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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2017 October 13 at $16^h\ 00^m$
in the Geological Society Lecture Theatre, Burlington House

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

The President. Good afternoon, ladies and gentlemen, and welcome to the first Open Meeting of the new session. I have to start with some sad news concerning the recent deaths of two Fellows who would have been known to many present here. Let me start by mentioning Dr. Helen Walker, who died in early September following a five-month illness. She was an extremely valued member of the RAS Fellowship who had worked at the Rutherford Appleton Laboratory for many years. She served in several roles in the Society, was on Council for ten years, including four years as Senior Secretary. She was elected to Fellowship in 1977. Secondly, I would like to mention Professor Leon Mestel who passed away in September at the age of 90. He was latterly Emeritus Professor at the University of Sussex. He received the Eddington Medal from the Society in 1993 for his fundamental work on cosmic magnetism, and then the Society's highest honour, the Gold Medal, in 2002. He was elected to the Society in 1950. So may I ask everyone stand for a minute to remember Helen, Leon, and other Fellows who have died since our last meeting. [Silence.] Thank you.

I have been asked to promote the new guide for Fellows, part of which has been emailed or sent to all Fellows, the 'Code of Conduct'. This is available in the office and on the website. I also draw your attention to the 'Diversity, Equality and Inclusion Policy'. Both of those documents have been approved by Council and we are all expected to adhere to them, of course. Let me also mention the RAS signing-in book. Since the RAS was founded, new Fellows attending their first meeting had been invited to add their signature to the signing-in book. This is different to the signing-in book at reception, which has more to do with health and safety. The current version of the book went missing for quite a few years, but it has magically been rediscovered. [Laughter.] So, if there are any Fellows who joined in the last few years and would like to add their name to the book, it will be available in the RAS library from $15^h\ 30^m$ until the end of the meeting. We now proceed to the programme.

We start with the lecture associated with the RAS's 'G' Award. This went to the *SuperDARN* consortium and the talk will be presented by Professor Mark Lester. The title is, 'The *Super Dual Auroral Radar Network*: new insights into Earth's space environment'.

Professor M. Lester. I would like to start by taking this opportunity to thank the RAS for the Team Award for Geophysics in 2017. The *SuperDARN* community is rightly proud of our achievements and it is very gratifying to receive this recognition. In my talk this afternoon I introduce Earth's space environment, give you an idea of what *SuperDARN* is and how it works, demonstrate some of the unique capabilities of *SuperDARN*, and, finally, discuss a few of the results that have come from analysis of *SuperDARN* data over the last 22 years. This is, of course, something of a personal choice but I hope it illustrates the scope of work which *SuperDARN* has covered.

I start by reminding everyone of the basic nature of Earth's space environment which is termed the magnetosphere. This is in fact a very dynamic system containing a range of different plasma régimes, each of which is threaded by Earth's magnetic field, and they are determined by the particle energies and their densities. The major controlling influence of the dynamics of this system is the solar-wind interaction with the magnetosphere and, subsequently, the ionosphere, which can be considered to form the inner boundary to the magnetosphere. Magnetic reconnection is the key process in this interaction through which mass, momentum, and energy are transferred from the solar wind into the magnetosphere, while reconnection is also a critical process in describing the dynamics of the geomagnetic tail.

Earth's ionosphere forms mainly as a result of photoionization of the atmosphere and, due to the structuring of the atmospheric density with altitude, several different layers are formed with peak electron densities at different altitudes, typically between 90 and 400 km. Plasma-loss mechanisms include recombination and attachment, while transport is also a critical process for understanding those layers, particularly the F region where the peak electron density most often occurs. Structuring of the ionospheric density depends on the different latitudes as a result of the nature of the field lines that thread the ionosphere. Polar latitudes are threaded by magnetic fields which usually connect directly to the solar wind, referred to as open field lines, allowing particle precipitation directly for the solar wind and magnetosheath, while mid-latitudes are nearly always on closed field lines, *i.e.*, field lines that extend directly from one hemisphere to the other. The auroral regions are a mix of closed and open field lines.

SuperDARN is a network of HF coherent-scatter radars which exist in the northern and southern hemispheres. Currently there are 23 operational in the northern hemisphere and 13 in the southern, with lead groups from ten different nations. These radars cover the mid-latitudes to the poles in both hemispheres while their coverage, in particular in the northern hemisphere, is almost global. They measure a number of parameters but those which we use routinely are the returned power of the signal, the line-of-sight velocity imposed on the returned signal, and a parameter termed the spectral width which gives information on the scattering mechanisms responsible for the returned signal. I shall not discuss this last parameter during my presentation. The line-of-sight velocity comes from the fact that, in the Earth's ionosphere, electric fields impose a drift on the ionosphere which is an $\mathbf{E} \times \mathbf{B}$ drift, where $\mathbf{E}$ is the electric field and $\mathbf{B}$ the magnetic field. *SuperDARN* can therefore provide detailed global and interhemispheric information on the distribution of those electric fields.

I start the discussion of new results by presenting three pieces of work which have significantly enhanced our understanding of magnetic reconnection within Earth's magnetosphere. The first concerns pole-ward-moving radar auroral forms. These features have been unambiguously identified as an ionospheric signature of magnetic reconnection at the day-side magnetopause and demonstrate how the radars provide an excellent tool for investigating the rate of reconnection as well as the scale size of reconnection. Simultaneous ultraviolet auroral observations from space by the *Polar* spacecraft demonstrate an auroral signature which travels down the dusk-side of the auroral oval, suggesting that the reconnection site also travels down the magnetopause, demonstrating that the event is not simply localized at a site at the magnetopause. An estimate of the reconnection voltage for a single event from this interval was 160 kV, which is much larger than the previous estimates that had been derived from single-radar/optical studies. This work opened up a debate, which continues to this day, about the contribution that such events can make to the overall reconnection rate.

The next study demonstrates the important role *SuperDARN* played in verifying the concept of the expanding–contracting polar-cap (ECPC) model for reconnection-driven dynamics in the magnetosphere. Ionospheric flow on the day-side is stimulated by the addition of newly created open flux at the day-side magnetopause through reconnection, while on the night-side the flow is stimulated by the closing of the magnetic flux in the tail. As the day-side reconnection rate exceeds that of the night-side, the polar cap expands, and, when the night-side reconnection rate dominates, the polar cap contracts. *SuperDARN* observations of the reconnection rate by measuring the flow across the reconnection site in the frame of the moving boundary have been crucial in demonstrating how reconnection exists simultaneously at the day-side and in the night-side, and are the only way we currently have of measuring the time variability of those reconnection rates simultaneously.

This leads us to the parameterization of ionospheric convection by the driving interplanetary magnetic field (IMF), both in terms of the direction and the magnitude. Such parameterization has usually been only considered in terms of the day-side drivers and has not included the night-side drivers. The ECPC model, however, demonstrates that this is not an adequate description and recent observations have just been published which now compare such average patterns deduced by IMF drivers alone and those which include night-side driving. Considerable differences in the average patterns are observed on the night-side.

I will now move to the structuring of the ionospheric plasma density, which is important for a number of reasons, notably that plasma-density variations impact significantly on the quality of signals that propagate through the ionosphere, *e.g.*, to and from spacecraft. Structuring of the polar-cap ionospheric plasma can be caused by two different processes: one is direct entry of plasma from the magnetosheath and solar wind, while the other is transport from other regions of higher density. *SuperDARN*, which also receives its ionospheric signal from plasma-density structures, has been used to demonstrate how plasma can be drawn from the mid-latitude regions into the polar cap, and then tracked from the day-side to the night-side. This method even allows us to predict the time of arrival of these regions of enhanced density. The patches which are transported anti-sunward across the polar cap can also evolve into blobs which leave the polar cap on the night-side, but *SuperDARN* has demonstrated that this can only happen at locations that map to on-going magnetotail reconnection.

At mid-latitudes the structuring is more often determined by enhanced westward convection in the dusk local-time sector, which results in increased recombination rates. Such strong flows at mid-latitudes are termed sub-auroral polarization streams (SAPS) and occur over a range of driving conditions, but the strongest, and hence those with most impact, are seen during high levels of disturbance, called magnetic storms. *SuperDARN* has been used to investigate the way in which such SAPS evolve from the low levels of activity through to the higher levels.

Having focussed very much on the scatter received from the ionosphere, I now move to two studies which have used scatter received from the ground or sea. Here the signal has been refracted at a point in the ionosphere to a point some distance from the radar and then scattered back along effectively the same path. Such ground-scatter measurements are excellent for investigating medium-scale travelling ionospheric disturbances (MSTID), and in the first of these two studies the North American *SuperDARN* radars demonstrate that the MSTIDs over mid-latitudes at this time are most probably related to polar-vortex variability, and possibly due to stratospheric wind filtering. This is important as it demonstrates a critical aspect of vertical atmosphere coupling whereby lower-atmosphere dynamics control the behaviour of the upper atmosphere.

To conclude, I'll briefly mention a second study using ground scatter where the co-seismic ionospheric disturbances following the magnitude-9 earthquake on 2011 March 11 have been investigated. After this earthquake, the Hokkaido *SuperDARN* radar observed apparent periodic upward and downward motions of the ionosphere with peak-to-peak amplitudes of up to 200 m s^{-1}. These disturbances travelled from the earthquake epicentre at velocities in the range 3·5 to 6·2 km s^{-1} and are interpreted in terms of the vertically propagating acoustic waves triggered by seismic waves. These results open up the possibility of monitoring earthquake-triggered disturbances over the sea, where there are normally few observation points.

In summary, I hope that I have demonstrated the breadth and scope of the science to which *SuperDARN* has contributed in a wide range of fields. The radar network continues to expand with a number of systems soon to come on line and evolve with new technologies and developments in signal processing which will enable improved scientific capability in the future.

The President. Thank you very much indeed, Mark. We have a brief time for questions or comments.

Professor Lyndsay Fletcher. When you measure the changes in total electron content are you certain that they are due to advection of plasma, or can they be transient ionization from other sources associated with auroral processes?

Professor Lester. That's a good question. In the polar cap you can create the plasma in two ways: you can either create it by dragging it from the day-side ionosphere, or you can get precipitation into the upper atmosphere which creates additional ionization. The fact that we are able to track this tongue using the radar observations tells us that it's actually coming from the day-side region, and it's being transported, not being created *in situ* by particle precipitation.

Professor S. Miller. The buoyancy waves, that are coming from the auroral regions, are drifting equatorward. Presumably they are carrying energy with them. Do you know roughly how much energy you are transporting out of that polar auroral region?

Professor Lester. You can't ask quantitative questions on a Friday afternoon! [Laughter.] The short answer is, I cannot remember, but significant amounts of energy. And what they are doing, those waves, is restructuring the plasma in a very unusual way. If they are caused by auroral activity, they are transporting energy into other parts of the ionosphere. I know the UCL group have done modelling of those waves. But the orographic waves, which are smaller scale, and also the polar-vortex waves, are a completely different kettle of fish. We do not really understand it, partly because when atmospheric modellers do their thing they put a boundary at 90 kilometres and they just have a gravity-wave parameterization scheme there, and that is obviously not working well.

The President. I am afraid the clock has caught up with us, so Mark, thank you very much indeed. [Applause.]

Our next talk is the so called RAS Diary Talk 2017. I assume that everybody here, as I do, carries the RAS diary close to them at all times. You will note that there is a section for anniversaries every year. We now have one talk every year associated with one of the anniversaries. I have been asked to advertise the work of one of our committees, the Astronomy Heritage Committee. The chair of that committee, who is over there, is Mike Edmunds. Is it your committee — not you — who chooses the title of this talk every year? Good. I think I woke Mike up! [Laughter.] The diary states: "1767: Nevil Maskelyne began publication of the Nautical Almanac", which leads us then to today's talk. It is given by Professor Jim Bennett on 'The origins of the *Nautical Almanac*, 1767'.

Professor J. Bennett. The Royal Society promoted an expedition to St. Helena to observe the Transit of Venus in 1761 and appointed a young Cambridge mathematician, Nevile Maskelyne, as observer, and as his assistant Robert Waddington, who is scarcely remembered today. He might be described as a commercial jobbing mathematician — a teacher, writer, surveyor, instrument maker — a fairly typical mathematical practitioner of the 18th Century. Maskelyne's brief was to observe the transit and then to remain on the island for a further seven months to take a series of stellar measurements with a substantial instrument, a 10-ft zenith sector. Waddington was to assist only with the transit observation and then return home.

On the East India ship, the *Prince Henry*, Maskelyne and Waddington did something extraordinary on the outward voyage — sometimes working in tandem, sometimes alone and each using their own Hadley quadrant — they made a set of lunar-distance determinations of their longitude, the first such measurements by British navigators at sea.

The basic idea was to use the measured position of the Moon to provide time at a distant, standard, meridian, such as Greenwich, and to compare this with local time, also derived astronomically, from the Sun or stars, the difference between the two being the longitude difference in time. Maskelyne knew two practical methods of applying this idea, one formulated by Halley and published posthumously in 1752, the other more recently by Lacaille. Halley's method could be performed by a single observer and Maskelyne began there, but as he came to know the officers of the ship, he switched to Lacaille's method, where three or four observers worked together, taking altitudes as well as the lunar distance.

Whichever method was used, the lunar distance to be compared with the observed value had to be extracted by long calculation from a set of astronomical ephemerides; Waddington said that Halley's method took six hours to complete. He was working along the same lines as Maskelyne, by training and collaborating with members of the crew. Both men arrived at St. Helena with a very unusual experience of longitude-finding and a determination to take this further when they got back to England.

They repeated the experience on their return voyages, but Waddington was in London six or seven months before Maskelyne, and he started to promote the method, to teach it, and to prepare publications on it. There is no indication that he thought of himself as a rival to Maskelyne; he thought he was part of a joint enterprise. Maskelyne seems to have paid scant attention to Waddington's activities; he was the senior person, the official astronomer, and he just got on with the programme with little attention to Waddington.

The standard story of the lunar-distance method generally cites two pivotal publications by Maskelyne, the *British Mariner's Guide*, where the method is explained, and the *Nautical Almanac*, first published for 1767. Waddington had beaten him to it on both counts, by publishing a textbook on the lunar method for longitude in 1763 March, *A Practical Method for finding the Longitude and Latitude of a Ship at Sea, by Observations of the Moon*. Maskelyne's equivalent, the *British Mariner's Guide*, appeared the following month. As with the *Nautical Almanac*, Waddington's method would require updated tables for each year and he published *A supplement to the treatise for finding the longitude* for 1764, where he promised a further supplement for 1765.

This was not sustainable. Waddington's was an individual commercial enterprise. By the time Maskelyne was preparing the *Nautical Almanac* for 1767, he was Astronomer Royal, and so was himself one of the Commissioners for Longitude, and had secured an Act of Parliament authorizing its publication. He had established a distributed cottage industry of calculators and comparers for preparing and checking the tables. His operation was underpinned by official funding. Waddington didn't stand a chance.

The basic arrangement of the *Nautical Almanac* followed a pattern that changed little over the first couple of decades. Each month had 12 pages — first an almanac page in the popular sense of a calendar, then two pages of solar data for the month and positions of Jupiter's satellites, a page of planetary information, and one for the daily configuration of Jupiter's satellites, and three pages of daily lunar diameters and positions. Then there were four for the main navigational data, the lunar distances themselves, two pages giving the angular distances to stars or the Sun to the east of the Moon for every three hours (Greenwich time), and two for the equivalent information to the west.

These four pages were the crux of the almanac. All that work of calculating the lunar positions had been removed from shipboard and farmed out to Maskelyne's cottage industry. These pages, as Maskelyne put it rather nicely, "are designed to relieve the Mariner from the Necessity of a Calculation, which he might think prolix and troublesome". The navigator now had to measure the distance, as well as the altitudes, and then, as it was said, "clear the distance", *i.e.*, make various instrumental corrections and compensate for refraction and parallax. He then found Greenwich Time by interpolating for this cleared distance in the row of data for his chosen star or the Sun and the date, and compared this with local time to find his longitude. He could do that in about half an hour.

The sequence of 12 pages was repeated for each month and (apart from one immediate change) it was maintained, presumably for the sake of familiarity for the users, even if it meant having a page with no information, such as when Jupiter was too close to the Sun for the satellites to be seen. Finally there were 23 pages of instructions by Maskelyne — the 'Explanation and Use'.

The whole enterprise was a success — it survived and became a model for others. Responsibility passed from the Astronomer Royal to a Superintendent of the Nautical Almanac in 1818, and in 1832 from the Board of Longitude to a Nautical Almanac Office responsible to the Admiralty. The Office became part of the Royal Observatory in 1937, moving to Herstmonceux and to Cambridge, and, with the closure of the RGO, to the Rutherford Appleton Laboratory, and in 2006 to the Hydrographic Office.

The full title of Maskelyne's publication was the *Nautical Almanac and Astronomical Ephemeris*. Though it gained its justification from Britain's maritime ambitions, there was room for plenty of astronomy. The two pages for the planets and for Jupiter's satellites had no navigational application. Maskelyne explained that the planetary positions would be useful for observatory work and he also added treatises on purely astronomical topics, such as a long tract on making mirrors for reflecting telescopes.

He wanted the *Nautical Almanac* to be a model of probity as well as precision, and in the tabulated data that aim was achieved, but other things could be neglected, such as the appendix of instructions. A change was introduced in only the second volume (for 1768), when the diagrams of the daily configurations of Jupiter's satellites were moved to the final page (p.12) of each month, clearly to allow the four pages of lunar distances to be presented on two openings — one for bodies to the east, the other to the west. No adjustment was made in the instructions for 13 years, with the wrong references to pages continuing and creating, we might presume, some confusion at sea.

We have to conclude that the data were more important — all the attention was directed there. The policy succeeded. The *Almanac* was one of the earliest examples of sustained public funding for science in Britain, even if the astronomy was somewhat slipped in under the wire by Maskelyne, who did nonetheless recognize that a kind of contract had been made with the public. Under criticism from the astronomer Jean Bernoulli with regard to the accuracy of the data — the vital content — Maskelyne mounted a vigorous rebuttal in the preface to the volume for 1771, fearful that it might be thought "that the Calculations of the Nautical Almanac are not made with the Care which the Public have a right to expect". This was an early explicit reference to the idea of *public* patronage and *public* service in science.

The President. We have very brief time for any questions or comments.

Dr. L. V. Morrison. Do you know roughly what accuracy Maskelyne obtained in his voyage to St. Helena? After all he found the island, which implies it was 10–20 miles. Or is it better than that?

Professor Bennett. Oh yes, it is better than that. But remember, he was not the commander. He was not in charge of those sorts of decisions. The captain was a man marvellously called Captain Haggis. Captain Haggis was a particularly astute navigator. He really appreciated Maskelyne's work. There's a myth or a story that goes around historians of navigation that there was almost a resistance, because sailors liked to have their customary habits and they didn't like new-fangled astronomical and technical developments. I have not found much evidence of that at all. These were East India men and Captain Haggis was really keen, as was often the case. It is quite a complicated story, because a lot of people were keeping account on the ship. Waddington's was, oddly enough, better than Maskelyne's and the Captain said that. So there were lots of people calculating the position. I had better not pin myself down to a particular distance, but it was certainly a lot better than 20 miles.

Professor Kathy Whaler. I was going to ask a very similar question. I notice on the Maskelyne document that you showed it said, 'longitude to within 1 degree!' I wondered how that compared with the dead reckoning.

Professor J. Bennett. Of course a degree is different in different latitudes, but you can find the island with much worse than 10–20 miles.

The President. I am afraid time is short, so can we thank Jim again. [Applause.]

Our final contribution today is the Harold Jeffreys Lecture for 2017. But I would like to take the opportunity, before the speaker gives the lecture, to present the citation since Tim Wright was not at the award ceremony:

"Professor Wright, of the University of Leeds, is an outstanding researcher and world leader in the field of applying satellite radar interferometry (InSAR) to measure tectonic and volcanic deformation. He is the Director of the UK-wide NERC-funded COMET, the Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics, and principle investigator on a number of other large collaborative projects. His research highlights include the first demonstration that inter-seismic strain can be measured using InSAR, and the discovery of a major continental rifting episode in Afar, Ethiopia. His ability to communicate complex, multidisciplinary problems to the public is evidenced by multiple television appearances on the BBC (news and documentaries) and Discovery Channel productions, in addition to extensive outreach activities. He was selected as the British Geophysical Association's Bullerwell Lecturer in 2015 and has also received awards from the Geological Society of London, the American Geophysical Union, and the University of Miami. For these reasons, Professor Tim Wright is awarded the position of the Royal Astronomical Society's 2017 Harold Jeffreys Lecturer."

Professor T. Wright. [It is expected that a summary of this talk will appear in a future issue of *Astronomy & Geophysics*.]

The President. Thank you so much, Tim. We have a couple of minutes for questions.

Dr. G. Q. G. Stanley. A wonderful presentation and very enlightening. I feel I will be going home and seeing if my house is subsiding. One thing I have noticed, as with the earlier presentation on *SuperDARN*, was earthquakes causing differences in data, which I guess is the piezoelectric effect. Have you looked into that area at all and seen anything?

Professor Wright. What's the postcode? [Laughter.] The ionosphere is noise for us. If he [Professor Lester] is still here I would be very interested in having a conversation about that. It is noise for us, but we do see a beautiful ionospheric signal and actually we have been developing methods for solving for that and removing it. As to ionospheric delays, we get phase changes proportional to the frequency squared, so if you split the frequency of the radar signal you can invert for the amount of ionospheric delay. We get snapshots from the InSAR. From GPS you can get beautiful time series so I have seen movies for the Japan earthquake where you see the ionospheric waves radiating out. Actually, you cannot walk in Japan without tripping over a GPS site. You have then a measurement between each GPS satellite and each GPS station of the delay, so you get beautiful maps of how those ionospheric waves propagate. It would be interesting to chat with somebody who might be able to use those data.

The President. Could I just ask, on the London map there was a cluster of points south of the river was there not?

Professor Wright. Yes. The Oval is there, and this is Kennington Park. I am not sure what it is.

Professor Bennett. The Northern Line extension?

Professor Wright. No, it seems like a broad signal. The only thing I could find from a news story from a couple of years ago is a big water main which burst there. I just wonder if it is some kind of movement there. The other signal is here, around Canary Wharf, and that is the rebound from all the money that has gone off to Europe. [Laughter.]

Dr. P. Wheat. I guess with GPS you have got to have a solid rock angle, going down to base rock. But when you have synthetic-aperture radar looking down at the Earth, is that reflecting off the rock layer, because the soil layers above are quite variable in height (flooding, evaporation, and all sorts of things)? And I have also heard about fluidized beds. Have they been picked up and what is the connection to the earthquakes?

Professor Wright. What you need for the technique to work are the scattering characteristics to remain constant in your pixel between your two images. So it is a relatively short wavelength and if the soil is wet, it will more or less come off the surface. If the soil is undisturbed you will get a signal back. If things are moving around, for example, a farmer ploughing his field, or you get liquefaction, then the phase measurement becomes meaningless. There are other things you can do to make those measurements, but they are not as precise. The other place it does not work is on water. The water surface is obviously changing. If vegetation is extremely dense in a rainforest it does not work. The radar comes in and is scattered around the forest canopy, and returns with essentially a random phase number. So it does not work everywhere. But with systems like *Sentinel 1*, with the short revisit times, we are getting better and better. The ground is more stable. If you are looking over days, not much changes unless you have a big event.

The President. Last question.

Professor Whaler. Given what you said about the faults jumping much further than we previously thought in the New Zealand earthquake, are there implications for the understanding of what an aftershock is, or whether that affects how we understand the tectonic cycle, rebound, relaxation, strain, and so on?

Professor Wright. I think there is a lot of interesting work going on now trying to understand what aftershocks really are. Traditionally aftershocks have a rather arbitrary definition. You say it is an earthquake that is smaller than the first earthquake and happens within a fault length of the original rupture. It is a rather arbitrary decision. Now we are seeing all sorts of interesting dynamic effects. There is an example that I did not show from Pakistan. There was basically an earthquake doublet: the second earthquake was triggered by the P-wave of the first, 50 kilometres away. It was essentially instantaneous (19 seconds apart). Do you call that an aftershock or a triggered event? We tend to talk about triggered events. Of course, the aftershocks can be bigger as well, they do not have to be smaller. There are some really interesting data coming out of Italy, that is also looking at how fluids are moving after the earthquake. You can see these migrating patterns of aftershocks, triggered by the fluids moving through the crust.

The President. Can we again thank Tim. [Applause.]

It just remains for me to remind you about our drinks reception held immediately now in the RAS library. And, finally, I give notice that the next monthly Open Meeting of the Society will be on Friday, 10th of November.

THE IMPACT OF WORLD WAR I ON RELATIVITY PART I

By Virginia Trimble
University of California Irvine, Las Cumbres Observatory and Queen Jadwiga Observatory, Rzepiennik, Poland

From an astronomical and relativistic point of view, the Great War began with the 1914 August capture and imprisonment of the members of a German eclipse expedition that had gone to the Crimea to look, at the request of Einstein, for bending of starlight by the Sun. And it ended in 1919 with the Eddington-inspired measurements of that light-bending from Príncipe and Sobral, and with the founding of the International Astronomical Union by scientists from "the countries at war with the Central Powers". In between came unprecedented death and destruction. The scientists lost were mostly too young to have made an impact. Exceptions include Henry Moseley (shot at Gallipoli in 1915 August, before he had finished sorting out the periodic table by atomic numbers) and Karl Schwarzschild (invalided home from the Russian front with pemphigus, to die in 1916 May), but many of the best-known of the next generation had, if citizens of the belligerent countries, served on the battle lines, and most of the rest contributed in some other way. It may come as a surprise to find that both theoretical physics and observational astronomy of relevance to General Relativity continued to take place, and that there was a certain amount of communication of results, information, and even goods in both directions. The early post-war years saw something of a flowering of the subject, before the majority of physicists turned their attention to quantum mechanics and astronomers to stellar physics, though each had been under consideration during the war. Part I will take us up to Einstein's 1915–1916 papers. Part II looks at what others did during the Great War. And Part III addresses aspects of the aftermath, including Einstein's 1922 visit to France.

Introduction

The decades on either side of 1900 saw a burgeoning of international activities in the sciences and life in general. Between 1900 and 1913, there were 428 international conferences in Paris, 168 in Brussels, 141 in London, and many others[1]. The International Association of Chemical Societies convened for the first time in 1911 (in Paris, of course) and resolved to rationalize the names of organic compounds and to produce a fourth edition of Beilstein's catalogue[2]. The Association International des Académies was formalized in 1899 (in Wiesbaden, despite the name). On the astronomical side, the AGK project had begun in 1868 and the Astrographic Catalogue ('Carte du Ciel') in 1887, under Admiral Mouchez at Paris[3].

The 1896 convention of the International Association for Geodesy was extended for a new decade in 1907 (their 1906 meeting in Budapest having introduced the rest of European earth-measurers to the virtues of Eötvös Lorand's torsion balance). Kapteyn's Plan of Selected Areas received general agreement in 1906, following just after the establishment of the International Union for Co-operation in Solar Research, sparked by George Ellery Hale[4]. At the suggestion of Karl Schwarzschild, the Union was considering expanding its remit to all of astrophysics at its 1910 meeting in Pasadena, but was still called the Solar Union for short at its last, 1913 August, meeting in Bonn.

Since we shall not pass this way again, let us pause to note that Paul Jacobson, former professor at Heidelberg, who had established a commission in summer 1914 to take on the chemical tasks, was not allowed to participate when the work actually got started under the International Union of Pure and Applied Chemistry[2]. And Henri Abraham, the founding General Secretary of the International Union of Pure and Applied Physics, who was confirmed in office in 1934 and who had made (from Paris) significant contributions toward early radar in the First World War, was deported and killed at Auschwitz during the Second.

Those eclipse expeditions and how I came to the project

Many years ago, I investigated whether scientific papers had grown monotonically longer more or less forever (the answer was a qualified yes)[5]. That was somehow in mind early in 2011 when I walked past the library shelves of *Nature* and noticed how skinny the volumes had become through the years 1915–19. Aha!, thought I, I wonder how else World War I shows up there. So I picked up the first 1914 August issue and started to read, eventually examining every page from 1914–1919 and later back to 1908 and forward to 1923. Within a couple of issues, there was the report of a Berlin eclipse expedition to the Crimea under Erwin Freundlich having been captured and imprisoned. Paul Halpern[6] tells us more about the background, and issues of *Sirius** and *Nature* more about the outcome.

World War II has been called the physicists' war (meaning radar, rockets, and fission bombs) and World War I the chemists' war (poison gases, of course, but also urgent need, in the face of various blockades, for nitrogen fixation, synthetic rubber and petroleum, dye stuffs, optical glass, and much else). Not surprisingly, in fact, no part of science, technology, or engineering came through either war unaffected. A handful of items that do not belong to us here include the first (accidentally) placebo-controlled test of vaccination (for

* *Sirius Zeitschrift für populäre Astronomia* is not very easy to find on the web (Sirius the star, Sirius XM radio, and others dominate). I had never heard of it, and, when first thinking about this investigation, wondered whether the new *Naturwissenschaften* or the already old *Astronomische Nachrichten* might have some of the same kinds of information as *Nature*, but as seen from the other side. Neither journal was readily available, so I asked Hilmar Duerbeck (then retired from the University of Münster, whom I knew slightly from his interest in "Who discovered Hubble's Law?") for advice and assistance. He responded quickly with copies of a number of articles, from *Sirius* for 1915–1924, dealing with astronomers serving or killed on active duty, the trials and tribulations of the captured eclipse expedition, and the issue of rivalry between the new IAU and the old Astronomische Gesellschaft. Hilmar's sudden, unexpected, and very sad death on 2012 January 5 obviously put an end to our collaboration, and I still haven't done much of anything about information that might be found in *Naturwissenschaften* or *AN*, the latter of which had both obituaries and observatory reports. Hilmar also checked relevant issues of *Die Himmelswelt* and indicated that neither they nor *Jahresberichte* were very informative. A University of California Irvine colleague fluent in Russian, Meinhard Mayer, expressed some interest in what might have gone on under the Tsar, but died before we had done much except talk about the topic. I have not attempted since to enlist collaborators, feeling that it is somehow unlucky.

typhoid fever), demonstration that round craters could come from oblique impacts, the first aircraft carrier, reluctant welcoming of women into industrial labs and production facilities, and a brief moment when Canada had the world's largest telescope. I have spoken about many such items at meetings on physics, chemistry, and astronomy, and hope some day to get it all on paper (or whatever anybody might be reading by then). This is the second instalment. The first, "Who got Moseley's Prize?" (meaning the Nobel he had been nominated for in 1915 just before he was shot at Gallipoli, and the answer is Charles Barkla), is in an American Chemical Society book[7].

The 'prequels'

It will perhaps have occurred to you that the present author is not the first person to have noticed that we are currently passing through the centenaries of World War I (called the Great War until the second came along, and extending from 1914 July in Sarajevo to 1919 June 18 at Versailles) and of General Relativity (1913, the *Entwurf* theory, to 1922, the first Friedman solution). The literature on each is enormous: something like 20 000 books on the War (of which I own about 0·3%) and 1700 books on Einstein*.

Newton (1642–1727) on gravity and Clausewitz (1780–1831) on war is perhaps too far back to go for 'origins', though the 'causes' of the Great War can be traced back at least as far as the Treaty of Vienna, which more or less put an end to the Napoleonic Wars. The assassin of Archduke Franz Ferdinand, who was the 'Trigger'[8], does not seem to have been a very interesting person. The handful of tomes on the beginnings of the War that I have read (refs. 9–13) put forward so many causes and condemnations as to make it seem inevitable. This is the last I will say about WWI *per se*, except when it impinges on the creation of the general theory of relativity or related topics.

As for the origins of GR, Fig. 1 is my own take and includes many of the outcomes as well. At a more technical, solemn, and serious level, something called *The Road to Relativity*[14] sounds (and is) particularly promising. The volumes by Kennefick[15] and Crelinstein[16] are Dr. Kormos-Buchwald's recommendation. The most succinct statement, made in print long ago, and reaffirmed this year by email, comes from Professor Gerald Holton at Harvard, "only Einstein; only there; and only then", where "there" means Berlin, and "then" means 1914–1916. Let's take them one at a time.

First: Biographers (read Pais[17] if you're having only one) and the man himself agree about Einstein's extreme ability to concentrate (sometimes to the exclusion of his family and friends, to put it very gently) and to keep after something until he saw it to be right, described as "the years of searching in the dark for a truth that one feels but cannot express, the intense desire and the alternation of confidence and misgiving until one breaks through to clarity and understanding, are known only to him who has experienced them himself"[18].

Second, about the place: Berlin saw the arrival of Einstein on 1914 March 29 (from what is now the ETH in Zurich). He had been offered membership in the Royal Prussian Academy of Science, a quite decent salary for the time and place, and no teaching responsibilities. Wife Mileva and sons Hans Albert

*Diana Kormos-Buchwald, director of the Einstein Papers Project in Pasadena, reports that there are something like 1700 books on Einstein, of which about 200 are biographies, the first in 1921; and she should know! And let me pause right here to acknowledge that she most generously sent me copies of the three volumes of 'Einstein papers'[20] that contain all the personal letters to and from him that have been found for the years 1914–1918. These will appear repeatedly below.

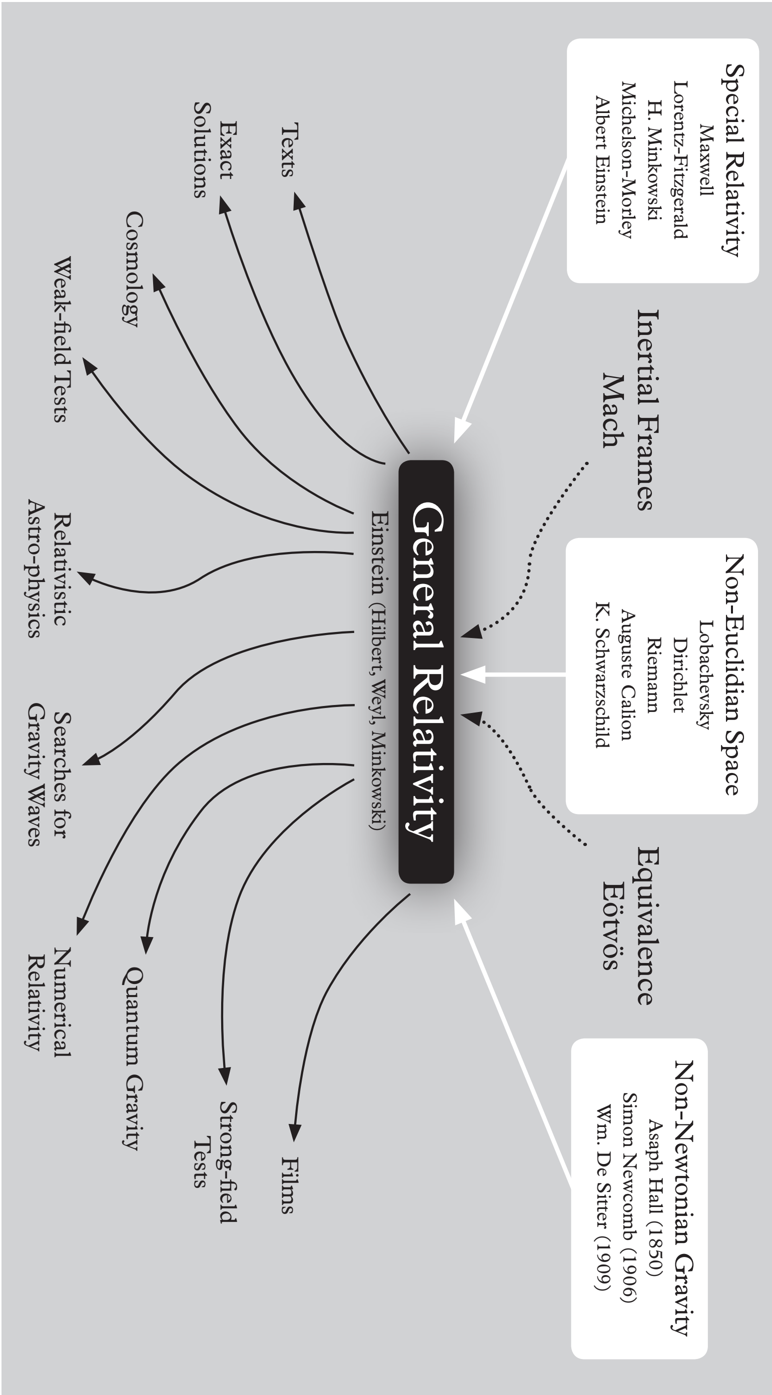

FIG. 1
The Origins and Outcomes of General Relativity

and Eduard came with him briefly, but soon returned to Zurich; among the other attractions of Berlin was the presence of Albert's cousin Elsa, whom he later married. Despite the 'no teaching' arrangement when he was appointed professor at the University of Berlin, he taught relativity starting in the autumn of 1914, and we find him doing so again for two hours a week in 1916. In 1917 he appears in a *Physikalische Zeitschrift* list of lectures to be given that year in Berlin, among those at more than a dozen German-speaking universities (including Vienna and Zurich), with the topic 'relativity'. In addition he lectured on quantum theory and statistical mechanics at various times. Emmy Noether also appears in that list, lecturing at Göttingen (*e.g.*, refs. 19, 20, pp. 561, 735).

In Zurich Einstein left behind friend and collaborator on the *Entwurf* theory (of which more shortly) Marcel Grossmann (1878–1936), but came to a large collection of physicists in Germany. Because Switzerland (and Holland) remained neutral during that war, he was able to continue to communicate with, collaborate with, and even visit physicists and mathematicians there.

The men whom Gutfreund & Renn regard as 'influential' for Einstein and who belong to the 'before-and-during-GR' period include the following (award yourself one Brownie Point for each name you can honestly say you already knew at least a little bit about — my score was 15 before beginning this project).

In Zurich: Paul Bernays (1888–1977), Michele Besso (1873–1955, Einstein's Special Relativity collaborator), Marcel Grossmann (1878–1936), Hermann Weyl (1885–1958, Zurich, later Göttingen and IAS Princeton).

In Leiden: Paul Ehrenfest (1880–1933), Hendrik A. Lorentz (1853–1928), Willem de Sitter (1872–1934).

In Italy: Tulio Levi-Civita (1873–1943, Padua, later Rome), Max Abraham (1875–1922, Milan, returned to Germany at declaration of war, war work, later Stuttgart).

In Austria–Hungary: Lorand Eötvös (1848–1919, Budapest), Friedrich Kottler (1886–1965, Vienna), Ernst Mach (1838–1916, Vienna to 1901, member of parliament 1901–1913, retired at home near Vienna 1913–1916).

In Russian territory: Gunnar Nordström (1881–1925, Helsinki, some time in Copenhagen).

In Germany: Max Born (1882–1963, Göttingen to radio operator to sound ranging), David Hilbert (1862–1963, Göttingen), Gustav Mie (1869–1957, Greifswald to Halle–Wittenberg in 1917), Hermann Minkowski (1864–1909, Göttingen), Walther Nernst (1864–1941, Berlin), Arnold Sommerfeld (1868–1951, Munich), Max von Laue (1879–1960, Frankfurt, later Berlin).

You might want to add any number of footnotes, for instance that you associate Mie and Nernst primarily with other parts of physics (more then than now, lots of creative scientists worked on many topics); that some of those folks won their own Nobel Prizes, and some didn't; that as early as 1913 Einstein had asked George Ellery Hale about the possibility of measuring light deflection in the Sun's gravitational field during the day; that the elder Bragg was also working on sound ranging on the Allied side while the younger one was on the front lines… . Out, bad dog, this belongs to a different WWI story!

Thirdly comes the time frame. I find it much harder to conceive of this as favourable, let alone uniquely favourable. Early in the war, Einstein declined to sign a statement by 93 other German savants denying responsibility for starting the war, and indeed was briefly involved in discussions of trying to provide a contrary document (there were not many takers)[21]. Later, inflation began to erode his salary, and a great deal of time went into trying to arrange travel back to Zurich, to see colleagues and his sons, and to Leiden. In due course, more and more effort had to go into organizing finances and, eventually, food. He was in fact quite ill through portions of 1917–18, though that was after the crucial time period for conceiving, working out, and publishing the basics of General Relativity. To realize how extreme things became, even for the 'privileged classes', just read the letters in ref. 20. Well, you can skip the equations for now, though we will need them later. On the other hand, there were surely many fewer requests for more distant travel, speeches, conference participation, and so forth than either before or after the Great War. Prewar, he appears in at least a couple of Solvay conference photographs, and in 1922 he made the visit to Paris postponed from autumn 1914*. Much-photographed trips to the United States in spring 1921 and to Japan in autumn 1922 followed the war, then to Tel Aviv, of which he was made an honorary citizen, and Jerusalem, where he spoke briefly in Hebrew then continued in French. So perhaps, indeed, only "there" and only "then."

The Entwurf theory

Entwurf is, I think, a lovely word, blending the Entmoot of *Lord of the Rings* with a greeting from Einstein's beloved canine, Chico[22]. Co-author Marcel Grossmann was the only person thanked in Einstein's 1914 paper on the foundations of General Relativity, and *Entwurf* is one of two significant gravitation papers by the pair[25].† The full title is '*Entwurf verallgemeinerten Relativistätstheorie und einer Theorie der Gravitation*'. In fact the word means sketch, outline, or draft, and is a compound of the German '*ent*' indicating entry into a new state, and '*wurf*' meaning throw, cast, projection, or direction[26].

What is in it? We'll peek in just a moment, but this was not Einstein's first attempt at generalizing his special theory to include accelerated observers. The story is told very concisely in Misner, Thorne, and Wheeler[27], section 17.7, at considerable length in the four volumes of *The Genesis of General Relativity*[28], with pedagogical intent by Dwight Neuenschwander[29], and at 'Goldilocks' length and level by Gutfreund & Renn[14].

The 1908 paper[30] 'On the relativity principle and the conclusions one draws from it' starts by supposing the equivalence of acceleration and gravitation. This is customarily illustrated with a small person in an elevator and accompanied by some mention of the experiments of Eötvös Lorand (or Roland Eötvös if you prefer). Eötvös had indeed introduced a number of European scientists to his work when an international geodesy society met in Budapest in 1906. In 1911 comes '*Über den Einfluss der Schwerkraft auf die Ausbreitung des Lichtes*'[31].‡ That "influence on the propagation of light" is, of course, what we now call bending of light and counts as one of three (or so) classic tests of GR. This early prediction, and the *Entwurf* version, were, however, for angles half of what is now calculated from the 1915–1916 general theory. The result, 0″·87 or thereabouts,

*The original invitation had come from Langevin, and the visit in the spring of 1914 was apparently uneventful. The visit in 1922 April was an extraordinary attempt at scientific reconciliation, also at the behest of Langevin. How it turned out belongs to Part III, but, if you can't wait, compare the discussion in the Introduction to Volume 13 of the Collected Papers of Albert Einstein with refs. 23 and 24.

†It was Michele Besso he thanks in the *Special* Relativity paper.

‡If you switch back and forth between the English and German titles often enough, you eventually stop noticing which is which. This probably says something good about Einstein's writing style, because I did not have the same experience when tackling Theodor Storm's *Immensee* some years ago.

at the limb of the Sun is numerically equal to (though I think intellectually distinct from) the Newtonian number found by Cavendish and Soldner (and a slightly different path from here leads us into gravitational lensing).

The year 1912 saw two papers and a note in proof on static gravitational fields and the question "Is there a Gravitational Effect which is analogous to Electrodynamic Induction?" The last of these enables us to answer the question "Was Einstein a Machian?" with a good, firm, "sometimes". Meanwhile, others were treading on his heels (and possibly also toes) — Max Abraham[33] with his own theory of gravity, incorporating Minkowski's formalism (in a way that Einstein criticized and Abraham modified), and Gunnar Nordström[34] claiming consistency with Special Relativity, briefly regarded with favour by Einstein, but later[35] disputed, in one of his relativity rare joint papers with someone not now greatly remembered. The co-author, Adriaan D. Fokker, was Dutch and a cousin of Anthony Fokker, the latter caught in Germany and put to work.*

What is in it? The *Entwurf* theory is an attempt to formulate equations that show how the gravitational field is related to the distribution of mass–energy that creates that field. It makes use of the Riemann tensor (a contribution of Grossmann), though not of the Christoffel symbols, but (*i*) it did not satisfy a correspondence principle in the sense of reducing to Newtonian gravity under suitable conditions (we are typically more used to thinking of 'correspondence principles' as pertaining to a classical limit of quantum mechanics); (*ii*) it led to an advance of the perihelion of Mercury equal to one-half the observed number (so we should not be surprised that it also predicted bending of light half that of the later theory); (*iii*) it did not permit treating a rotating reference frame as equivalent to a system at rest (a failure of Mach's principle in one of its many meanings); (*iv*) it was not fully covariant, which Einstein still thought would be a "good thing" because of its association with energy–momentum conservation, though he had apparently shown that generally covariant theories would violate causality.

In case you hadn't thought of them together lately, Einstein was one of the people who recognized very early the outstanding quality of Emmy Noether's mathematical ability and the significance of her best-known theorem about symmetries and conservation laws.

Back to the calculating board: 1914 October to 1915 December

The dates are from the submission of the *Entwurf* paper to that of the last of the four "now I've got it!" GR papers. What was Einstein doing? Who else was involved? And what difference did the war make? We make contact with the outbreak of the war *via* a footnote to letter 34 (in ref. 20) to Ehrenfest (1914 August 19) indicating that the value of the items Fruendlich left behind was 20 000 marks for a Zeiss telescope and 2086 marks for other items. Albert then turns his attention to assuring his son Hans Albert (*Lieber* Albert) that he is packing up everything to send to the three of them in Zurich (September 10) and explaining to L(*iebe*) M(ileva) that he can send no more money, because he has no more until he is paid again. His regular salary was 900 marks per annum

*The first 'ace', the famous Roland Garros, equipped his propeller with metal blades, and shot down five enemy planes by firing directly through the propeller. He eventually shot himself down by shooting his own propeller off. Anthony Fokker designed the synchronized propeller and machine gun. He also designed the Fokker D-7 and Fokker D-8 aircraft.

(paid quarterly in arrears) and a special personal salary of 12 000 marks, at least the first year. He later speaks of himself as living the simplest, almost meagre existence, having to pay for his mother's cancer operation, and so forth.

Issues of money, and, increasingly, food appear scattered through the science[20]. Some of it sounds a bit petty, but I think Mileva must have been terrified at having sole responsibility for two sons, one of whom, it was already clear, was going to be a 'special child'.

Both international and academic politics took up a good deal of his time during this critical window. Einstein was asked for advice on how a Swiss university should fill an empty chair (since German candidates were not appropriate during hostilities and no Swiss candidate obviously stood out). We might think of looking to France or Britain, but they (and he) did not, and he tried repeatedly to get Erwin Freundlich reappointed from a routine task in stellar astronomy to a position where he could contribute to observational tests of relativity, particularly gravitational redshift in binary stars and light bending by Jupiter. We might think this latter impossible, and Einstein thought it nearly unnecessary, with GR adequately supported by the perihelion-of-Mercury calculation and gravitational redshift of the Sun.

On the international front, he regarded the war, from the beginning, as ample folly (and other harsher words), for which His (God's) nonexistence alone could excuse Him (Doc. 44)[20]. Einstein hoped initially that scientists from the various combatant countries might at least retain some support for internationalism (while reminding those who wanted to coordinate such writing or activity that he was a Swiss national not a German)* but soon realized his colleagues were no more open-minded on that than the general population. Invoking a hero from the past, an organization called the *Berliner Goethesbund* asked for a supporting statement from Einstein. He drafted a couple but was apparently unable to satisfy them. Personally, he was very much incommoded by the difficulty of crossing even the neutral Dutch and Swiss borders to meet with colleagues and visit his sons in Zurich. Those difficulties and Einstein's disconnect from the majority of his war-supporting colleagues of course intensified through to the end in 1918, as did the problems of food, money, and illness. Yes, he had the flu in 1918 as did family and friends.

Whatever the original arrangement may have been, Einstein in fact gave lecture courses on relativity in the fall of 1914–1915 and summer 1915 semesters. He adjusted the timing of the latter in order to visit his sons in Switzerland, the elder of whom, however, did not desire the visit. So it did not happen.

Turning to science, I found it a surprise that relativity was not the only issue Einstein was thinking about during this critical '*Entwurf*-to-triumph' period. Topics that turn up in the correspondence include the design and operation of a planimeter, the spectrum of helium, the Bohr atom, the atmospheric absorption of light, and the possible existence of a magneton (quantum of magnetic field). The most important, however, were (*i*) entropy and the issue in thermodynamics of whether one can ever reach zero degrees K in a finite set of operations (letters mostly to and from Michael Polyani, and later with Planck and Ehrenfest, concerning some formulae due to Tetrode, who was a

*He later resumed German citizenship.

person much though he sounds like a tensor), and (*ii*) an on-going series of experiments with Wander de Haas (1878–1960).*

What were they measuring, or attempting to measure, and why? Ampère's Molecular Currents. At least 19 of the 1914–18 letters touch on the subject; many also address Einstein's efforts to help the de Haas family move from Berlin to the Netherlands, and getting their furniture sent after them. Einstein remarks that to help someone move during war time is a test of true friendship! As for the physics, Ampère is associated with the force between a pair of current-carrying wires. The experiment put a thin iron rod in a magnetic field maintained by coils parallel to it. The spinning electrons act like little magnets and line up with the field. Switch the field back and forth to excite oscillations in the torque on the rod, and the measured period and amplitude tell you the charge to mass ratio of the electron (Millikan did this differently!). Not surprisingly, the main problem is correcting for all the other forces and effects around, and Einstein in effect signs the work over to de Haas in 1915 May (letter 82), a couple of papers being published in due course[36]. In spite of the difficulties, they did firmly establish that the current carriers have negative charge†. You knew that? Yes, but the equations for electricity were originally written down on the assumption that the carriers had plus charges, as defined by Benjamin Franklin long ago. In the 'relations were becoming both strained and numerous' department, de Haas was also the son-in-law of Hendrik Lorentz (1853–1928), who took some interest in the analysis of the experimental data (letter 79) and was also in the same time frame in correspondence with Einstein about tensors in/and relativity.

At long last, the essential work that turned *Entwurf* into the four papers presented to the Berlin Academy on 1915 November 4, 11, 18, and 25. These were all Thursdays, as were the dates generally given for his submission of *Entwurf* (1914 November 29), Schwarzschild's solution (1916 February 24), of which Schwarzschild had informed Einstein by letter, and the first paper mentioning gravitational waves (1916 June 22). Apparently it was just that the Berlin Academy met on Thursdays, and reading a paper to them counted as submission for the proceedings. The Paris Academy also continued its regular weekly meetings through the War, and you can read summaries of what went on in *Nature*. For the Berlin Academy, you must go to the German literature. And by December 9 (letter 161) Einstein could assure Sommerfeld that the four November papers were the most valuable finding he has made in his life (or would ever make, we would now say). He also described them as the final stage in the battle over the field equations, being fought out before your eyes!

Facing up to General Relativity

This brings us to GR and what Einstein did between the *Entwurf* (of which he had almost immediately doubts) and the triumph.

First he needed a metric. That's the entity that is the same for all observers allowed to exist in the theory. For flat Cartesian surfaces, it is $ds^2 = dx^2 + dy^2$ (or

*"Have I heard of this guy?" De Haas is possibly slightly more familiar as part of the de Haas–van Alphen effect, which dates from 1930, was predicted by Lev Landau also in 1930, and fully explained by Lars Onsager only in 1952. The words from Wiki say that it is the oscillation of the magnetic moment of a pure metal crystal when an applied magnetic field increases (at a level of 2–3 tesla). The resistivity, specific heat, and sound attenuation also oscillate. Pieter van Alphen was de Haas's student.

†The Einstein–de Haas effect (that oscillation of torque in the iron rod) is also somewhat quantum mechanical, in the sense that to calculate the right response to a given applied field, you need a Landé *g* factor near 2 and Quantum ElectroDynamics. Now the only puzzle is the name. Why Ampère? Why molecular (when apparently individual atoms and their electrons are involved)? And why current? V. Ya. Frenkel wrote on the topic in 1979 in case you remember him from other things I have written.

the square root thereof), the distance between two points on the plane. Adding time, as in Special Relativity, makes it the distance between two events.

Hermann Minkowski (1864–1909) had shown in 1907 that the invariant interval in Special Relativity could be expressed geometrically as

$$ds^2 = c^2\,dt^2 - (dx^2 + dy^2 + dz^2),$$

the Minkowski metric. Notice that ds^2 means $(ds)^2$ not a second derivative, and that, with this sign convention, positive values of ds^2 describe pairs of events that you can get between (travelling at $v = c$ or less) in time to experience both. $ds^2 = 0$ is a photon or other massless particle that travels at $v = c$.

The full three space + one time dimension equivalent is $ds^2 = g_{\mu\nu}\,dx^\mu\,dx^\nu$, where μ and ν run over 0 (time) 1,2,3 (space) and we meet the Einstein summation convention, that an index that appears both 'upstairs' and 'downstairs' is to be summed over. Einstein wrote his metrics and such that way, and his mathematical notation is much easier to read than his handwriting (see ref. 14, which reproduces one of his manuscripts). The metric was well in place before *Entwurf*.

His goal was to express the geometry of space–time (the $g_{\mu\nu}$ tensor) as a function of the distribution of mass–energy in the space–time to be modelled. Clearly this also has to be a tensor, generally called $T_{\mu\nu}$. As before, the index names can be any letters you want, and you can choose to make either time-like or space-like intervals between the events the ones with positive ds^2 (textbooks differ on the choice). $T_{\mu\nu}$ will have components for density of matter and energy, for fluid flows, for various stresses, and so forth. It is symmetric, so that there are at most ten independent pieces, not sixteen. Electromagnetic energy and momentum count too, and yield coupled Einstein–Maxwell equations (but this is not a unified theory).

The *Entwurf* theory had the stress–energy tensor. But he also needed an equation of motion to describe the motion of particles in a given gravitational field, as well as a field equation to characterize the gravitational field generated by its matter and energy sources. The former was in place by 1912. The latter presented more serious problems.

Einstein was sure that the proper field equations would have several properties: (*i*) reducing to the Newtonian solution when fields were weak, (*ii*) treating gravitation and acceleration as interchangeable (the equivalence principle), (*iii*) conserving energy and momentum, and (*iv*) full covariance.

Entwurf was happy with (*i*) and (*ii*). But the form he had chosen for the tensor (a function of $g_{\mu\nu}$) representing the geometry of space time resulted in field equations that, if forced to be covariant, did not conserve energy and momentum (or conversely).

We absorbed conservation with whatever our earliest care-givers fed us. But what is covariance? Einstein wrote: "The general laws of nature are to be expressed by equations which hold good for all systems of coordinates, that is, are covariant with respect to any (coordinate) substitution whatever (generally covariant)". At this point, I am plagiarizing freely from ref. 37*, on the grounds that, whatever authorial copyrights still exist are now mine as sole heir and executrix.

Let's try once more. You have the physical system you want to study (the $T_{\mu\nu}$) and what you think are the right field equations, $T_{\mu\nu}$ = some function of $g_{\mu\nu}$. You solve the equations in some coordinate system and predict how a particle should move in that physical set up. You transform to another coordinate system and oops, you no longer have a solution of the field equations; your theory is

*This source makes time-like intervals positive, though I don't think I knew that when I married him.

not fully covariant. Notice that Einstein insisted upon retaining conservation when, in the *Entwurf* theory, it conflicted with full covariance. Something must have gone wrong with his $G_{\mu\nu}$, the function of the metric $g_{\mu\nu}$ to be set equal to $T_{\mu\nu}$.

At *Entwurf* time, he knew (thanks to the mathematical expertise of Marcel Grossmann) about the Riemann and Ricci tensors (which can describe the curvature of space) and the work of Levi-Civita, and made use of them. Through the critical ten months before the November papers, there was extensive correspondence between Einstein and Levi-Civita, Hendrik Lorentz, and Hilbert (de Sitter comes a bit later) about the proper ways to write and use tensors in theories of gravity. The 'tone of ink' fluctuates. He is first deeply impressed by and attracted to Hilbert; then for a time regards him as an idea-thief, and then again later as a friend. There are to Lorentz 14 letters, Hilbert 16, Levi-Civita 12 (ending with a sort of "this correspondence is now closed"). It is clear from the letters and postcards (which apparently crossed the Swiss and Dutch borders more readily than sealed letters) which survive that others, perhaps many, do not, having been discarded by their recipients, the heirs, or non-relativists, interested only in cutting off the autograph.*

But it is a 1915 September 30 note to Erwin Freundlich (Doc. 123) concerning rotating systems that reveals the contradiction clearly for us bears of very little brain (which Freundlich was not!!). Using a $T_{\mu\nu}$ for a slowly rotating coordinate system and the last (time coordinate) of the *Entwurf* equations, he finds $g_{44} = 1 - (3/4)\, \omega^2 (x^2 + y^2)$ while the direct transformation from the Galilean case yields $g_{44} = 1 - \omega^2 (x^2 + y^2)$. He therefore realized that his 1915 calculation for the relativistic excess of the perihelion advance of Mercury would be suffering from the same fault, which is why it came out 18″ per century rather than the measured 43″ per century. He was not, however, sure whether it was the field equations themselves or his application that caused the discrepancy. Implicitly the *Entwurf* prediction for light bending will have some similar error. As it happens, weak gravitational redshifting is not affected.

The secret word, as Einstein wrote to Sommerfeld on 1915 November 28 is "*Christoffel'sche Tensor*", translated as Christoffel's symbols (Doc. 153), and indeed they are not tensors in terms of how they transform between coordinating systems.

The notation of the letter is not quite modern, but returning to ref. 37, we find the field equations given as $(8\,\pi\, G/c^4)\, T_{\mu\nu} = R_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} R$ where $g_{\mu\nu}$ is the original metric tensor you thought of; $R = g^{\mu\nu} R g_{\mu\nu}$ (there are rules for raising and lowering indices)

$$R_{\mu\nu} = R^{\alpha}{}_{\mu\alpha\nu} = \frac{\partial \Gamma^{\alpha}{}_{\mu\nu}}{\partial x^{\alpha}} - \frac{\partial \Gamma^{\alpha}{}_{\mu\alpha}}{\partial x^{\nu}} + \Gamma^{\alpha}{}_{\mu\nu}\Gamma^{\beta}{}_{\alpha\beta} - \Gamma^{\alpha}{}_{\mu\beta}\Gamma^{\beta}{}_{\nu\alpha}$$

(called the Ricci tensor)

$$R^{\mu}{}_{\alpha\beta\gamma} = \frac{\partial \Gamma^{\mu}{}_{\alpha\gamma}}{\partial x^{\beta}} - \frac{\partial \Gamma^{\mu}{}_{\alpha\beta}}{\partial x^{\gamma}} + \Gamma^{\mu}{}_{\sigma\beta}\Gamma^{\sigma}{}_{\alpha\gamma} - \Gamma^{\mu}{}_{\sigma\gamma}\Gamma^{\sigma}{}_{\alpha\beta}$$

(the Riemann, Riemann-Christoffel or curvature tensor; it is really big when space is greatly distorted by mass, and blows up at singularities), and

$$\Gamma^{\gamma}{}_{\mu\alpha} = \tfrac{1}{2} g^{\gamma\nu} \left[\frac{\partial g_{\nu\mu}}{\partial x^{\alpha}} + \frac{\partial g_{\nu\alpha}}{\partial x^{\mu}} - \frac{\partial g_{\mu\alpha}}{\partial x^{\nu}} \right].$$

* Signatures/autographs of Albert Einstein, unattached to letters with scientific content, retail for prices like \$300–\$500, more than George Bernard Shaw (who wrote a great deal) but much less than Richard Wagner (who wrote mostly music).

Einstein wrote the Christoffel symbols as $\left\{\frac{\gamma}{\mu\alpha}\right\}$.

And that's all there is to General Relativity, except the detail that the physical system you want to study gives you $T_{\mu\nu}$ and you have to run around guessing metrics $g_{\mu\nu}$ until you find one which, subjected to this massive mathematical manipulation, gives you back the $T_{\mu\nu}$ you want.

All of us who have taught or taken a required course in GR (and learned that it is more blessed to give) will agree that the underlying idea of a relationship between the distribution of mass–energy and the geometry of space–time is a straightforward one, but the arithmetic is a bit grim. Einstein himself wrote that somewhere, and also expressed to Karl Schwarzschild (ref. 20, Docs. 176, 181) surprise that the exact solution for a point mass could be formulated so simply, mentioning that the computational problems are inordinately large, and that he proposed to present Schwarzschild's work to the academy next Thursday (1916 January 13). The next month Einstein informs Schwarzschild that there are no gravitational waves analogous to electromagnetic waves (that is dipole, and of course correct — the reality of quadrupole waves belongs to another story) (ref. 20, Doc. 194).

This concludes Part I. Part II will look in (perhaps excessive) detail at many of the other scientists and mathematicians who interacted with Albert Einstein, General Relativity, and, inevitably, the Great War in the period 1913–1919. Part III deals with the aftermath of both GR and WWI, primarily in the time frame 1919–1926.

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*See the editorial note 'Einstein on Gravitation and Relativity: The Collaboration with Marcel Grossmann' in *The Collected Papers of Albert Einstein*, **4**, pp. 294.

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 259: HD 2454, HD 15306, AND HD 114520

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The stars referred to in this paper are three of the six late-type stars identified as 'barium dwarfs' by Gray *et al.*[1], who expected that they must all be members of binary systems. They arrived on the Cambridge radial-velocity programme for various different reasons, mostly *before* attention was called to them by Gray *et al.*, and two of the three discussed here have indeed proved to be spectroscopic binaries. The orbit of only one of them, HD 114520, is given in this paper; among the rest of Gray's stars, the orbit of HD 34654 has already been presented in the immediately previous paper in this series, while there is an intention that HD 26367 will be the subject of a separate collaborative paper. HD 2454 (HR 107), however, has not so far (five years) exhibited any significant change in its radial velocity. One of the other 'Gray' stars, HD 15306, has exhibited a gradual change of velocity, but it has not by any means been seen round a complete cycle, and the observations presented here probably need to be continued for a lot longer before its orbit can be determined.

Introduction

The title of this paper (its own title, following the title of the series to which it belongs) may be seen as something of a fraud, because two of the stars identified in the title are merely discussed briefly, the orbit of only one of them (HD 114520) being actually presented here. The characteristic that is shared by the stars noted in the title is that they have all been considered to be 'barium stars', a small group of late-type stars whose spectra exhibit over-abundances of certain chemical elements produced by the '*s* process' of energy generation in stellar cores. A particularly obvious example of the spectral lines that are enhanced in such spectra is the Ba II line at λ4554 Å, but the somewhat analogous* Sr II λ4215 Å is also strengthened in barium stars, together with the molecular bands of CH and CN. The existence and nature of barium stars as a distinct group was announced, fully fledged, by the powerful syndicate of Bidelman & Keenan[3] in 1951. Because the Ba II and Sr II lines are recognized luminosity indicators in the classification of late-type stellar spectra, their abnormal enhancement in barium stars is misleading, being easily mistaken for

*The *exact* analogy is between the λλ 4554 and 4934-Å lines of barium and λλ 4077 and 4215-Å of strontium, respectively; those pairs represent the same transitions as the *K* and *H* lines, respectively, of Ca II. There are analogous pairs of lines in Mg II (but they cannot be observed from the ground, being at wavelengths below the atmospheric cut-off) and in Be II. The Be II lines are at λ 3130 Å — just accessible above the atmospheric cut-off; but careful photographic observations[2] there of the spectra of both Vega and Sirius at the very high dispersion of 0·83 Å mm^{-1} did not reveal them in either star.

evidence of high luminosity.

The transmutation of elements by nuclear reactions in the cores of stars cannot be expected normally to be evident in spectra, which obviously can represent only the stellar surface. The particular characteristic that allows barium stars to outflank that objection is that they are generally members of binary systems. It is the primary (more massive) star in the binary system that initially produces the *s*-process elements in its core; subsequently, towards the end of its evolution, it disperses them in a massive stellar wind that, in part, deposits the new elements onto the surface of its companion star before the evolving component itself subsides into a white dwarf. The star that is left principally in view, therefore (the original secondary, which may still be on the main sequence), has a *surface* composition that is representative of the *core* of a highly evolved object. Gray *et al.*[1] showed that observations made by the UV spacecraft *GALEX* provide evidence of far-UV excess luminosity in the cases of all the barium stars that they studied, implying the existence of white-dwarf companion stars. Although the binary nature of barium stars had been recognized[3] since 1951, it was not until 30 years later that the first orbit for such a system was given, in a paper[4] of which the present writer was one of the authors. It had a period of about five years, which is a quite characteristic value for barium stars.

HD 2454 (*HR 107*)

This object is to be found in the large but ill-starred constellation Pisces, a degree or so south of the midpoint between the third-magnitude star γ Peg and the fifth-magnitude δ Psc. It is the brightest of the stars discussed in this paper, and is the only one to have a *Bright Star* designation. Several *UBV* photometric determinations are available, with results close to $V = 6^{m}{\cdot}04$, $(B-V) = 0^{m}{\cdot}43$, $(U-B) = -0^{m}{\cdot}07$. The *Henry Draper Catalogue* type is F2, whereas subsequent MK classifications (the first of which was by Barry[5]) put it somewhat later.

TABLE I

Radial-velocity observations of HD 2454

(*all obtained with the Cambridge Coravel*)

Date (UT)	*MJD*	*Velocity km s⁻¹*
2011 Aug. 10·16	55783·16	−7·4
Sept. 13·08	817·08	−6·9
28·07	832·07	−7·6
Oct. 19·03	853·03	−7·4
Nov. 17·95	882·95	−6·9
2012 Jan. 12·78	55938·78	−7·6
Aug. 5·12	56144·12	−7·4
2013 Feb. 1·77	56324·77	−7·6
Sept. 3·08	538·08	−7·3
2014 Jan. 7·77	56664·77	−7·1
Oct. 31·95	961·95	−6·8
2015 Feb. 3·77	57056·77	−7·2
2016 Jan. 20·76	57407·76	−6·9

Barry's classification was 'F6 Va vw', where 'vw' stands for 'very weak'. That refers to a general weakness, in the observed part of the spectrum (the near-UV), of the metal lines in comparison with those in many otherwise similar stars, a characteristic that may well account for the *Henry Draper Catalogue* type being pitched a bit too early. Such a rationalization of the discrepancy may, however, be too facile, because Harlan[6] subsequently offered a classification of F3 II; but he was evidently misled by the unusual strength of the Sr II lines into proposing much too high a luminosity. That spectroscopic anomaly was recognized quite soon afterwards by (Anne) Cowley[7], who gave the type of HD 2454 as F5 V with the rider "Sr enhanced".

HD 2454, being a 'bright star' in the sense of having an entry in the *Bright Star Catalogue*, as well as in normal parlance, and also exhibiting some unusual characteristics, has accumulated in *Simbad* a bibliography of about 150 papers. The present writer does not feel an obligation to summarize them all in any detail because they seem mostly to have been prompted by the anomalies already noted above; moreover, the star is rendered of relatively small interest for the purposes of the present paper because it has shown no certain signs of radial-velocity variability. The 13 radial velocities measured at Cambridge since 2011 are listed in Table I.

HD 15306

HD 15306 is a ninth-magnitude star in Cetus, just south of the celestial equator; it is about 3° north-following Mira Ceti. Its *BV* photometry has been provided by North *et al.*[8] in a 1994 paper as $V = 8^{m}\cdot92$, $(B - V) = 0^{m}\cdot36$. Its spectral type is given as F5 in the *Henry Draper Catalogue*, but just on the basis of an objective-prism spectrum Bidelman[9] recognized the excess strength of the Sr II λ4077-Å line. A subsequent classification has been given by Houk[10] as 'Fm δ Del'. North seems to have had a particular interest in HD 15306 (and other 'barium' stars). His first publication[11] that refers to HD 15306 was in 1987, and gives the star's distance as 177 pc, M_V as $+2^{m}\cdot70$, and [Fe/H] as +0·034. Subsequent publications, which were collaborative, include, first, one[12] in 1991, giving the distance as 152 pc and [Fe/H] as $-0\cdot34 \pm 0\cdot09$, and then in 1994 (in a paper already cited as ref. 8), Table 2 gives the still lower (logarithmic) metal abundance* of [M/H] = –0·5; but (seemingly inconsistently) in the same paper Table 7 gives a list of the logarithmic abundances for individual elements, which are near zero for elements up to Ni but are around +0·7 for six rare-earth and related elements (Sr, Y, Zr, Ba, Ce, and Nd).

The star was placed on the Cambridge radial-velocity observing programme in 2011. On the occasion of the first observation the writer set on the nearby but more obvious (brighter) star HD 15275 by mistake. He subsequently observed it three more times (only one of which was by accident!) and offers the results in the little Table II here. Meanwhile he obtained ten observations of HD 15306 over an interval of five years, during which it became apparent that there was a slow but definite decrease in the radial velocity. It does not seem likely that it will be possible to assign reliable orbital elements at all soon. Since the longevity of the star is sure to exceed that of the writer, the latter rather uncharacteristically offers only a partial data set here and is not in a position to put forward any orbital elements. The radial velocities presently available are set out in Table III.

*Relative to abundances in a standard star (HD 7439)

TABLE II

Radial-velocity observations of HD 15275

(*all obtained with the Cambridge Coravel*)

Date (UT)	*Velocity km s⁻¹*
2011 Sept. 13·15	+0·7
28·13	+0·8
Nov. 10·96	+0·8
2015 Feb. 9·81	+0·8

TABLE III

Radial-velocity observations of HD 15306

(*all obtained with the Cambridge Coravel*)

Date (UT)	*MJD*	*Velocity km s⁻¹*
2011 Sept. 28·13	55832·13	+46·8
Oct. 24·06	858·06	+48·0
Nov. 23·01	888·01	+46·1
2012 Jan. 3·84	55929·84	+46·4
Feb. 3·82	970·82	+47·6
Sept. 6·13	55176·13	+46·4
Dec. 1·97	262·13	+46·0
2014 Feb. 11·77	56699·77	+44·5
2015 Feb. 9·81	57062·81	+43·3
2016 Jan. 15·85	57402·85	+43·9

HD 114520

This is a 7^{m} star in the field of the North Galactic Pole, in Coma Berenices. It is a little over 1° following the fifth-magnitude F star 39 Com. It has an 11^{m} companion star about 10″ away, first noted by Couteau[13], who put his name to the pair as COU 96. Photometry of HD 114520 has been given by Fernie[14] as $V = 6^{m}{\cdot}86$, $(B-V) = 0^{m}{\cdot}42$, $(U-B) = 0^{m}{\cdot}03$. The *Hipparcos*[15] parallax, as slightly revised by van Leeuwen[16], is $7{\cdot}07 \pm 0{\cdot}71$ milliseconds of arc, corresponding to a distance modulus of $5^{m}{\cdot}75$ and thus to an absolute magnitude close to +1·1, showing the star to be a giant. The 10% uncertainty in the parallax implies a 20% uncertainty in the luminosity and thus to $0^{m}{\cdot}2$ in the absolute magnitude, so it seems clear that the classification by Harlan[17] of the spectrum of HD 114520 as F2 II over-states its actual luminosity. That was recognized 25 years ago by Mendoza V & Arellano Ferro[18] on the bases of (*a*) the equivalent width of the infrared oxygen triplet at λ7774 Å and (*b*) from a photometric index that they called Λ(9) that was defined by interference filters. Giridhar[19], too, noted that HD 114520 is not a supergiant, and then in a collaborative paper[20] gave some results of spectroscopic observations made with the 2·1-m McDonald reflector. Those showed slightly raised abundances for carbon and calcium, with near-solar abundances for all the other elements that they could measure; the distance of the star was estimated to be 150 pc, implying a luminosity in the vicinity of class IV. A recent word on the star has come from *Gaia*[21], whose results includes a parallax* of 4·99 ± 0·36 milliseconds, smaller than the *Hipparcos* one by a factor very close to $\sqrt{2}$ and thereby doubling the calculated luminosity and correspondingly making the absolute magnitude $0^{m}\cdot 7$ brighter, at $M_V \approx +0^{m}\cdot 4$. Gray, Napier & Winkler[22] classified the star as 'F5 IV–V Sr II', noting that its spectrum is "Almost identical to [that of] Procyon, except [that] Sr II λ 4077 and λ 4216 are enhanced"†.

As far as its radial velocity is concerned, four measurements of HD 114520 were made in the Crimea in the 1940s, but were published only as a mean of –6·1 ± 3·2 km s^{-1} by Shajn[23]. Four more were given by Nordström *et al.*[24] (and subsequently slightly revised by Holmberg *et al.*[25]) from Haute-Provence, again as a mean value. Three early DAO velocities were published by Hill *et al.*[26]; eight McDonald ones, dating from 1981–83, were published by Parsons[27]. Dr. R. E. M. Griffin has kindly provided 11 velocities obtained with the DAO 48-inch telescope in 2007–2009.

The star was placed on the Cambridge radial-velocity observing programme

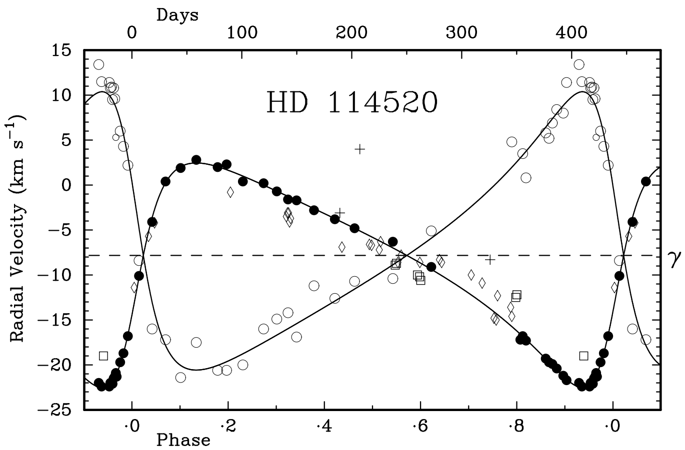

FIG. 1

The observed radial velocities of HD 114520 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The orbit depends on the Cambridge observations that are plotted as circles, filled for the primary and open for the secondary. Plusses plot the velocities given by Shajn[23], while open squares plot those of Parsons[27]; they were not used in the solution of the orbit. The open diamonds represent observations made by the present writer, many of them at the DAO, but reduced as if they were single-lined, and were therefore not included in the solution.

*The parallax is specified to 15 decimal places and its uncertainty to 16, although two places (as used here) are enough to do full justice to the actual precision of the result.

†Since the Sr II lines are the ones usually used as indicators of stellar luminosity, it would seem that Gray *et al.* must have had some compelling (though unspecified) reason to attribute to HD 114520 a lower luminosity than those lines indicated and to note them as "enhanced" with respect to the luminosity that they adopted.

TABLE IV

Radial-velocity observations of HD 114520

Heliocentric Date	*HMJD*	*Velocity* Prim. km s⁻¹	*Velocity* Sec. km s⁻¹	*Phase*	*(O – C)* Prim. km s⁻¹	*(O – C)* Sec. km s⁻¹
1947 Mar. 27·47	32271·47	−3·1	—	0·432	+0·9	—
1948 June 25·27	32727·27	+4·0	—	1·474	+9·1	—
1951 Mar. 16·27	33721·27	−8·3	—	3·745	+5·5	—
1981 Mar. 22·31	44685·31	−12·5	—	28·798	+3·6	—
23·33	686·33	−12·2	—	·801	+4·0	—
May 23·28	747·28	−19·0	—	·940	+3·5	—
1982 Mar. 5·39	45033·40	−10·0	—	29·594	−1·5	—
7·38	035·38	−10·2	—	·598	−1·6	—
8·38	036·38	−10·6	—	·601	−1·9	—
1983 Apr. 26·75	45450·75	−8·9	—	30·547	−1·8	—
27·83	451·83	−8·7	—	·550	−1·5	—
2007 July 12·28	54293·28	−14·8		50·753	—	—
14·28	295·28	−15·0		·758	—	—
2008 May 6·37	54592·37	−6·9		51·436	—	—
June 26·32	643·32	−8·6		·553	—	—
2009 Apr. 7·43	54928·43	−0·8		52·204	—	—
May 28·32	979·32	−3·5		·321	—	—
29·35	980·35	−3·1		·323	—	—
30·39	981·39	−3·1		·325	—	—
31·27	982·27	−4·1		·327	—	—
June 1·22	983·22	−3·7		·330	—	—
Dec. 27·54	55192·54	−17·2	—	·808	−0·6	—
2011 May 19·03	55700·03	−21·3	—	53·967	−0·4	—
June 3·99	715·99	−11·4		54·004	—	—
16·97	728·97	−5·7		·034	—	—
2012 Jan. 4·27	55930·27	−6·6		54·494	—	—
6·27	932·27	−6·7		·498	—	—
13·26	939·26	−7·2		·514	—	—
Feb. 2·24	959·24	−7·8		·560	—	—
19·22	976·22	−8·6		·599	—	—
Mar. 8·09	994·09	−8·3		·639	—	—
10·12	996·12	−8·6		·644	—	—
Apr. 6·07	56023·07	−10·0		·706	—	—
16·03	033·03	−10·9		·728	—	—
30·02	047·02	−12·3		·760	—	—
May 11·99	058·99	−13·6		·788	—	—
13·03	060·03	−14·6		·790	—	—
13·03	060·03	—	+4·8	·790	—	+2·8
22·97	069·97	−16·8	+3·5	·813	0·0	+0·2
25·96	072·96	−17·3	+0·8	·820	−0·1	−2·9
June 12·97	090·97	−19·3	+5·8	·861	0·0	−0·6
15·93	093·93	−19·7	+5·2	·868	0·0	−1·7
18·96	096·96	−19·9	+6·9	·875	+0·2	−0·5
22·97	100·97	−20·4	+8·4	·884	+0·2	+0·4
28·92	106·92	−21·2	+8·0	·897	+0·1	−0·8

TABLE IV (*concluded*)

Heliocentric Date	*HMJD*	*Velocity* Prim. km s⁻¹	*Velocity* Sec. km s⁻¹	*Phase*	*(O–C)* Prim. km s⁻¹	*(O–C)* Sec. km s⁻¹
2012 July 1·91	56109·91	−21·7	+11·4	54·904	−0·1	+2·2
15·90	123·90	−22·4	+11·5	·936	+0·1	+1·1
22·90	130·90	−22·4	+11·4	·952	−0·2	+1·4
23·89	131·89	−22·0	+10·8	·954	+0·1	+1·0
24·89	132·89	−22·0	+10·9	·957	−0·1	+1·2
25·89	133·89	−22·1	+9·5	·959	−0·3	0·0
26·89	134·89	−21·5	+10·8	·961	+0·1	+1·6
27·88	135·88	−21·3	+9·6	·963	+0·1	+0·6
28·88	136·88	−20·9	+5·3	·966	+0·2	−3·4
Aug. 1·87	140·87	−19·7	+6·0	·975	+0·2	−1·1
4·86	143·86	−18·7	+4·3	·982	0·0	−1·3
8·86	147·86	−16·8	+2·2	·991	−0·1	−0·9
2013 Mar. 27·09	56378·09	−6·3		55·517	—	—
2014 Jan. 10·24	56667·24	+2·0	−20·6	56·178	0·0	−0·5
Feb. 2·26	690·26	+0·4	−20·0	·230	−0·6	−1·2
21·16	709·16	+0·2	−16·0	·273	+0·2	+1·5
Mar. 5·19	721·19	−0·7	−14·9	·301	0·0	+1·8
23·16	739·16	−1·7	−16·9	·342	0·0	−1·5
Apr. 8·09	755·09	−2·8	−11·2	·378	−0·2	+3·1
27·07	774·07	−3·8	−12·6	·422	−0·1	+0·3
May 15·03	792·03	−4·8	−10·7	·463	0·0	+0·9
June 18·93	826·93	−6·3	−10·4	·543	+0·7	−1·5
July 23·90	861·90	−9·1	−5·1	·622	+0·3	+0·8
2015 Jan. 11·28	57033·28	−10·1	−8·4	57·014	+0·2	−3·6
23·23	045·23	−4·1	−16·0	·041	−0·5	−3·0
Feb. 18·22	071·22	+1·9	−21·4	·101	−0·1	−1·3
Apr. 1·06	113·06	+2·3	−20·6	·196	+0·6	−1·0
May 27·01	169·01	−1·6	−14·2	·324	−0·3	+1·8
2016 Feb. 16·19	57434·19	−22·0	+13·4	57·930	+0·5	+3·1
Apr. 7·09	485·09	−4·2		58·046	—	—
17·09	495·09	+0·4	−17·2	·069	+0·1	+0·6
May 15·05	523·05	+2·8	−17·5	·133	+0·3	+3·1

1947–1951: Shajn[23]
1981–1983: Parsons[27]
2007–2009: R. E. M. Griffin (DAO)
2011–2016: R. F. Griffin (Cambridge)

in 2011 May, and when it was observed again in the following month it had changed by about 10 km s^{-1}, so it was watched quite attentively (32 measurements in 2012). The traces mostly show a weak secondary component, which had not been recognized by previous observers; it is quite often blended badly enough with the primary one that it is not possible realistically to determine the two velocities individually. Table IV sets out the 38 observations where both components were separately measurable, plus 16 where their blending together was too serious for double-lined reductions to be practicable. The velocities obtained for the 16 blends, and those previously obtained by others who regarded the star as single-lined, have not been used in the solution of the orbit, which is based on the writer's observations alone and is illustrated in Fig. 1; its elements are given overleaf.

P	$=$	$437{\cdot}7 \pm 0{\cdot}5$ days	T_{56}	$=$	MJD $56589{\cdot}0 \pm 0{\cdot}7$
γ	$=$	$-7{\cdot}80 \pm 0{\cdot}08$ km s^{-1}	$a_1 \sin i$	$=$	$63{\cdot}8 \pm 0{\cdot}7$ Gm
K_1	$=$	$12{\cdot}48 \pm 0{\cdot}11$ km s^{-1}	$a_2 \sin i$	$=$	$79{\cdot}6 \pm 1{\cdot}6$ Gm
K_2	$=$	$15{\cdot}58 \pm 0{\cdot}29$ km s^{-1}	$f(m_1)$	$=$	$0{\cdot}0541 \pm 0{\cdot}0018\ M_\odot$
q	$=$	$1{\cdot}248 \pm 0{\cdot}026$ ($= m_1/m_2$)	$f(m_2)$	$=$	$0{\cdot}105 \pm 0{\cdot}006\ M_\odot$
e	$=$	$0{\cdot}529 \pm 0{\cdot}009$	$m_1 \sin^3 i$	$=$	$0{\cdot}341 \pm 0{\cdot}016\ M_\odot$
ω	$=$	$249{\cdot}8 \pm 1{\cdot}2$ degrees	$m_2 \sin^3 i$	$=$	$0{\cdot}273 \pm 0{\cdot}010\ M_\odot$

R.m.s residual (unit weight) $= 0{\cdot}31$ km s^{-1}

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*Lanz comes off badly in the running headline of the printed paper, where his name is systematically omitted.

CORRESPONDENCE

To the Editors of 'The Observatory'
Early Solar Photographs by G. Roster (April 1893)

A great effort has been made in the last twenty years to obtain a better reconstruction of the Sunspot Number using historical observations that cover the last four centuries[1–4]. Moreover, spatial information about sunspots in the past is being recovered by several teams. The information includes Butterfly Diagrams[5,6], sunspot catalogues[7], and even sunspot-group-tilt records[8].

The use of antique solar photographs to increase our databases or simply to check well-known data[9] is of great interest. However, there are relatively few photographs of the Sun compared to drawings of the solar disc[10]. Therefore, we want to highlight three solar photographs taken by Giorgio Roster in 1893. Roster (1843–1894) was a doctor, chemist, and photographer. He was interested in the usefulness of photography in sciences and in works on microphotography and telephotography[11]. The library of the *Museo di storia della scienza* of Florence preserves part of Roster's legacy in the section *Carte e raccolta fotografica Roster*, in which we want to highlight the title *Telefotografie Roster V: Macchie solari; teleobiettivo Roster, 1892–1893* (https://bibdig.museogalileo.it/Teca/Viewer?an=964650). That title contains three solar photographs taken from Florence with a Roster tele-objective. The Roster tele-objective permitted him to modify the enlargement thanks to the possibility of separating or bringing closer the positive and negative elements of the tele-objective. The comparison among the Roster photography and the *Greenwich Photoheliographic Results* (*GPR*) permits us to infer the position of the solar north. The main characteristics of the three photographs are: (*i*) Date: 1893 April 21. Time: 5:15 p.m. Magnification: 61×. (*ii*) Date: 1893 April 25. Time: 4:40 p.m. Magnification: 68×. (*iii*) Date: 1893 April 30. Time: 17:00 p.m. Magnification: 71×.

It is important to note that there are some defects in the objective that could be confused with sunspots, although those imperfections are easily identifiable by comparing the three photographs. In any case, sunspot groups are visible just coinciding with their heliographic coordinates provided by the *GPR*. In addition, the photographs are not correctly orientated. The solar north will be at the top of the photographs if they are rotated –81°, –99°, and 99° respectively. Finally, it is interesting to note that, although there are drawings of the solar disc in the collection of the Kalocsa Observatory[12] for the days 21 and 30, there is no such thing for day 25. Thus, Roster's photographs fill that gap in the graphical information of the Sun.

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Yours faithfully,

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REVIEWS

The Quantum Labyrinth: How Richard Feynman and John Wheeler Revolutionized Time and Reality, by Paul Halpern (Basic Books), 2017. Pp. 311, 23 × 15 cm. Price $30·00 (about £23) (hardbound; ISBN 978 0 46509758 6).

"In a quantum labyrinth, Theseus would take not just one path to the centre but a multitude simultaneously." The labyrinth could be 'multicursal' (with many paths) or 'rhizomic' (with an infinite number, but the 'rhizo' root means pertaining to a root or roots). The author has in mind something more like Feynman's sum-over-histories than Hugh Everett's many-worlds approach. The next part of the title tells us that the book is indeed (mostly) about Richard Phillips Feynman (1918–1988) and John Archibald Wheeler (1911–2008). The latter was the PhD adviser (and much more) of the former and had the rather sad experience of outliving his student by 20 years and a few months. Other scientists who appear prominently are Bohr, Einstein, Dyson, Everett, Misner, and a little less prominently (based on number of index entries) Dirac, Oppenheimer, von Neuman, Weisskopf, Teller, and DeWitt.

Halpern (a professor of physics at the University of the Sciences in Philadelphia) has interleaved the stories of their lives and accounts of their work, both together and separately (and occasionally in opposition), which he concludes have revolutionized how we think about time and reality. Feynman's life is a good deal easier to find out about. Halpern cites eight biographies, five books of quotes, and several 'about-RPF' items; but only one (of two existing) JAW autobiographies and a couple of 'about-JAW' items. Both published lots of papers, a few together. In addition to reading many of them, Halpern also interviewed the three Wheeler and two Feynman children, and a number of younger physicists who worked with them (mostly with Wheeler, who had many students, some well-known, while Feynman had few). I knew RPF reasonably well, modelling for him when I was a Caltech student and occasionally lunching with him between 1971, when I returned to California, and his death (hearing his voice last just a few weeks before, when he was still teaching a graduate seminar). Wheeler was more nearly an acquaintance, mostly through the East Coast relativity community between 1973 and 2003, though I dined alone with him once in Cambridge (UK) when I had been 'stood up' by another colleague. His damaged thumb was the near loss from his childhood adventure with dynamite mentioned by Halpern.

The author has clearly been thinking a long time about the two men, their interactions, and surroundings. One of the interviews (with Bryce DeWitt) dates back to 2002. Still, it is possible to disagree with him about some of the human issues. Halpern indicates that there was very little damage done when JAW left part of a secret document on a train in 1953 January. Indeed, he was really only reprimanded, but I have been told by others that Eisenhower's anger at the event contributed toward the subsequent persecution of another well-dressed physicist, J. Robert Oppenheimer.

There are interesting personal details that were new to me — that Wheeler took art lessons when he was in Paris; the best published description of RPF's second marriage (his own words were that it made him feel like a certain New Yorker-type cartoon, in which a fairly 'nerd-like' man is walking up the walkway towards a house that has a normal front, but most of the rest is the leering, angry body, face, and arms of a woman reaching out to strangle).

On the science side, I would have liked a single, coherent description of the absorber theory of radiation, which was Feynman's thesis work with JAW, appears in his Nobel lecture, and was the topic of a talk he gave for Caltech graduate students soon after his 1965 prize was announced. Instead, it appears in fragments through about seven places in the volume, so I can give you only what I remember from that 1965 talk: If you want to cancel out the advanced potentials in Maxwell's equations with the advanced potentials radiated back to you from distant matter, the future universe must be a perfect absorber, which is true in steady state and a closed relativistic universe but not in an open one. Some of the items I marked as "eh?" and "oops" probably result from an effort to cast mathematically complex ideas in a zero-equation format, but "protons and neutrons consist of quarks and antiquarks" (p. 118) is just wrong.

The items closest to astronomy (Big Bang theory, black holes) have come out better, and there is the curious coincidence that the Oppenheimer–Snyder paper (on continued gravitational contraction) and the Bohr–Wheeler paper on nuclear fission both appeared on 1939 September 1, better known as the day Germany entered Poland to begin World War II.

The specific scientific achievements discussed, in addition to the absorber theory, include, for the two together, work on the Manhattan project (Feynman mostly at Los Alamos, working on bomb design, Wheeler mostly at Hanford Washington, working on isotope separation), and on the 'super' (hydrogen) bomb, which Wheeler supported firmly (partly perhaps because of having a brother killed in 1944 in Europe) and Feynman with some reluctance, but fear that the Soviets might get it first.

Wheeler: nuclear physics with Bohr; invention of s-matrix theory in 1937 (but the name came later); concerns relating to the arrow of time (cosmological, thermodynamic, quantum, biological); quantum information; transition to relativity (black holes, a name he popularized but did not invent, cosmology, white holes); more wide-ranging relativity issues (worm holes, geons, 'mass without mass' quantum gravity, *etc.*); and, late in life, interest in the history of physics and "How come existence?"

Feynman: quantum electrodynamics (Nobel Prize 1965); arrow of time; sum over histories and Feynman diagrams; 'partons' (not quite quarks); superfluids and superconductivity (he felt he should have focussed harder and beaten Bardeen, Cooper, & Scrieffer); computer simulations, AI and related issues (led partly by his son Carl); nanotechnology; *Challenger* commission; and some interest in gravitation (the Feynman lectures, 1962–63, never published but copies of the lecture notes exist and use the word "graviton" which goes back to 1942, meaning "plane waves of a particle of spin 2 (graviton)". He was among those who showed that a zero-rest-mass, spin-two force-carrier would carry something like gravity, but generally found GR conferences annoying.

Here, however, is my 'clock striking 13' item. When the book arrived (directly from the author and with an autograph) of course I looked first for myself in the index. 'Yup', p. 218–19 on interaction with RFP, but it said also "Wheeler's former student Joe Weber." 'Ooops.' Back to the index to look under W for my late husband. There he is again (p. 192 ff) described very firmly as a JAW graduate student in 1956 and later. Weber received his PhD from the Catholic University of America on 1951 March 29, for a thesis with Keith Laidler, having been hired as a full professor of electrical engineering by the University of Maryland in 1949. His trip to Princeton and Leiden in 1955–56 was his first sabbatical. Within a page or two, we also meet RPF demonstrating the reality of gravitational radiation with an example that also includes electromagnetic forces. That was never really the issue. What Leopold Infeld, Nathan Rosen, and at times Einstein had doubted is whether a system (like a binary black-hole pair) with only gravitational forces could radiate energy. Most of us feel that recent events have settled that question and Halpern believes that RPF would be pleased, though he once told Weber to go work on neutrino detection. And SN 1987A (p. 257) was, of course, only the first naked-eye supernova for 373 years, not the first supernova for 400. — VIRGINIA TRIMBLE.

The Origin of Mass: Elementary Particles & Fundamental Symmetries, by J. Iliopoulos (Oxford University Press), 2017. Pp. 149, 22·5 × 14·5 cm. Price £25 (hardbound; ISBN 978 0 19 880517 5).

This is a popular-science book which explains why the discovery of the Higgs boson is important. The author had worked at CERN and Harvard before he moved to the *École normale supérieure* in Paris, and is probably most famous for being the 'I' in the GIM mechanism, which led to the prediction of the charm quark.

After a foreword by François Englert (who shared the 2017 Nobel Prize with Peter Higgs for the prediction of the Higgs boson, often referred to in the book as the BEH or Brout–Englert–Higgs particle; Brout had died in 2011 and hence could not share the Prize) and a brief introduction, the second chapter is 'A brief history of cosmology' which, despite the links between cosmology and particle physics, seems a bit out of place in a book of this length, especially since it is a very broad overview of cosmology, rather than concentrating on particle-physics aspects. There are also a few surprises here, such as the "mathematician" Willem de Sitter (who did study mathematics along with physics but is famous for his contributions to cosmology and astronomy and is usually referred to as an astronomer — he was Director of Leiden Observatory — or cosmologist), the expansion in the de Sitter model being very fast (unclear what that is supposed to mean), and Slipher measuring the redshifts of objects without exact positions (perhaps distances are meant). At least Lemaître is not referred to as a Jesuit (which he wasn't); he is called, among other titles, an abbot and a bishop (which he was, but both were essentially honorary titles). Nevertheless, this is a reasonable history of cosmology to the extent that it is possible in just 16 pages, though Fig. 2.2 (a 'history of the universe with structure formation' cartoon, of which there are many variants) is reproduced so small that the text cannot be read. Most or all of this material will be familiar to many readers of this *Magazine*, since the standard highlights are presented. (I have read so often that Lemaître first published his expanding-universe theory in an "obscure journal", referred to here in English as *The Annals of Brussel's* [*sic*] *Scientific Society*, that that journal by now must be one of the most prominent in the history of cosmology!)

Subsequent chapters cover symmetries, various problems of mass in particle physics, spontaneously broken symmetries, and the standard model (of particle physics). (Alas, despite the clear explanations in the book, the origin of mass is too involved to be summarized in a book review.) An epilogue looks to physics beyond the standard model. A summary of elementary particles is in the 28 pages of Appendix 1 (longer than any chapter), a good introduction for those who have little knowledge of that topic; the work of Lie and Cartan in group theory is summarized in the shorter Appendix 2. A five-page small-print index finishes the book. The general format is similar to another book[1] of the same size from the same publisher (perhaps part of a series) recently reviewed[2] in these pages; as in that book, there are several figures, some in colour, throughout the text, though also many pictures of scientists in this one. While neither contains end-notes, this book contains many, sometimes long, enjoyable footnotes.

Apart from the chapter on cosmology (though there are no serious mistakes there), it is obvious that the author is writing about a subject that he knows in detail. Such explanations can sometimes be hard to follow because some things which are obvious to the author might not be to the reader, but that is not the case here. It is also clear that the author understands the topic, rather than, as one finds in many popular-science books, repeating standard explanations adapted or even copied from another author. While the book is not a technical monograph, the explanation of the origin of mass is more involved than a superficial description, and is a good introduction for non-experts who might wish to investigate this in more detail. My only reservations in recommending it involve editing: some corrections by a native speaker of English should have been made and, though there are few actual typographical errors, the book suffers from a somewhat sloppy style which I find in most books I review these days. Nevertheless, I do recommend it, especially because it fills an otherwise rather vacant niche between superficial popular-science books and more-technical expositions, and is obviously written by an expert in the field. — PHILLIP HELBIG.

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Our Place in the Universe: Understanding Fundamental Astronomy from Ancient Discoveries, by Sun Kwok (Springer), 2017. Pp. 267, 23·5 × 15·5 cm. Price £19·50/$34·99 (paperback; ISBN 978 3 319 54171 6).

This excellent book is based on a course given to students from all faculties of the University of Hong Kong over a period of six years. It starts from basic observations of the Sun and Moon, stars and planets, which could be made by anyone -— more readily in the past when skies were darker and distractions fewer — from which the reader is led to make deductions about the Earth and its place in the Universe. The course continues through study of the motions of the Sun and Moon and development of calendars. The motions of the planets and the problems they posed are set out in detail, along with the step-by-step development of geometric models, through Ptolemy, the eccentric, epicycles and the equant, Copernicus and Kepler, finishing with the physical model of Newton.

This trajectory is, of course, familiar, but there are many aspects of the journey that set this book apart. The author aimed to show the process of discovery, not just the outcome, and that is achieved through clear exposition and consideration of alternatives. The discussion and appraisal of the contributions by Copernicus and Kepler are very balanced. The significance of Tycho's observations of the supernova in 1572 and comet in 1577 are brought out, as is the need for and value of more accurate observations. A bonus is the introduction of Chinese astronomical observations and deductions in parallel with the more familiar Greek/Babylonian tradition. The author also draws a parallel between the conservatism of Confucianism and that of the medieval Christian Church and their influence on the adoption of a heliocentric cosmology.

Like the course, the book is strongly visual, providing very many diagrams and illustrations showing the observable phenomena and their variation with time and latitude. My favourite illustrations are those of the five very different trajectories of the positions of Venus in the evening sky as a function of date shown in Chapter 10, but there are any number to choose from. Most of the examples are for observers in the Northern hemisphere but this is not always made clear and could be confusing, *e.g.*, the shadow of a gnomon when shortest does not point North (Ch. 3) for observers in the Southern hemisphere.

Each chapter concludes with a number of interesting, open questions, and there is a set of searching review exercises at the end of the book, followed by laboratory exercises involving direct observation or, more realistically, the use of readily available planetarium software. There are appendices adding numerical results and a useful glossary. The writing is very clear, evidently honed by giving the course, anticipating likely questions or sources of confusion, making the book a pleasure to read. This book can open our eyes to the phenomena around us and what we can learn from them. It will appeal not only to astronomers but also to inquisitive general readers, and is strongly recommended. — PEREDUR WILLIAMS.

Exact Solutions in Three-Dimensional Gravity, by A. A. García-Díaz (Cambridge University Press), 2017. Pp. 434, 25·5 × 18·5 cm. Price £135/$175 (hardbound; ISBN 978 1 107 14789 8).

2+1 dimensions is the lowest dimension in which Einstein gravity works, and it exhibits some interesting features, such as space–time being flat where there is no matter. The topic has been studied for about 50 years, and there are, remarkably, large numbers of exact solutions that have been found. This book presents a comprehensive account of them, including a section on topologically massive gravity. It is obviously a labour of love, which runs to over 400 pages, and which will be of interest to relativists, providing links between the solutions and those for the more familiar 3+1 space-time. — ALAN HEAVENS.

The Formative Years of Relativity: The History and Meaning of Einstein's Princeton Lectures, by H. Gutfreund & J. Renn (Princeton University Press), 2017. Pp. 432, 26 × 21 cm. Price £27·95/$35 (hardbound; ISBN 978 0 691 17463 1).

Some books never go out of print from the day they are first published — the *King James Bible*, Virgil's *Aeneid* probably, and, authors Gutfreund & Renn tell us, Albert Einstein's 1922 *The Meaning of Relativity*, his technical introduction to the special and general theories. Gutfreund & Renn have published two previous tomes, each containing a classic Einstein text, which they surround with historical context. One has previously been reviewed in these pages (**136**, 195, 2016).

Meaning was based on five lectures Einstein gave at Princeton in 1921 May. They were delivered in German, recorded by a stenographer, and summarized in English after each lecture by Prof. Edwin P. Adams for an audience whose numbers declined rather steeply through the five days. Adams, after many iterations with Einstein, also provided the first English text, published in 1922–23 in the US and UK. The present volume is based on the last, 1956, edition to which Einstein had some input. The stenographer's records survived, and we are also given an English translation of the first two lectures, done by Dieter Brill, Professor Emeritus at the University of Maryland; I think his name should have appeared on the cover, or at least the title page. Diana Kormos-Buchwald, of the Einstein Papers Project in Pasadena, has provided a 'Foreword', and she doesn't make the cover either.

Very approximately, the 400-plus pages are one-quarter *Meaning*, one-quarter appendices to later editions, and the rest is context from the authors, the translated popular lectures, and biographical notes on 51 men and one woman (Emmy Noether) said to have been involved in various ways in the early development of relativity theory and relevant observations. There is partial overlap with the 40 influential folks from *Road to Relativity*, and the first thing to notice is that there are more astronomers this time around. Some you know (Hale, Hubble, and Humason), others you might (Walter S. Adams, W.W. Campbell, Vesto Melvin Slipher), and some might require you to pull out your copy of the *Biographical Encyclopedia of Astronomers* (Hugo van Seeliger, Ludwick Silberstein, Charles St. John). Ditto probably for the physicists and mathematicians (many of whom again are Jewish and sometimes moved quickly in 1933 or 1938).

What else is here for astronomers? Three sequential chapters are entitled 'Einstein and the astronomers', 'The genesis of relativistic cosmology', and 'The controversy over gravitational waves', this last reaching forward to the first *LIGO* event. We also meet the *Global Positioning System* and *Gravity Probe B* (which more or less verified the Lense–Thirring effect, also known as 'dragging of inertial frames' by rotating bodies).

Some aspects annoy: personal letters among Einstein and his collaborators (*etc.*) are necessarily referenced to the publications in the Collected Papers, but so are his journal publications, rather than giving journal title, volume, page numbers, years, and (ideally) titles. Others are of the form "See 'The Entwurf Theory', p. 42" and send one back through the notes to all the previous chapters to find the full references.

We are not entitled to be annoyed that Einstein called the redshifts of distant galaxies "Doppler effect". We now make a distinction between motion through space and motion 'of' space, but he did not. True mistakes occur, for instance a book by Helge Kragh that deals with Big Bang *versus* Steady State is said (p. 89) to address whether or not to include the cosmological constant in Einsteinian universes. A 'bravo' for crediting Daniel Magnus Popper for the first correct gravitational redshift of a white dwarf (40 Eridani B, p. 68), but a 'missing persons' bulletin for the complete omission of Orest Chwolson (sometimes Khwolson) from the discussion of gravitational lensing*, though we get Emil Arnold Budde†, Heinrich Zanger, and Rudi W. Mandl. The shrinkage of the expansion parameter, *H*, from Hubble's value to the present (and hence the increase in estimated age for an expanding universe) is credited only to Allan Sandage by name, though the first factor of two came from Walter Baade and David Thackeray looking at stars in M 31 and the Magellanic Clouds.

Attributing Campbell's early work to 1981 (I suppose 1891 was meant) is just an 'oops', while the discussion between Einstein and de Sitter about cosmological solutions of the field equations is full of 'aha!' experiences, including de Sitter's objections to (*i*) Einstein's assumption of a mechanically quasi-stationary world (p. 77) and (*ii*) Einstein's introduction of invisible masses into the Universe (p. 72). Since the mass was to be located at an outer boundary only, it does not count as early dark matter. We get at least one 'tell me more', on p. 60, where Leonhard Grebe and Albert Bachem are said to have measured a gravitational redshift for the Sun of about 80% of the GR prediction. Their paper is not referenced, just letters between Einstein and Arthur Eddington discussing the supposed 1919 measurement.

As for other questions you might ask (Was Einstein a Machian? Did he think gravitational waves/radiation could carry away energy from binary stars and such?), you must read the book for yourself. But, in justice to all parties concerned, let me make clear that the 1916 letter to Karl Schwarzschild assured him that there was no gravitational radiation analogous to electromagnetic radiation. This is perfectly true: EM radiation is dominantly dipole, and only with scalar–tensor theories of gravity, like Brans–Dicke, do you get dipole gravitational radiation (and yes, Joseph Weber looked for it, as well as for the quadrupole radiation predicted by General Relativity). — VIRGINIA TRIMBLE.

New Frontiers in Black Hole Astrophysics (IAU Symposium 324), edited by Andreja Gomboc (Cambridge University Press), 2016. Pp. 361, 24·5 × 17 cm. Price £100/$125 (hardbound; ISBN 978 1 107 16994 4).

Editor and SOC Chair Gomboc tells us that 130 experts from 30 countries presented 24 invited talks, 57 contributed ones, and 30 posters at this first IAU Symposium to be held in Slovenia, of which about three-quarters made

*His paper appeared in *Astronomische Nachrichten*, **221**, 329, 1924, is a single paragraph called '*Über eine mogliche Form fiktiver Doppelsterne*' though the picture shows an Einstein ring, and the same page has a one-paragraph Einstein item, so he must have seen Chwolson, even if Gutfreund and Renn did not.

†It is irresistible to mention that Budde had been a director of a Siemens company, since I sat, or rather lay, next to one of their products only three days ago.

it into the proceedings (assuming there were no contributions from inexpert participants). These proceedings should probably be regarded as a tasting menu with the menu missing, because the conference summary (by SOC co-chair Carole Mundell) did not make it into the proceedings, while the historical introduction came from your present reviewer, so you know what that was like!

Active galactic nuclei received the most attention, gamma-ray bursters, second, and tidal-disruption events third. Some of the theorists attempted to describe what black holes might do if gravity is something other than General Relativity and/or particle physics is something other than the Standard Model. The most forlorn hopes observationally would seem to be searches for single stellar-mass black holes and for black-hole binaries with no accretion. The latter could turn up as orbits of their companions in *Gaia* data, but it is not quite clear whether the expected number for a five-year mission is zero or 10^5.

The prize for best use of astrophysical metaphors goes to Charles Bailyn, who showed images of (*i*) a smoking gun (evidence for black holes in quiescent BHBs), (*ii*) the Rosetta stone (disk–jet connection), and (*iii*) the tip of an iceberg (quiescent BHB demographics). The most puzzling image came from a museum-type exhibition at the time of the meeting, which appears to show the fossilized dropping of an ancient mammal on top a circular trash bin. Colour would probably not have helped, but would have for some of the reproductions of observations and simulations that attempt to show more than a plot of 'this *versus* that'.

Careful reading identifies interesting quirks. Covino *et al.* show a photograph of the *Rapid Eye Mount Telescope* "located at the ESO premise of La Silla". And I will offer the standard small prize to the first reader to come up with another English word for which the plural is an equally bad guide to the meaning of the singular. Jegremov makes clear neither why "NUT space" is so called nor how Polish doughnuts got their names. Alexander sketches a TDE "zoo", whose four cages are labelled 'Single MBH', 'Binary MBR', 'Replenishment', and 'State'. Squeezars live in the Single MBH cage. And the editorial custom of listing only the first three authors when the total number exceeds N makes possible order-of-magnitude estimates of collaborations sizes. For *H.E.S.S.* (the *High-Energy Spectroscopic System*) we get all the way to Aye; for *VERITAS* (the *Very Energetic Radiation Imaging Telescope Array System*) to Arl; for *MAGIC* (*Major Atmospheric Gamma-Ray Imaging Cherenkov*) to And; *Fermi-LAT* to Aje; *IceCube* to Abd; and winner and still champion, *LIGO* to Abb. All are cited by Lindfors in drawing analogies between supermassive BH in galaxy centres and stellar-mass ones in binaries. May they all win prizes enough for every author to receive at least the price of the proceedings volume! — VIRGINIA TRIMBLE.

New Scientist Instant Expert — Where the Universe Came From: How Einstein's relativity unlocks the past, present and future of the cosmos (John Murray Learning), 2017. Pp. 208, 21·5 × 13·5 cm. Price £12·99 (paperback; ISBN 978 1473 62959 2).

There is no author listed on the cover, but inside there is a list of ten authors ("academic contributors" with one-sentence biographies), and 14 more ("writers") are thanked by name. Before those, the Editor-in-chief (for this book) Alison George (*Instant Expert* editor for *New Scientist*) and Editor (for this book) Stephen Battersby (physics writer and consultant for *New Scientist*) are mentioned. I recognized Marcus Chown from the second list and several from the first list for their popular-science writing; all of them are reasonably well known as scientists, writers, or both; I reviewed a book[1] by one of them not long ago in this *Magazine*. This book is one of a series, and is based on talks at the 2016 *New Scientist* masterclass 'Relativity and Beyond' as well as articles previously published in *New Scientist*. Having recently reviewed another book[2], which was surprisingly good, in another series, I was more optimistic than I might otherwise have been towards this book with no author mentioned on the cover, so was surprised that, after a short introduction, the first chapter starts with "In 1915 a patent clerk in Switzerland". That might be a misprint for '1905', but the topic is General, not Special, Relativity. By 1915, of course, Einstein was neither a patent clerk nor in Switzerland, but already one of the most respected scientists in the world.

Fortunately, though, that is the only major goof in the entire book, which is well written, gives a new twist on a mostly old tale, and is so well edited that it reads as if written by one author. The nine chapters cover the basics of relativity and space–time, black holes, gravitational waves, cosmology, dark matter, dark energy, and modifications to and extensions of relativity. Those are followed by 50 ideas in five lists; most are in the 'fun fact' category. A glossary, index, and picture credits (where Volker Springel has his first name changed to Vogel) round out the book. One could write much longer books about each of the chapters, so condensing the material down to such a short book is a formidable task, especially if the level is the same for all topics. Surprisingly, that comes off well. General Relativity is the unifying theme, but this is not a rehash of standard textbook stuff. Recent results are incorporated seamlessly into the text, which is careful not to repeat myths (which legendary figures such as Einstein tend to attract).

Somehow, there is even room for additional topics one might not expect in a book such as this: campaigns against relativity, both by otherwise serious scientists and by crackpots; backreaction; branes; Unruh radiation; MOND; other types of modified gravity; the mathematical universe[3]. Of course, even though there are a few equations in the book, such descriptions are rather superficial, but — echoing Einstein's own advice — are not too simple, and are essentially correct. (Only in the discussion of possible anti-gravity devices did I think that a bit more scepticism was needed; other controversial topics such as black-hole firewalls are described as such and all sides are presented, though the authors hint at what they believe to be the correct interpretation.)

Twenty-nine figures and 20 boxes of supplementary text are scattered throughout the main text, as well as a few short interviews, all of which complement the main text rather than distract from it. The final chapter starts out with a diagram showing how principles are combined and lead to problems, and another illustrating possible solutions to those problems. In a sense, they are a very compact summary of the book, and are briefly explained in the next few pages.

I recommend the book for beginners interested in relativistic astrophysics and for those who work in other fields who want an overview of current topics together with the necessary historical background. The only thing missing is recommendations for further reading at a similar or slightly higher level. A starting point could be the three books discussed in the reviews referenced below. — PHILLIP HELBIG.

References

(1) P. Helbig, *The Observatory*, **134**, 214, 2014.
(2) P. Helbig, *The Observatory*, **137**, 30, 2017.
(3) P. Helbig, *The Observatory*, **134**, 150, 2014.

Non-Stable Universe: Energetic Resources, Activity Phenomena, and Evolutionary Processes (ASP Conference Series, Vol. 511), edited by A. M. Mickaelian, H. A. Harutyunian & E. H. Nikoghosyan (Astronomical Society of the Pacific), 2017. Pp. 312, 23·5 × 15·5 cm. Price $88 (about £63) (hardbound; ISBN 978 1 58381 906 7).

Here are the proceedings of an international symposium marking the 70th anniversary of the Byurakan Astrophysical Observatory, held there in 2016 September, addressing (mostly) activity in stars, nebulae, and galaxies, with a sprinkling of exoplanets and history of astronomy. Of the 79 listed participants, 36 were from Armenia, plus six and two (non-participating) members of the SOC from the Armenian diaspora, based on surnames ending -ian or -yan. At least one abstract speaks of "Armenia and the Armenian nation", suggesting a concept not shared by all countries.

The first question that came to mind was, to what extent is Armenian astronomy moving out from under the monumental intellectual shadow of Viktor Amazaspovitch Ambartsumian (1908–1996), who firmly held to the view that stars and galaxies all emerged from initially super-dense material, and who encouraged members of the observatory staff to investigate astronomical sources from that point of view. The answer is "partly". At least three of the presentations, by Gabriel A. Ohanian, Haik A. Harutyunian, and Ara K. Avetissian (all of Byurakan) make cases for some aspect of Ambartsumian's ideas, now regarded in most places as non-standard. On the other hand, at least 12 of 28 presentations with BAO or other Armenian authors could have been given anywhere, based on self-citations in their papers to appearances of their work elsewhere, most often in *A&A* and *MNRAS*. This is a lower limit because several of the papers from BAO, Yerevan State University, *etc.* have no self-citations at all, and the authors are probably students just entering into the community.

I have written elsewhere (perhaps even in these pages) that the lingering influence has been detrimental to the community, and, on balance, I suppose that is true. On the other hand, it is unlikely that a community founder could have been such an aggressive and successful advocate for astronomy in what became his home country if he had not been an equally aggresive advocate of his own ideas. Ambartsumian was actually born and schooled in Tbilisi (Georgia) and then a student, staff member, and professor in Leningrad until 1943. He was a vice-president of the IAU (1948–55), President (1961–64), and President of ICSU (1968–72), and the editors of these proceedings note that, in terms of number of IAU meetings hosted, the village of Byurakan is one of the ten "largest" cities in the world.

Physically the proceedings are rather old-fashioned. There is not a hint of colour, even in images of the sky or simulated results that would have benefitted. Mercifully the people pictures are also black and white, and a few (I think deliberately) funny. The discussants of "hot topics of stellar evolution" are two of the glummest faces to be seen. The ratio of unoccupied to occupied seats for a participant "delivering an invited talk" suggests that the rest of the 79 should also have been invited. Another nice touch: Edward Khachikian, one of the senior Armenian astronomers (well, he visited Caltech when I was a student there around 1966), gave his e-address as edkhach28@. Of all the numbers he could have chosen, 28 was the number of the IAU Commission of which he was President. Initially called Nebulae (with Bigourdan as President), it was Galaxies during Ed's term (and later mine). It sadly is no more. The standard photo of the participants indicates that quite a few were women, and another of the 'session' photos that they tended to cluster. In all cases the drinks in hand seem to be coffee or sodas.

Scientifically, the proceedings are a bit of a disappointment. Several of the more interesting titles appear only as one–two-sentence abstracts (including two of the supernova talks), with no reference to publication of the material elsewhere. Martin G. Abrahamyan invokes anticyclonic Burgers vortices for planetesimal formation, but does not cite the eponymous Johannes. Oleg Yu. Malkov strives bravely to remind us all that binary stars are essential if one is to understand star formation, galactic evolution, and all the rest, and that the distribution of binary-system mass ratios is a key input, and you can guess whom he doesn't cite.

Not to be found easily elsewhere are the two papers on history of astronomy in Armenia. Elma S. Parsamian addresses mostly rock carvings and a megalithic henge, and Grigor H. Broutian focusses on the beginning of the Protohaykian calendar. Both are BAO staff members, and each paper has some odd-feeling items. Parsamian states that the constellations were established in Armenia and Turkey at a time ending about 2800 BC, citing Maunder (1906) and Olcott (1914) as his only authorities. There has surely been a great deal of work on this topic since. She associates one of the sites with observations of heliacal risings of Sirius in the period 2600–2800 BC. Broutian on the other hand associates the beginning of the pre-Christian Armenian calendar (the Haykian) with the heliacal rising of Betelgeuse in 2341 BC. More impressively the Protohaykian calendar, he concludes, began about 9000 BC, a date he also assigns to the observational platform of Metzamor, discussed by Parsamian (and dated to 2800 BC by her). He also assigns dates within years on the basis of crop-harvest festivals, on the grounds that "the plant and the climate of the location … cannot be changed", citing a book by N. I. Vavilov. Since the last Ice Age is generally advertized as ending in 8800 BC (with many wet and dry cycles since) and crops were only just being domesticated then (see, *e.g.*, Jared Diamond's *Guns, Germs, and Steel*, which is the sort of thing one ought to read anyhow), "cannot be changed" cannot be correct. And there are several more curious items, though the reminder that dates of heliacal rising drift, due to stellar proper motions and precession of the equinoxes, is correct and useful.

Broutian cites lots of papers, but they are nearly all his own and in Armenian. I wonder if our young Prof. Kevork Abazajian could help? —VIRGINIA TRIMBLE.

Foundations of Nuclear and Particle Physics, by T. W. Donnelly, J. A. Formaggio, B. R. Holstein, R. G. Milner & B. Surrow (Cambridge University Press), 2017. Pp. 646, 25·5 × 19·5 cm. Price £64·99/$84·99 (hardbound; ISBN 978 1 521 76511 4).

Foundations of Nuclear and Particle Physics is a comprehensive text-book for particle and nuclear physics. It is one for which those working in the physics of lepton interactions with nuclei have been waiting for many years. The authors have collected and presented well-established knowledge, with emphasis on recent methods in modelling nuclei in scattering. The text-book could be easily used for teaching undergraduate courses in advanced particle physics or nuclear physics. Due to the background of most of the authors, I think that students interested in theoretical physics will enjoy it most. Although the book offers a reasonable transition from particle physics to nuclear physics, the authors propose two roadmaps depending on whether the book is used for teaching and learning particle or nuclear physics.

After each of the chapters, there is a set of problems to solve and crystallize the knowledge gained. The exercises cover an extensive range of sophistication, from solving simple kinematics of two-body scattering to in-depth analysis of one-pion exchange-potential. Many of the tasks will be difficult to approach without prior experience in various theoretical methods, *e.g.*, expansion of Hartree–Fock Green's function.

There are 21 chapters, but they could be divided into four distinct sections. In the first part (Chapters 1–6) the Standard Model is introduced. That includes the Weinberg–Salam model, the Higgs mechanism, mixing of quarks and neutrinos, and the approach to give neutrinos masses, QCD and confinement, and Chiral symmetry, as well as brief descriptions of renormalization methods. In Chapters 7–11 a detailed description of the scattering of leptons, quarks, and nucleons is presented. Many additional pieces of necessary information are also presented: experimental results for interaction cross-sections, the structure of nucleons and form factors, and the physics of jets. In Chapters 12–16 the methods of nuclear physics are described, including the structure and properties of few-body nuclei, properties of finite nuclei, and relativistic modelling of nuclear matter. Finally, Chapters 17–21 combine the knowledge from the first 16 chapters. That includes beta decays, physics of neutrinos and relativistic heavy ions, nucleosynthesis, stellar evolution, and physics beyond the Standard Model.

In conclusion, this is an excellent text-book for teaching advanced particle and nuclear-physics courses and should be extremely useful for people starting research in lepton–nucleus scattering physics. — JAROSLAW NOWAK.

Gas Accretion onto Galaxies, edited by A. Fox & R. Davé (Springer), 2017. Pp. 373, 24 × 16 cm. Price £112/$179 (hardbound; ISBN 978 3 319 52511 2).

This book offers a comprehensive and detailed overview of the processes that gas goes through as it is accreted onto galaxies, compressed into stars, ejected, and, in some cases, re-accreted onto the same galaxy. It covers the many aspects of this seemingly straightforward process and its impact on galaxy properties, such as metallicity, and how it has changed our understanding of the Universe as a whole.

Each chapter is written by a different author, a person very knowledgeable in the topic covered by their respective chapter, and I was glad to see that very recent research was also included in the discussion (several cited papers were published earlier this year [2017]). As gas accretion is a broad and complex subject, some prior knowledge is required to make the most of the book, though the figures, tables, and illustrations used helped clarify the points the author of a chapter tries to make. Many theories on the mechanisms of galactic gas accretion have been put forward to explain the observations, and these are discussed in each chapter along with their merits and pitfalls. Each author also gives his/her opinion on the next steps needed, both in simulations and in observations, for the next breakthrough in the field of galactic gas accretion. In this case, as in many others, it is simple: higher-resolution simulations, and more observations to dispel parameter degeneracies.

One thing I feel the book lacks is a final, dedicated, short chapter summarizing the future directions that this field of research needs to move in, in terms of both observations and simulations, to sow the seeds of expectation. Furthermore, and probably due to the fact that each chapter was written by a different author, how well a concept is explained can vary quite a bit from chapter to chapter, as does the depth of detail given. As an exercise to any future readers, do keep your eyes peeled for some amusing typos, especially the "Keck Comic Web imager".

Overall, I would recommend this book to someone seeking an in-depth overview of a topic covered in the book, though, as mentioned above, a level of understanding of gas kinematics within galaxies is needed. — ELECTRA PANAGOULIA.

A Dirty Window: Diffuse and Translucent Molecular Gas in the Interstellar Medium, by L. Magnani & S. N. Shore (Springer), 2017. Pp. 306, 24 × 16 cm. Price £112/$179 (hardbound; ISBN 978 3 662 54348 1).

What a good title! (I wish I had thought of that). This book is about the dirt on the window through which we observe the Universe, *i.e.*, the interstellar gas and dust. Studies of the interstellar medium of the Milky Way Galaxy over the last half century or so have established that interstellar gas and dust play a key role in the evolution of the Galaxy. Interstellar matter is the reservoir of material from which new stars are formed, and interstellar space is the sink into which debris from stellar winds and from stellar explosions — in the form of novae and supernovae — are retained. The interstellar medium exists in a variety of conditions, ranging from extremely hot, low-density, fully-ionized gas to relatively dense gas that is very cold and largely neutral. Dense opaque clumps of cold neutral gas are the sites of star formation, and of the glorious post-formation events such as stellar jets and outflows. Studies of star-forming regions are very active areas of astronomy at present.

The diffuse and translucent interstellar clouds discussed here are material that may evolve into star-forming regions. These clouds are warmer and less dense than gas in star-forming regions, and are pervaded by radiation from nearby stars. Clouds like these are where simple molecules were first identified some 80 years ago, and have been a major topic of interest since. It is these clouds that are the focus of this new book.

The authors stress that this isn't a text-book; rather, it presents their point of view as their work (as experts) has taught them. Nevertheless, this book would be an excellent introduction to the subject. The book adopts a largely historical approach, with comprehensive references. Each reader will find much of interest in the wide coverage of selected topics. I found two chapters particularly interesting. One concerned the relationship between CO (1–0) emission and H_2 column density — the so-called X-factor; that chapter summarized some of the methods of determining X. The other chapter that seemed topical to me dealt with instabilities and turbulence in clouds, beginning with a thought-provoking question: what is a cloud? The authors end with a number of open questions, showing that the subject is still evolving.

The book is recommended to anyone with an interest in the interstellar medium. — DAVID A. WILLIAMS.

Energetic Particles in the Heliosphere, by G. M. Simnett (Springer), 2017. Pp. 241, 24 × 16 cm. Price £82/$129 (hardbound; ISBN 978 3 319 43493 3).

This book provides a broad survey of our current knowledge of energetic charged particles throughout the heliosphere, most obviously the electrons and ions energized by solar processes and observed by instruments on a wide range of spacecraft, but also particles energized in planetary magnetospheres and particles entering the heliosphere from interstellar space. It shows how the heliosphere is full of energetic particles (as well as magnetic fields and the background plasma of the solar wind): particles that can reveal much fascinating physics, both in terms of how such particles are energized and how they propagate through space under the influences of the ambient magnetic fields and of structures in the plasma that forms the solar wind. As the author notes, this physics is fundamental to our understanding of the wider Universe — of how charged particles are energized and propagate in more distant astrophysical environments. The Solar System is a wonderful natural laboratory for understanding plasma physics and its role in particle energization. Thus the book can serve not just as a snapshot of our current wealth of knowledge but also a demonstration that we have much more to learn.

The first three chapters of the book provide a valuable introduction to the subject. The first provides historical background including the 1912 discovery of cosmic rays, the growth of cosmic-ray studies prior to the advent of spaceflight in 1957, and the first satellite experiments to detect energetic particles in space. This is followed by a second chapter that provides an excellent overview of the instrumental techniques used to detect and measure the properties of energetic charged particles in space (*e.g.*, the energy, charge states, and masses of those particles). A third chapter provides an overview of particle energization processes.

We then move to the core of the book: a series of seven chapters looking at how we can use energetic particles to study various aspects of the heliosphere, most obviously its inner and outer parts, but also high latitudes (*i.e.*, far from the plane of the ecliptic where the planets and most spacecraft travel), the interaction with the interstellar medium, and the role of planetary magnetospheres. Those chapters provide a comprehensive review of our observational knowledge using data from a wide range of satellites, and highlight many important case studies that have been published in the peer-reviewed literature. The author brings out the diversity of behaviours that exist within these data and discusses the implications for our understanding of particle energization and propagation.

It is the wealth of data presented in these chapters that is the strength of this book. It shows that this is a wonderful, if sometimes bewildering, topic. I did find myself wanting more synthesis of the physics beneath the observations, but then realized that I was being unfair. There is still much to do to achieve that synthesis as the author notes in his final chapter on 'What about the future?'. There are still many unknowns that our science needs to resolve.

I have a couple of minor quibbles. The annotation in a few of the figures is hard to read as the figures seem to be fuzzy copies from figures in old printed-journal papers; it would not have been hard to clean up that annotation — as has been done in the case of some other figures in the book. Also I was puzzled to see a statement that the largest high-energy solar proton event yet recorded occurred was in Chicago. There is perhaps a need to raise awareness that the greatest intensity of that event (on 1956 February 23) was recorded at Leeds in the UK. This is well shown in the excellent modern GLE database at Oulu (gle.oulu.fi) where Leeds and four other stations in Europe and North America exhibited intensities higher than Chicago.

But these are minor quibbles. The book provides an excellent overview of our current knowledge of energetic charged particles in heliosphere. It brings out the complexity of these data and highlights the challenges that we face when interpreting these data against our still-limited theoretical understanding of how the heliosphere works. I hope it can act as a challenge for future scientists to develop a better understanding of the heliosphere and thus of how we can use energetic-particle data to infer knowledge about the sources of these particles and of the heliospheric structures through which these particles propagate to reach our instruments. — MIKE HAPGOOD.

Annual Review of Astronomy and Astrophysics, Volume 55, 2017, edited by S. M. Faber & E. van Dishoeck (Annual Reviews), 2017. Pp. 497, 24 × 19·5 cm. Price from $419 (print and on-line for institutions; about £318), $107 (print and on-line for individuals; about £81) (hardbound; ISBN 978 0 8243 0955 8).

A major player in the field of galactic structure and evolution opens the latest volume of the *Annual Review*: Ken Freeman's astronomical autobiography spans over 60 years and takes us from the Eggen, Lynden-Bell and Sandage model of the Milky Way through to the dark-matter infested galaxies under investigation today. Galactic structure also features in several other reviews this year. Alexander considers the effects, particularly dynamical ones, on stars due to a massive black hole at the centre; Sgr A* is such an example and has recently been discussed in these pages (**137**, 267, 2017). According to Kaaret, Han Feng & Roberts, such a source might only need accretion from the interstellar medium to make it very bright at X-ray wavelengths; less-massive objects would require more substantial 'food' to make them as luminous. Meanwhile Naab & Ostriker study galaxy formation over time (*i.e.*, *z*), finding that mass inflow and outflow are of critical importance. That result is enforced by the discussion, by Tumlinson, Peeples & Werk, of feedback and recycling of material from the circumgalactic medium.

Of particular (nostalgic) interest to me was the review by Linsky of the diagnostic value of chromospheric indicators, with particular reference to assessing the suitability of stars to host interesting (*i.e.*, possible life-bearing) exoplanets; it seem that all those data we collected with *IUE* still have value! And continuing with an eye on those exoplanets, Kaltenegger looks forward to being able to characterize them more-fully for signs of life.

Magnetic fields are the subject of two reviews, with Han discussing both interstellar and intergalactic media through polarization and Zeeman observations, while altogether stronger fields — and in particular their decay — are considered by Kaspi & Beloborodov in young and very magnetic neutron stars (magnetars), of which 29 were known at the time of writing.

For those at the coal-face, harvesting those gigabytes of data, the discussion of Monte-Carlo methods in data analysis by Sharma will be of interest. And finally, for the sceptical, some comfort may be had in the examination by Bullock & Boylan-Kolchin of challenges to the ΛCDM paradigm to be found on the small scale.

All in all, a worthy successor to the first 54 volumes of the series. — DAVID STICKLAND.

Planet Hunters: The Search for Extraterrestrial Life, by L. Ellerbroek (Reaktion Books), 2017. Pp. 267, 22 × 14·5 cm. Price £16·95 (hardbound; ISBN 978 1 78023 814 2).

This book describes the discovery during the last 22 years of an increasing number of exoplanets — nearly three thousand by the summer of 2016 — and this is in itself a fascinating story. The book's underlying theme, however, is the on-going search for extraterrestrial intelligence — it is repeatedly pointed out that the prime motive for exoplanet hunting is the potential of such places as a home for alien life — and this in my view dilutes its impact inasmuch as there is a fundamental difference between the narration of attained achievement and the presentation of as yet unrealized possibilities.

The book is clearly intended for the general reader (who is more likely to be interested in alien life than exoplanets), and the author, who is personally acquainted with most of the scientists involved in exoplanet discovery, and SETI, has understandably endeavoured to enhance the human interest of the story by providing vivid descriptions of their backgrounds, interests, appearance, and other personal characteristics. This may well enhance the book's appeal to those who like a friendly, gossipy book about people, but I confess it put me in mind of the small boy who, on return from a special school lecture about penguins, told his mother that he had been told a lot more about them than he wanted to know.

The discovery of exoplanets is a remarkable human achievement, made possible by the astonishing improvements in scientific instrumentation in recent times, in particular spectrometers and photometers and the computer capacity to process and preserve their measurements, and of course satellite availability. The two primary methods used to track down planets — the transit of the planet across the face of the star which affects the latter's brightness, and the regular change in radial velocity of a star/exoplanet system as detected *via* its Doppler effect — are well and clearly described in the book, as are the stories of the various people who devised these methods, developed them, and ultimately and tenaciously drove them to their success.

Also described in the book is the setting up of the SETI institute in 1984 and the activities of Frank Drake and others during the previous twenty-five years in their search for possible interstellar communications being broadcast from extraterrestrial sources. The Green Bank conference of 1961 and the Drake Equation are well described, and the book admits that there is a feeling among some professional astronomers that hunting for — and speculating about — alien intelligent life is not exactly true scientific research. The enthusiast may (rather pompously) claim that he or she is seeking to answer the ultimate — are we alone? — question, but will nevertheless encounter in doing so derisory references to little green men. But the book makes it clear that there are many such enthusiasts and their quest continues.

The final chapters are about astrobiology. The author cites evidence that there is molecular activity within the chemistry of dust in outer space, and mentions research now in progress to develop means to detect primitive life on exoplanets *via* atmosphere analysis. He ends, however, on a pessimistic note, quoting from a talk by Manuel Güdel at a conference in Heidelberg in 2013 which suggests that the suitability of the Earth for the development of intelligent life has arisen from a sequence of unlikely events that could well be unique; and he concludes with the remarkably inconclusive observation that "There are two possibilities — either life is everywhere, or Earth is a one-off."

The book opens with a brief history of the development of astronomical knowledge, and this is built up around the unhappy story of Giordano Bruno, who was burned to death in 1600 for various heresies including his insistence that there existed "a plurality of worlds", and who is cited by the author as "the first planet hunter". Certainly his fiery demise makes for a strong human-interest story, but he was not the first person to speculate about exoplanets, and Nicholas of Cusa has a much better claim to be cited in this context, having asserted in a book in 1440 that the stars were other suns which supported other inhabited worlds. Nicholas, however, did not meet a dramatic end, and was in fact made a cardinal in 1448.

In summary Dr. Ellerbroek's book is entertaining and contains much interesting information about important new astronomical techniques, but its discursive and anecdotal style does not assist the rapid assimilation of its key points, though it may well enhance the book's appeal to a general readership. — COLIN COOKE.

Comets: Nature and Culture, by P. Andrew Karam (Reaktion Books), 2017. Pp. 200, 21 × 15 cm. Price £14·95 (paperback; ISBN 978 1 78023 830 2).

Comets are newsworthy, and always have been. In fact, when it comes to astronomical objects, comets are very near the top of the list of the public's favourites. And it is not always good news. Even though some credit comets with bringing water to Earth and even seeding our planet with life, others look on the gloomy side and herald them as predictors of doom, disease, and disaster. Scientifically comets have always been an interesting subject. The challenge of discovering their orbits, periodicity, origin, composition, structure, decay, tail production, impact rate, numbers, and physical nature has been a spur to planetary scientists since the 16th Century.

Karam has a bright, breezy, and introductory approach and tackles the subject in two ways. First he investigates the cultural influence of comets, and considers their role in art, fiction, fantasy, graphics, and astrological prediction. Here the book benefits from a host of superb illustrations and the author's commendable writing ability. The influence of Halley's Comet, and the effect of great comets on the likes of Julius Caesar and the Heaven's Gate Cult enliven the text. Unfortunately Karam was on less firm ground when it came to the science. Much was made of cometary impacts, but too little was said about the relative roles of comets and asteroids when it came to modifying the features of a planetary surface and atmosphere. Also the problems of the formation and decay of the cometary nucleus, the role of comets in planetary formation, and the remaining mysteries in cometary science revealed by recent spacecraft examinations were glossed over. — DAVID W. HUGHES.

Cosmic Debris: What it is and What we can do about it, by Jonathan Powell (Springer), 2017. Pp. 267, 23·5 × 15·5 cm. Price £26·99/$39·99 (paperback; ISBN 978 3 319 51015 6).

Synonyms for the word 'debris' are detritus, refuse, rubbish, waste, litter, scrap, dross … which is a bit harsh for the topics in the book under review. Powell, a Welsh science writer and broadcaster, concentrates on asteroids, comets, meteorites, and meteoroids. There are chapters on what happens when these bodies hit planet Earth, and events like Chelyabinsk, Tunguska, and the demise of the dinosaurs are discussed, as are the potential effects of the re-entry of the litter in low Earth orbit that has resulted from the profligacy of the space age. Final chapters consider amateur observations of meteors and meteor showers, comets, and asteroids

The author skims the 'what it is' in the book's title in an engaging and readable fashion and has produced an entry-level text for a fascinating topic. The 'what we can do about it' is dealt with very briefly. I got the impression that the only realistic approach was to run round like Private Frazer in *Dad's Army*, muttering "We're doomed! Doomed! DOOMED! I tell ye". Nothing is made of the fact that Earth has been bombarded much more severely in the past than it will be in the future, and life has survived. — DAVID W. HUGHES.

Spectroscopy for Amateur Astronomers, by M. F. M. Trypsteen & R. Walker (Cambridge University Press), 2017. Pp. 151, 28·5 × 22·5 cm. Price £34·99/$49·99 (hardbound; ISBN 978 1 107 16618 9). **Spectral Atlas for Amateur Astronomers**, by R. Walker (Cambridge University Press), 2017. Pp. 277, 28·5 × 22·5 cm. Price £59·99/$89·99 (hardbound; ISBN 978 1 107 16590 8).

Attractively produced as a working pair, these books are the products of a lifetime of familiarity with observing the spectra of cosmic objects of all kinds, conditions, and states. The *Atlas* is in effect a modern version of the 1943 *MKK Atlas*, at one time a centrepiece of almost all student astronomy studies and courses. Greater understanding has affected or altered the descriptions of, and explanations for, some of the classes and their variants, but the essence is the same: to display the spectra of standards and prototypes, to show differences attributed to whatever physical causes, and to add as much background astrophysics as is both warranted and reasonable. An important development on the 1943 *MKK Atlas* is the addition of displays as graphs as well as images, and detailed labelling of the wavelengths of critical features.

The supporting volume, *Spectroscopy for Amateur Astronomers*, is less easy to assess, as it is neither the convenient explanatory handbook which the topic requires, nor the full-blown text-book which the serious student needs. It is, rather, a collection of notes on various aspects of both practical and theoretical spectroscopy — almost a 'guide' to the cosmos — and on recording and analysing what one can observe. A substantial list of references, plus tables of star names, a magnitude scale, and similar packets of useful information for the sky-watcher, are also included. There is, as expected, a tendency to use terms and descriptions from the angle of the amateur with home equipment, rather than of the professional at a fully-equipped observatory. The selection of standards against which to contrast non-standards is helpful only in principle, since in the real world of stars the dispersion which we now come to expect around each class, sub-class, metallicity, or rotation value needs to be understood as natural, and that the astronomer cannot assign stars into boxes as though their differences had a monotonic explanation. Descriptions that appear to be authoritative are not always quite correct or current, as (for instance) in the case of the Am/Fm stars, which are explained confidently by the popular hypothesis that all are members of short-period binaries, when there are known to be exceptions which test that hypothesis quite severely.

The *Atlas* compares spectra by ranging one above the other, which works well for the most part though in some cases the chosen aspects of the graphs are such that deep lines are too deep for the display, and ranging two such deep-lined spectra vertically is rather too tight. The units employed are not always well described (or all that familiar), and the spectra themselves were not flat-fielded — though the essence of flat-fielding is discussed in the companion volume.

Walker is not a native English speaker, and his writing is affected by some mis-selected words, such as "according" for "corresponding", missing the pejorative implication of "so-called", confusing prepositions, and — in at least one place — spelling "braking" as "breaking" (but dwellers of glass houses should not throw stones ...). Not all of the statements are correct (Morgan, Keenan & Kellman, for instance, were affiliated to Yerkes Observatory, not Mount Wilson), and to be told that (in a reference to the Ca II lines) "For main-sequence stars of the G class the K line is always slightly more intense than the H line" was a bit surprising. Nevertheless, the pair of books, or as individuals according to need, should be welcome additions to the library of every serious amateur astronomer. — ELIZABETH GRIFFIN.

Hubble's Universe: Greatest Discoveries and Latest Images, 2nd Edition, by T. Dickinson (Firefly), 2017. Pp. 332, 25·5 × 25·5 cm. Price £25 (hardbound; ISBN 978 1 77085 433 8).

Just three years ago I gave an enthusiastic welcome to the first edition of *Hubble's Universe* in these pages (**134**, 388, 2014), and I can do the same for the second edition. It is essentially the first edition plus a new chapter bringing the story up to date following the 2009 May upgrade to *HST* in which the *Wide Field Camera 3* and the *Cosmic Origins Spectrograph* were installed. As an example of their benefit, the new volume shows a wonderful high-resolution image of the 'Pillars of Creation' taken by *WFC3* — much more impressive than the earlier version. Numerous other beautiful images adorn this second edition, including a spectacular fold-out panorama of a part of the Andromeda Galaxy. The book concludes with an up-beat prospectus for the results expected from the *James Webb Space Telescope* currently scheduled for launch later this year. The first edition was inspirational, and this second is equally so; and at a price modest by modern standards, it's a bargain. — DAVID STICKLAND.

Astronomy for Older Eyes, by J. L. Chen (Springer), 2017. Pp. 233, 23·5 × 15·5 cm. Price £22·50/$39·99 (paperback; ISBN 978 3 319 52412 2).

At age 67 and as a retired GP with an interest in ophthalmology I approached this review with enthusiasm. The book did not disappoint. From the beginning it might well be better entitled "Ageing for Astronomers", though I accept this would not be as appealing. After lamenting the increasing average age of amateur astronomers, the author goes on to describe the evolution of astronomical equipment through his lifetime and problems inherent in decreasing portability as the size of equipment increases. Later sections discuss the advantages of some telescopes regarding portability.

He covers elementary theories of ageing, the importance of exercise as one gets older, and the value of different foods to delay perhaps the ageing process. This is a somewhat contentious area as problems that are exacerbated by shortage of essential nutrients are not necessarily improved beyond normal when those foodstuffs are eaten in excess. The problems that eyes develop through the normal ageing process are well covered. There is much guidance on the use of astronomical equipment as the years go by.

The section on diseases of the ageing eye and their management is sound and includes the important point that if treatment is required for refractive errors, cataracts, and other eye disease it is vital to emphasize to the ophthalmologist that you are an active observer, as some therapies such as Lasix surgery may, in some situations, have a detrimental effect.

He does not neglect the social value of astronomical societies, star parties, and astronomical tourism. All of these latter matters are described very much from a North American point of view, as is the advice upon the disposal of astronomical equipment at the end of life.

The appendices of the book contain a summarized version of much of the advice given earlier but without an ageist slant, followed by extensive deep-sky catalogues. The appendices really are about astronomy rather than ageing — and therefore less depressing! — MIKE RUSHTON.

A Question and Answer Guide to Astronomy, 2nd Edition, by C. Christian & J.-R. Roy (Cambridge University Press), 2017. Pp. 344, 25 × 17·5 cm. Price £19·99/$29·99 (paperback; ISBN 978 1 316 61526 3).

This is a reference book for astronomy and provides an amazingly wide range of information from 'How are stars named?' to the 'Solar System', 'Stars', 'Universe', and 'Life', to 'Which telescope should you choose?'. As a second edition, it is an update on the first published in 2010 and so includes more recent material up to the first half of 2016. The structure is in seven sections, each of which asks up to 40 'questions'. The answers to those questions then provide the astronomical information.

In general, I am not a fan of being given information in a Q and A format — how do you know exactly what to ask and how do you find it in the book? — so it is essential that the index works well. This book passes that test and does work as a reference text with a sizeable bibliography attached. Also, there is good cross-referencing within each answer to other connected answers. Each answer also has at least one illustration — photographs, diagrams, graphs, and artists' impressions are all used — and these add positively to interest and understanding.

The subject matter varies in level from the fairly straightforward 'What is a shooting star?' to more complex explanations of Relativity and String Theory, and so, in some ways, it is quite an ambitious book. I also enjoyed reading anecdotes of some of the major discoveries (*e.g.*, expansion of the Universe) involving characters who are not usually mentioned.

I do have one or two minor, personal quibbles. As a North American book, Pluto tends to be included in Solar System discussions even though its status has changed. Explanations involving circular motion are still using centrifugal, rather than centripetal, force. And I'm not sure why the question 'Have any astronomers won the Nobel Prize?' is in the Galaxies and Universe section. On the whole though, it's all there — you just have to find it! — DEBRA HOLTON.

THESIS ABSTRACT

INTERACTION BETWEEN INTERSTELLAR MEDIUM AND BLACK-HOLE ENVIRONMENT

By Michal Zajaček

Studying the interaction between the interstellar medium and the black-hole environment on the parsec scale is of crucial importance to the full understanding of galaxy evolution. Since the Galactic Centre is the closest galactic nucleus, it offers us the unique possibility to study observationally the dynamics of individual stars as well as the properties of the Nuclear Star

Cluster as a whole.

This thesis deals with the transition region where the complex interstellar medium in the Galactic Centre meets a rather simple object at the very centre — most probably a black hole of 4×10^6 solar masses characterized by only three classical parameters: mass, spin, and electric charge. Recently, a NIR-excess object named DSO/G2 was detected that is moving on a highly eccentric orbit, with the pericentre reached in 2014 at ~2000 Schwarzschild radii. The monitoring, the analysis of NIR data, and the comparison with models have provided an unprecedented opportunity to constrain the properties of the previously unexplored region around Sgr A*, as well as to determine the nature of this enigmatic source.

In a series of papers, we explored the dynamics of different scenarios for DSO/G2, its interaction with the ambient medium close to the Galactic Centre, and the radiative properties of its NIR continuum emission. The main findings include the asymmetry of the stellar bow-shock evolution along the orbit when the outflow from the Galactic Centre is present. Subsequently, using polarimetry measurements and 3-D Monte Carlo radiative transfer, we were able to set up a model of a young star with a non-spherical dusty envelope that can explain its compactness and its NIR-excess as well as its linearly polarized emission. Finally, we explore a possibility that the DSO and objects with similar characteristics could be candidates for young neutron stars that should be observable in NIR bands with current and future facilities, which can help to resolve the 'missing pulsar paradox'.

Approaching the innermost region of the Galactic Centre, we explore the problem of an electric charge associated with Sgr A*, which is assumed to be zero in most studies. We found that a stable charge can be maintained by several mechanisms. One of the most promising is the charging due to the rotating black hole that is immersed in a uniform magnetic field. Realistic values of the charge that we calculated do not influence the space–time metric, but can significantly influence the dynamics of plasma in the vicinity of the Galactic Centre. Furthermore, we also propose a novel observational test for detecting the signature of the charge using a bremsstrahlung brightness distribution. — *University of Cologne; accepted 2017 October 12.*

Here and There

MAYBE SIZE DOESN'T MATTER

— reports the discovery of an apparent supernova … with his 0.3-cm f/6 Schmidt Cassegrain Telescope and … CCD camera … — *The Astronomer*, **54**, 33, 2017.

AND WE THOUGHT HE WAS FROM WEST TEXAS

This one was taken by Neil Armstrong of the Little West Crater. — *A&G*, **58**, 3.11, 2017.

ON-GOING OROGENY

… Mauna Kea, the summit of which is over 100 00m above sea level … — *Phys. World*, July 2017, p. 7.