data Analysis Software and Systems XXV (ASP Conference Series, Vol. 512), edited by Nuria P. F. Lorente, Keith Shortridge & Randall Wayth (Astronomical Society of the Pacific, San Francisco), 2018. Pp. 714, 23·5 × 15·5 cm. Price $88 (about £69) (hardbound; ISBN 978 1 58381 908 1).

This volume contains the papers from the 25th ADASS conference held in Sydney in 2015 October. It provides a useful snapshot of the state of the art, or at least planned art, at that date. This volume, at 692 pages, looks like the fattest yet, perhaps a reflection of the number of new projects under way. All the major new observatories are covered quite extensively, for example, *ALMA*, *JWST*, *Euclid*, *SKA*, *LSST*, *E-ELT*, *etc.*, but there are also many papers from smaller project teams or even individuals. I noticed many more papers from China and New Zealand than in earlier years; this may reflect improved funding there or may be partly because of their proximity to Australia. It was interesting to read about the new radio observatories in China.

One of the main problems from some of the newer ground-based observatories is the huge data rate: for example, the *SKA* correlators will disgorge about 1 TB/s. This forces the use of serious hardware and software resources and also means that the earlier stages of processing have to be automated. As a result this volume carries many papers on data pipelines and algorithms for automated data reduction. Many astronomers are aware, however, that too much automation increases the risks of failing to notice outliers, which in the past have sometimes led to the detection of new phenomena or classes of object. It is therefore encouraging that a whole section of the conference was devoted to improving the human–machine interfaces, especially in data visualization. Buzzwords that are currently popular or even notorious in other areas of computing, for example, virtual reality, neural networks, and artificial intelligence, make a fleeting appearance in one or two papers, but no more than that, perhaps reflecting the cautious and realistic approach needed when developing large-scale astronomical systems.

Like conference proceedings generally this book is quite expensive to buy so is likely to attract few individual purchasers, but for those interested in recent developments in projects allied to their own, it might well be rewarding to browse a library copy, or search the on-line version. — CLIVE PAGE.

Einstein, by Thomas Ryckman (Routledge), 2017. Pp. 405, 21·5 × 13 cm. Price £105 (hardbound; ISBN 978 0 415 77326 3), £20·99 (paperback; ISBN 978 0 415 77327 0).

A back-cover blurb from Dennis Lehmkuhl (Einstein Papers Project) says that the author "describes … these struggles (with classical physics, relativity, and quantum theory) in a way that is accessible to students of philosophy without a background in physics." The converse does not seem to be true, if I can describe myself as a student of physics without a background in philosophy (well, one undergraduate year and one graduate term course, the latter on philosophy of science).

My copy was a review one, sent to Another Publication, which I asked for with the feeling "Ah! At last I can hear the truth of the Einstein–Bergson debate (1922 April in Paris) on the nature of time." No such luck! Henri Bergson does not even make the index, though a volume about him in the same Routledge series is scheduled for future publication. I wonder whether Einstein will make its index?!

The three main sections of the tome deal with Quantum Theory (mostly the old, pre-1925 sort), Relativity (both Special and General), and Geometry and Philosophy. The philosophical questions with which Einstein is said to have engaged are (we resort again to the back cover) concept formation, the role of epistemology in developing and explaining the character of physical theories, and the debate between positivism and realism.

Astronomy peeks out in several places, including what the author first calls gravity waves and then gravitational radiation (*versus* gravitational waves, the "consensus decision"), gravitational redshift (discounting solar results, not mentioning white dwarfs, and so giving full credit to Pound, Rebka and Snider).

The index is annoyingly spotty — none of R. V. Pound, G. A. Rebka, J. L. Snider, and Mossbauer (whose effect they used), make the cut, though Hartland Snyder does, for his work with J. R. Oppenheimer on continued gravitational collapse. Ryckman notes Einstein's opposition to this.

There are some interesting numbers, for instance that the 39 microsecond-per-day difference between clocks on the ground and in GPS satellites is made up of +46 μs from gravitational redshift and –7 μs from time dilation, but also some not-quite-certain statements. The reader is told firmly that Russell Hulse and Joe Taylor in their study of PSR B1913+16 did not carry out a direct observation of gravitational waves, but *LIGO*, on 2015 September 14, did.

I ended up puzzled about why the book was written: to emphasize the philosophical aspects of Einstein's thought we are told. But the author begins by quoting and agreeing with scientific biographer (the only one) Abraham Pais, that "calling Einstein a philosopher sheds as much light on him as calling him a musician". A "philosopher-scientist" perhaps? That would suggest that there is an "Einsteinian philosophy", which, Ryckman concludes, there is not. These past few years have seen a great pile of unread Einstein books. This could go near the bottom, at least for astronomers. — VIRGINIA TRIMBLE.

Theory and Experiment in Gravitational Physics, 2nd Edition, by Clifford M. Will (Cambridge University Press), 2018. Pp. 350, 25 × 19·5 cm. Price £49·99 (hardbound; ISBN 978 1 107 11744 0).

The basic context for this book is the question "is general relativity (GR) correct?", or more precisely, "does GR accurately describe classical (non-quantum) gravity in the Universe in which we live?" This question is of interest both in a foundational sense (how do we conceptualize space, time, and gravity?) and because of GR's many contemporary applications in astrophysics, precision metrology, and geodesy (including the now-ubiquitous GPS and other global satellite navigation systems).

Specialized theoretical frameworks are needed to answer this question, and more generally to understand and test the experimental foundations of GR and other gravity theories. Will's book is a masterful survey and review of these theoretical frameworks and of many of the key experimental results. As a leading researcher in this field for some 50 years and the author of many pedagogical and review papers (*e.g.*, refs. 1 & 2) the author is extraordinarily well-qualified to write such a book. This book's 1st edition (CUP, 1991) has long been the standard reference work in this area, and I was excited to see a new edition.

The equivalence principle (EP) played a key role in Einstein's discovery of GR, and Will's book includes a detailed discussion of the different forms of the EP and their implications. In Newton's original formulation, the EP is the observation that "all bodies fall in a gravitational field with the same acceleration regardless of their mass or internal structure". We now refer to this as the 'weak EP'. Einstein generalized the weak EP to what we now call the 'Einstein EP', the observation (axiom) that in a freely-falling 'elevator' (*i.e.*, a closed experimental system), small enough that gravitational tidal effects are negligible, not only Newtonian kinematics but *any* local non-gravitational experiment — including ones involving electromagnetism, Special Relativity, quantum mechanics, *etc.* — will behave as if no gravitational fields are present. (The Einstein EP also includes the invariance of the experimental outcomes with when and where in the Universe the 'elevator' is located, and with the velocity of the 'elevator'.)

The various forms of the EP are strongly supported by experiment, with a wide range of high-precision null experiments constraining possible violations to be very small.* For example, comparisons of different types of atomic clocks moving in the solar gravitational field show that they remain synchronized to within one part per million of the gravitational redshift from their movement, while a recent analysis of data from the *MICROSCOPE* satellite mission shows that titanium and platinum test masses have equal free-fall accelerations in the Earth's gravitational field to within one part in 10^{14}. As well as testing the foundations of gravity theories, such experiments are also implicitly searches for possible 'new physics' such as (hypothetical) new long-range forces beyond the four known fundamental forces of Nature, or string-theory or brane-world effects.

Despite the EP's historical role in the birth of GR, the modern perspective on the EP is somewhat different. As Will's book carefully explains, the Einstein EP provides strong evidence that gravity can be accurately modelled as a curved-space–time phenomenon. However, GR is only one of many such 'metric' gravity theories, and by itself the Einstein EP provides no evidence favouring one over another.

Will's book also discusses further generalizations of the EP which do allow distinguishing between different metric gravity theories. For example, the 'strong EP' essentially removes the Einstein EP's restriction to non-gravitational experiments, allowing the 'elevator' to contain (for example) a Cavendish experiment to measure the Newtonian gravitational constant G, or even the Earth–Moon system. GR satisfies the strong EP, but many other metric gravity theories violate it. Experiments such as laser ranging between the Earth and retroreflectors on the Moon strongly support the strong EP.

Another important theoretical framework for comparing different gravity theories is the parameterized post-Newtonian (PPN) formalism. Will played a key role in developing that formalism in the 1970s, and his book includes a detailed presentation of it and a sampling of experimental results interpreted using it.

The PPN formalism focusses on the 'slow-motion weak-field' limit of a metric theory of gravity, where all matter velocities v are (assumed to be) much slower than the speed of light, and the dimensionless gravitational potential GU/c^2 is much less than unity in magnitude. The metric can then be written as a power series in a set of metric potentials (defined by integrals over the mass density), and the series truncated at (typically) the leading-order terms

---

*In the late 1980s and early 1990s there were suggestions of violations of the weak EP which were hypothesized to be due to a new long-range interaction commonly known as the 'fifth force'. However, after much further experimental work almost all researchers in this field reached a consensus that the apparent fifth-force results were due to subtle systematic experimental errors, and did not represent 'new physics'.

beyond the Newtonian limit. This yields a set of ten free coefficients ('PPN parameters') which together characterize the post-Newtonian weak-field limit of the gravity theory.

Any given metric theory of gravity will have a particular set of PPN parameters, and correspondingly many slow-motion weak-field experimental tests of gravity theories can be interpreted as measuring one or more PPN parameters. For example, the deflection of light in a gravitational field and the additional 'Shapiro' time delay experienced by light passing close to a massive body are both determined by the same PPN parameter, usually denoted γ. Various Solar System experiments show that $\gamma = 1$ (the GR value) to within one part in 10^5.

Starting with the discovery of pulsars by Jocelyn Bell in 1967, it has become possible to test gravity theories beyond the slow-motion weak-field limit. Will's book devotes several chapters to discussions of the structure and motion of systems of 'compact objects', in practice neutron stars and/or black holes. A particularly fruitful class of compact-object systems for testing gravity theories are binary pulsars. They have strong relativistic effects, and their orbital motion can (in favourable cases) be observed with high precision over large numbers of orbits.

A particularly interesting binary-pulsar effect is the gradual decay of the pulsar's orbital motion due to energy and angular momentum radiated *via* gravitational waves. In GR the lowest-multipole gravitational radiation is the quadrupole, and the emitted gravitational waves carry positive energy (so the binary pulsar loses energy and its orbit decays). However, in many other gravity theories (*e.g.*, those of Rosen and Ni) there is also *dipole* gravitational radiation, and as Will puts it (summarizing a result that he himself published in 1977) "in most cases the dipole radiation, and sometimes also the quadrupole radiation carried negative energy". This negative energy would lead to a binary pulsar system *gaining* orbital energy. Those predictions were put to a crucial test by Arecibo Observatory observations of the Hulse–Taylor binary pulsar B1913+16, which found that the pulsar orbit was indeed decaying, and doing so at a rate agreeing with the GR prediction. This ruled out Rosen's and Ni's theories.

More recently, the discovery of the 'double pulsar' J0737–3039 has allowed a number of highly precise tests of whether its orbital dynamics can be accurately modelled with GR. Will's book includes an impressive figure (figure 12.3, credited to Michael Kramer) showing the complete mutual consistency of six independent constraints on the masses of the two individual neutron stars comprising that system, assuming a GR model for the system.

The recent direct detection of gravitational waves from binary black-hole and binary neutron-star systems by the *LIGO* and *Virgo* gravitational-wave detectors opens a new arena for testing gravity theories. Colliding black holes and neutron stars are (obviously) highly relativistic systems, where different gravity theories may make quite different predictions despite having identical PPN limits. For example, in GR gravitational waves travel at the speed of light and have exactly two independent polarizations, but some other gravity theories predict different speeds and/or polarizations. Observations of gravitational waves from the binary neutron-star coalescence event GW170817 show that gravitational waves do indeed travel at the speed of light to within a few parts in 10^{14}, while observations of the binary black-hole coalescence event GW170814 provide moderate support for there being only two gravitational-wave polarizations (Bayes factors of 200 and 1000, respectively, against two different alternatives).

This is an area of active current research, and Will's treatment is (appropriately) more abbreviated than for older topics, but still forms a useful introduction. The coming years should see many more binary neutron-star and black-hole coalescences observed, some with much higher signal/noise ratios, leading to greatly-improved high-precision tests of GR (and other gravity theories).

My only significant complaint about Will's book is the poor quality of the index. For example, despite relevant material in the main text I found no index entries for 'Kerr metric', 'Kerr black hole', 'black hole spin', 'diagonal' or 'off-diagonal' metric components, 'dipole gravitational radiation', 'R^2 gravity', or 'quadratic gravity' (although there is an entry for '$f(R)$ theories').

In summary, this is a superb book. The writing is clear and readable, and there are extensive references to the original literature for those wanting to explore further. The technical background required of the reader is basically a solid familiarity with GR, with many sections (particularly in the discussion of the EP) still accessible to readers with lesser backgrounds, particularly if the reader is willing to 'read around the equations'. The reader can gain some sense of the 'flavour' of Will's book by browsing Will's classic *Living Reviews in Relativity* paper[2] (available open-access on-line), but this book is an invaluable survey and reference for those wishing to delve further. — JONATHAN THORNBURG.

References

(1) C. M. Will, *American Journal of Physics*, **78**, 1240, 2010.
(2) C. M. Will, *Living Reviews in Relativity*, **17**, 4, 2014.

Quantum Space: Loop Quantum Gravity and the Search for the Structure of Space, Time, and the Universe, by Jim Baggott (Oxford University Press), 2018. Pp. 441, 24 × 15·5 cm. Price £20·00/$24·95 (hardback; ISBN 978 0 19 880911 1).

This is a popular-science book about loop quantum gravity (LQG), though longer and more detailed than most such books. It was written with the cooperation of Carlo Rovelli and Lee Smolin, two of the principal players in that game, and includes many personal anecdotes and direct quotations from them. "*This book is their story*" [emphasis in the original] as Baggott states at the beginning. Baggott has written more than a dozen popular-science books, though the topic of this one is somewhat more specialized. The chapters are divided into three parts: 'Foundations' sets the scene with a recap of well-known physics, concentrating on General Relativity and quantum mechanics; 'Formulation' is a review of the history of LQG; and 'Elaborations' discusses current topics in LQG as well as other topics which are related and/or of interest to Rovelli and/or Smolin, such as interpretations of quantum mechanics, cosmological natural selection, and the nature of time.

The chapters in the third part are followed by an epilogue, which is essentially an annotated conversation with Rovelli and Smolin. A 33-page glossary might help some readers, though those unfamiliar with most of the terms here will probably find parts of the main text rather hard to follow — not because the terms are not well explained, but because more background knowledge than just definitions might be needed. Thirty-one pages of endnotes give useful pointers for those wishing to find out more, as does the six-page bibliography, though I prefer the former to consist only of references, with additional information appearing as footnotes to the main text (there are a few such footnotes; it isn't clear why some such information is there but most in the endnotes). An 11-page index distinguishes between the main text, the glossary, figures, and end- or footnotes. There are 31 black-and-white figures scattered throughout the text.

Already in the preface, it is clear that this is not just a book about LQG, but also one which clearly favours LQG over string theory. At the same time, it is also made clear that there is no observational evidence for LQG and that the theory is incomplete. The prologue introduces Smolin and Rovelli, and mentions the influence of Einstein, both in terms of inspiration and as a role model for writing popular-science books. (Unfortunately, Einstein's pun in his description of his popular exposition of relativity is lost in translation.)

While I can see the motivation for wanting the book to be more or less self-contained, almost 100 pages of background is probably a bit too much for many readers, especially since most probably will have read several similar such accounts. It is a reasonably good summary, though the description of the equivalence principle and its relation to the curvature of space and space–time is confusing at best. The three classic tests of General Relativity are introduced by saying that there are four; it is not clear what the fourth is — perhaps gravitational waves. It is not clear why "gravitational waves are of a very different kind to light waves" (perhaps because the lowest-order radiation is quadrupole?), but it is certainly not the case that they "can only be produced by two large masses rotating around each other", though of course such systems are those which have been detected. Also somewhat unclear is the description of the similarities and differences between the Earth and Einstein's static universe, related to confusing dimensions of space with those of space–time (something which occurs elsewhere as well). The author probably knows what he wanted to write, and most readers will, but, as in some other examples, someone reading that for the first time will be confused. That also applies to the description of the role of the cosmological constant in Einstein's static universe and, much later in the book, to the description of the Hubble constant. I'm inclined to put those confusing passages down to bad editing, though, as he gets many things right which others don't: he doesn't make the common mistake of claiming that Wheeler coined the term 'black hole', and with regard to the flatness problem at least adds a footnote stating that "some theorists insist that it's not a problem at all", possibly a reference to the recent detailed discussion by Holman[1] and/or works cited therein. (Also, considering the length of the book as well as the breadth of topics covered, the density of things to quibble about is probably lower than in most similar books.)

The second and third parts, about one-hundred pages each, make up the bulk of the book, and the material here will probably be less familiar to most readers. The juxtaposition of explanations of various aspects of LQG and other topics, quotations from Smolin and Rovelli, and personal anecdotes about them and others make for interesting reading. In addition to surveying the basic ideas of LQG, many current topics are illuminated from an LQG perspective: the problem of information loss in black holes, the holographic principle, the parallels between black-hole physics and thermodynamics, interpretations of quantum mechanics, and the nature of time. However, I prefer a more systematic overview; I can't escape the feeling of having read much but without absorbing more than the most basic qualitative description. Of course, that might be partly my fault: at some level, qualitative explanations (there is little mathematics in the book) work only if one already understands the concept, so perhaps I expected too much. On the other hand, perhaps Baggott tries to do too much; many concepts are presented in considerable detail for a popular-science book, even though some are only loosely related to LQG.

Although loop quantum cosmology is discussed briefly, there is not much astronomy in the book. In the category 'interesting if true' belongs the idea that very short gamma-ray bursts might be due to 'Planck stars', black holes which do not collapse to a singularity but rebound due to quantum-gravity effects. (Those might also explain fast radio bursts.) However, keeping in mind Sagan's dictum that extraordinary claims require extraordinary evidence, it is hard to see how those could be the smoking gun of LQG, since other equally convincing explanations are possible.

Not being an expert on LQG, I worry about the possibility that some explanations in the second and third parts might be inaccurate, similar to those in the first part discussed above. (It would be nice if there were some books on LQG at a level between this one and technical monographs, but that isn't (yet) the case.[2]) Also, although Baggott freely admits that he is partial to LQG over string theory, there is the danger that the reader might obtain a too imbalanced impression — not because it is easy to make a convincing case for string theory, but because some of the problems of LQG are glossed over. Nevertheless, the book is a good introduction to LQG and related ideas, and enjoyable to read. — PHILLIP HELBIG.

References

(1) M. Holman, *Foundations of Physics*, **48**, 1617, 2018.
(2) C. Rovelli, personal communication.

When the Earth was Flat: Studies in Ancient Greek and Chinese Cosmology, by Dirk L. Couprie (Springer), 2018. Pp. 361, 24 × 16 cm. Price £109·99/$159·99 (hardbound; ISBN 978 3 319 97051 6).

In this well-illustrated, profusely-referenced, and scholarly tome we are taken back to the days of Anaximander, Anaximenes, Democritus, Leucippus, and Xenophanes when the Earth was thought to be flat. We start in pre-Socratic times, around the year 600 BC and end in the era of Pythagoras and Aristotle when empiricism introduced the possibility of sphericity. Here the demise of flatness came with the interpretation of the convex circular shadow cast by Earth on the Moon during eclipses, the variations in the observed sky as one travels either north or south, and observations of ships as they left port and eventually disappeared over the horizon. In the early-Greek model the heavens are regarded as a hemispherical or spherical surface surrounding a flat Earth

The book contrasts and compares the Greek view with ancient Chinese hypotheses. In early China the Earth was again thought to be flat, but this *gai tian* model also envisaged the sky as being flat too, and circular, and parallel to the Earth's surface. This view was maintained in the far-east until Chinese astronomy was influenced by visiting Jesuit missionaries in the 17th Century. The differences between the two cultures is fascinating. Maybe the sole use of the Chinese sky as a portent of astrologically significant events prevented any thoughts as to the physicality of our planet and its surroundings.

Dirk Couprie, the author, is associated with the Department of Philosophy at the University of West Bohemia in Pilsen, Czech Republic. In this highly specialized and learned exposition much is made of the textual, conceptual, and doxographic problems of the relevant literature. The author is also to be congratulated on his clarity and thoroughness. I was saddened only by the fact that he did not seem to get around to producing an index. — DAVID W. HUGHES.

A History of Optical Telescopes in Astronomy, by Wilson Wall (Springer), 2018. Pp. 173, 24 × 16 cm. Price £99·99/$139·99 (hardbound; ISBN 978 3 319 99087 3).

When Galileo first turned his telescope to the sky in 1609 he set in train a revolution in both science and technology. Glass-working graduated from a craft to an art and eventually to a science. Geometrical optics led to physical optics. As astronomers sought greater magnification and light grasp, they were faced with increasing engineering problems to keep the optical components in alignment. Since the time of Newton it has been recognized that the Earth's atmosphere is a limiting factor. Observatories were established at high altitudes and more recently in Earth orbit.

The present book is a popular history of the astronomical telescope, from its first invention, to the *James Webb Space Telescope*, whose launch is planned for 2021. Each chapter is largely independent of the others with its own list of references, and this leads to some occasional duplication. In a short book there is insufficient space to cover the rich history of the astronomical telescope, but this book succeeds in picking up the most important points, including the limitations of contemporary technology. There are six blank pages at the back which could well have been devoted to further detail. There are illustrations, both monochrome and colour, but only two show telescopes — Hevelius' 210-foot refractor and the *Hubble Space Telescope*. There are no line diagrams.

There is only one algebraic equation, in Chapter 2, which describes the focal ratio of a lens. Readers not grounded in mathematics can find the same equation expressed in prose at the beginning of Chapter 4. It is difficult to explain optical aberrations without algebra or geometry. Chromatic aberration is sometimes attributed to diffraction and in other places correctly to dispersion.

Dollond's production of an achromatic doublet lens was a major advance for which he received a patent. Other opticians were tempted to flout the patent. (The book says they 'flaunted' the patent but 'flout' is obviously meant.) One subterfuge adopted by a rival was to market telescopes under the name Dolland; that would be a minor point except that the book uses the same antepenultimate letter in some places where Dollond is intended.

Following the historical chapters there is a table of the time-line of the optical telescope, which extends back to 3000 BC. There is a column of astronomical events together with another of general contemporaneous events. The table contains some egregious mistakes: in 1752 when Mayer published tables of the Moon, he is confused with Marbach, his birthplace; in 1798 Brandes and Benzenberg measured the height at which comets burn in the atmosphere; in 1802 Herschel is conflated with Wollaston who first observed dark lines in the solar spectrum. In the 'general column' there is a selection of key dates, from Stonehenge to Concorde. In 1776 the declaration of independence is recorded with 'strange' added without explanation, and even more strangely in 1824, the Imperial Yard is defined as the length of a pendulum beating seconds at Greenwich. The final chapter contains short biographies of people mentioned in the previous pages. — DEREK JONES.

Astronomy of the Milky Way: The Observer's Guide to the Southern Sky, by Mike Inglis (Springer), 2018. Pp. 300, 25·5 × 18 cm. Price £22·50/$39·99 (paperback; ISBN 978 3 319 72949 7).

This book follows the Milky Way in the direction of increasing Right Ascension from 6^{h} to 18^{h} and Declination from 0° to –90°. Any constellation within those limits that contains part of the Milky Way is included. A general description of the constellation is given followed by a more detailed description of selected objects of interest such as bright, double, and variable stars, open and globular star clusters, gas clouds, dust clouds, and galaxies.

Unfortunately there are numerous errors in the star charts, including incorrect captions, minuscule R.A. and Dec grid coordinates, legends with the object of interest not present or shown on a different chart, and objects labelled more than once. Generally the images are of reasonable quality though it did seem strange that there were no contributions from astronomers resident in the Southern Hemisphere. The tables are likewise not without errors. One includes the incorrect statement that Procyon is the 2nd-brightest star in the sky. The main text contains numerous spelling, typographical, and factual errors (*e.g.*, the star cluster NGC3201 at declination –46° 24′ is most assuredly not visible from the latitude, +51°, of London). Of NGC5128 it is stated "Alas it is too far south for northern observers, but it can be seen from the southern United States", and apparently Proxima Centauri (dec. ~ –61°) is too far south to be seen by any northern observer. I was also very surprised to learn that "good observers" had reported seeing stars as faint as magnitude 8 (no reference given) with the naked eye and, "Contrary to popular belief, there are some open star clusters that can be seen with amateur equipment...". Footnotes are not exempt from errors either, with the unit for density cited as km/m^3. The author does not reference directly the source material which he presumably used in writing the book.

This is the second edition of the book, and in the preface the author expresses the hope that he would be able to correct the errors present in the first edition. In the humble opinion of this reviewer that has not happened; the book lacks any sign of either copy editing or proof reading. Given the large number of errors in the text and the lack of proper referencing I feel unable to trust the text, the star charts, or the tables — in short I cannot recommend this book at all. — RICHARD DODD.

FROM THE LIBRARY

A Guide to Handheld Military Binoculars, by Stephen Rohan (Optical Press, Bradbury, CA), 2001. Pp. 187, 28 × 22 cm. Price $40 (about £30) (hardbound; ISBN 0 9709003 0 9). (Copies are available on Amazon for rather higher prices! — Ed.)

The reader is probably wondering why a book about military binoculars is being reviewed in a journal devoted to astronomy and its history. The answer is simple. Post-war military surplus including eyepieces, large aerial-camera lenses (used for astrophotography), and binoculars had a profound impact on both amateur and professional astronomy. For one thing, wide-angle Erfle eyepieces were developed during the war. The binoculars designed and manufactured by the major powers were the result of many years of development. After the telescope was invented in the early 1600s by Galileo and others, its use spread quickly among most of the world's military and naval powers. Eventually the idea came about to mount two telescopes side by side and use both eyes. Because of the type of telescopes used, these were called Galilean binoculars. The French perfected the design and produced thousands in the 1800s. They were marked 'Paris'. They can be seen in many 19th-Century photographs of the US Civil War and other conflicts in Europe; General Custer even had a pair at the famous Little Big Horn battle.

The next major design step was made by the German Zeiss works. Prismatic binoculars became the choice of every nation. By inserting prisms between the objectives and eyepieces designers were able to increase the magnification, increase the diameter of the objectives, and increase the field of view. The increased distance between the objectives also resulted in an increase of the stereoscopic effect. A little note of terminology here for initiates: all binoculars have their sizes engraved on the shoulders next to the eyepieces unless they have been painted over or ground off. The first number is the magnification. Then there is a small × followed by the diameter of the objective in millimetres (although in some German and Japanese binoculars the field of view in degrees replaces the diameter of the objective). Thus 7 × 50 would mean 7 times magnification and 50 mm diameter — an ideal and standard night glass.

In addition to the large quantity of US and UK binoculars that were surplused out, many returning veterans brought back German and Japanese models as prizes of war. After WW II there was a tremendous surge of interest in all things technical — astronomy, radio building, anything you can imagine. This was brought about by the interest awakened in the hundreds of thousands of people sent to military technical schools. Many new magazines were started. *Sky & Telescope*, a major astronomy magazine, was full of advertisements for surplus optics and binoculars. Their regular department 'Gleanings for ATM' (amateur telescope makers) published many articles describing how to convert large aerial-camera lenses into astrocameras. Surplus binoculars and kits to assemble them were widely advertised. Every month the classified section *Skygazers Exchange* had advertisements for Japanese and German binoculars brought home from the war. Several Japanese amateur astronomers obtained large Japanese military binoculars and became famous comet discoverers. The famous British amateur George Alcock made many of his comet and nova discoveries with a captured pair of German 25 × 105s. I wonder how much of this interest in astronomy was sparked by the thousands of veterans who had been out in the vast Pacific, the Atlantic, North Africa, or blacked-out Germany, had used a high-quality pair of binoculars to look at the pristine night sky they never saw from their home cities? Almost every picture of military personnel shows one or more with binoculars draped around their neck. Before the war only a handful of people could afford high-quality binoculars — now everyone could. Even NASA got into the surplus-equipment market using large aerial-camera lenses converted into cameras to record spacecraft launches. NASA also acquired a large quantity of US Navy binoculars, engraving their name on them and loaning them to dignitaries and prominent visitors during launch events. I am fortunate to own a pair of them — they are superb.

Dr. Henry Paul, a famous amateur astronomer and telescope maker of the period wrote three books, *Outer Space Photography for the Amateur, Telescopes for Skygazing,* and *Binoculars and All-Purpose Telescopes*, which are available through Amazon, well-illustrated and dealing mainly with surplus optics. I recommend them all. I have put in all this preliminary information so that people of the last two generations can appreciate the effect on the astronomical community of the ex-military optical equipment and thus enjoy this book even more.

In the first section of the book under review, pages *i* to *iv* describe why it was written, how binoculars were constructed, and the terminology related to them. Pages 1 to 49 describe American binoculars, pages 50 to 135 German, 136 to 160 British, and 161 to 179 Japanese. The remaining pages contain a bibliography and index. The book is very well illustrated with plan-view photographs of every major binocular. It contains data on the diameter of the objectives, the magnification, the field of view, and a short narrative on that particular binocular. There is also a star-rating system denoting the relative rarity. All that is missing is the limiting magnitude. I can assure you, though, with the experience of using dozens of these binoculars in my lifetime that every pair that is coated will perform to the Dawes Limit.

Dozens of these binoculars, seventy years after the war, still show up at car-boot sales, swap meets, antique shops, and on the internet. They are usually in good condition due to the ruggedness of their construction. I would like to point out a couple of noted examples with which I have had experience. On page 47 are described 6 × 42 SARDS — this is an abbreviation of the Square Deal Optical Company. Although SARD made other sizes, when knowledgeable amateurs refer to 'SARDS' they usually mean these 6 × 42s. They are also known as 'Milky Way' glasses. The reason is that with specially constructed prisms and eyepieces giving very high eye relief they have a 12-degree field of view with a sharp image almost to the edge of the field. These binoculars were especially designed to be used in anti-submarine blimps and Catalina patrol aircraft to search the oceans for submarine periscopes or downed aviators or floating seamen, which are very difficult to spot in a choppy ocean. Who knows how many lives may have been saved by the very surplus pair you may have in your hand! A pair was also mounted above the pilot's head in the P-61 Black Widow Night Fighter. After the pilot used radar to vector him in behind the intruder aircraft he could swing the binoculars down and close in visually and make the kill. For amateur astronomers they are superb Milky Way glasses. At some dark-sky site on a warm summer's evening you can lie on your back and have the most beautiful wide-field views of the Milky Way you have ever seen. Unfortunately they are a little harder to find and may cost a little more, but don't pass them by — they are well worth the cost. I am fortunate to have two pairs in my collection.

Another notable binocular is the US Navy Mark 17 shown on page 44. When Navy lookouts complained in the middle of the war that they would like a binocular with a little more magnification and a little more light-gathering power, the Naval Gun Factory (where binoculars were repaired) responded with a typical American stop-gap measure. They acquired a quantity of standard 7 × 50s and cut off the objectives, put on tube extensions, and used the easily-obtainable, superb, 63-mm objective from the large elbow telescopes they had in profusion, and produced them quickly enough to satisfy the fleet. I also have two of these and they are very good night glasses with a 5-degree field that makes it easy to locate faint objects at the limit of the standard 7 × 50s.

Another direct relationship between military binoculars and amateur astronomy occurred when a bottle-neck in production resulted because the manufacturers were unable to produce the prisms fast enough to keep up with the rest of the parts. Enter Russell W. Porter, the designer of the 200-inch telescope. Porter was one of the original founders of the Springfield Vermont Telescope Makers. This group eventually led to the present day, world-wide, telescope-making community. Porter, with two other amateur telescope makers, Fred Ferson and Paule Linde, organized two dozen of their fellows and succeeded in producing 34000 of those prisms for binoculars and gunsights. Although this was a small portion of the total needed, it succeeded in closing the production gap until modern industrial methods could be employed. Porter also wrote the production manual for them. That is why US binoculars are, I believe, better than those of other countries. This book is invaluable when out hunting old binoculars. So, next time you are at a swap meet, a star party, or in an antique shop, and you see an old pair of dusty binoculars take a step back. You may have found a possession you will enjoy for the rest of your life. — LEONARD MATULA.

OBITUARY

René Gili (*1951–2018*)

René Gili was born in Lachen, near Zurich (Switzerland), on 1951 August 17, but he grew up in the west of Nice, on the French Riviera. For economic reasons he had to start working very young and so did not have the opportunity for academic studies, but he soon developed a strong interest in, and great competence for, astronomical imaging.

René came to the Observatory at Nice as an amateur astronomer in the 1970s, where he met Paul Couteau, a specialist in binary stars. He soon gained enough skills to be allowed to operate the large equatorial refractor (76-cm aperture, 18-metre focal length) alone and to make binary-star measurements with other astronomers. He also had other interests such as astrophotography (planets) and artistic pictures of birds and wildlife.

René Gili initially helped Paul Couteau with his double-star measurements, but from 1987 he began his own measurement programme. The results of this micrometric work first appear in 1997. In the early 2000s he started automating his methods and equipment. He used an intensified CCD camera in association with Jean-Claude Thorel, Maurice Salaman, and Guy Morlet. More recently, René built an optical speckle instrument for the large refractor known as *PISCO 2*, with the help of Jean-Louis Prieur, Marco Scardia, and Daniel Bonneau. He also bought, using his own funds, several high-performance EMCCD cameras. An optical engineer, Yves Bresson, and the '*Service de mécanique mutualisé de l'observatoire de la Côte d'Azur*' contributed to the optics and mechanics.

René's speckle optics feature Risley prisms to compensate for atmospheric dispersion, and filter wheels to select the wavelengths and bandpass. As the large refractor dates from 1887 and has no electronic encoding, he solved the problem of high-precision pointing with a smart use of webcams placed at the eyepieces of the original alignment optics near the centre of the instrument 10 metres away, allowing him to have convenient displays on his PC screens of the values read on circles and verniers. Thanks to his skills, and to the outstanding atmospheric seeing quality of the Nice Observatory site, the images obtained reach the theoretical limit achievable with the 76-cm aperture in the visible: 0·16 arc second. The binary-star data easily reaches 13th magnitude, often at large magnitude differences. René's clever pointing system allows a large number (several dozen) of double-star measurements per hour. René Gili has his name attached to more than one hundred new couples which he has discovered, and several thousand of his recent measures made since 2014 with *PISCO 2* remain to be exploited and published. His natural enthusiasm and competence made him a connoisseur of the mechanics and optics of the great Nice refractor and, as a consequence, from 2008 to 2012, René was involved in optical tests of diffractive imaging made with the large equatorial mount, for a future space project, the Fresnel imager, developed by Laurent Koechlin's team in Toulouse and Jean-Pierre Rivet in Nice. René was a member of the Double Star Commission of the Société Astronomique de France, and he also published in the Société's astronomical review *Observation et Travaux*.

Although reserved in character, René Gili had a very rich personality, and his knowledge spanned a broad spectrum of interests, from astrophotography to opera music. These qualities made him a skilled and productive observer. He is thought to have died in Nice in 2018 at the end of August. — LAURENT KOECHLIN & MARCO SCARDIA.

Here and There

FROM WHAT VIEWPOINT?

The cluster is 95 arcseconds across, meaning it is three times the size of the full Moon, . . — *JBAA*, **127**, 376, 2017.

A VACUUM OF UNDERSTANDING

… [the image] is blurry because the [Ryugu] rover was rotating through the air as it snapped the shot … — *New Scientist*, 2018 September 29, p. 6.

WE'RE INCLINED TO DISAGREE

The transit method works best for planets close to their star, because these block out more light. — *New Scientist*, 2018 November 10, p. 39.

AN UNCERTAIN INCLUSION

AD 19 There is a very uncertain report of a comet seen from China. — *The Observatory*, **138**, 348, 2018.