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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2018 March 9 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 colleagues. Welcome to the Ordinary Meeting of the Royal Astronomical Society. We start with a few announcements. First of all, I think it was revealed at the last Open Meeting that there were two Fellows who had recieved awards in the last New Year's Honours list. They were not here then, but one of them is here today. I would like us to acknowledge Kathy Whaler, who is here somewhere. Kathy, would you stand up? [Applause.] I do not have the citation in front of me, but can you just remind us?

Professor Kathy Whaler. It was just 'For services to geophysics'.

The President. Wonderful. Thank you very much and many congratulations. Now we have some more winners. I hope many of you will have noticed in the library over tea that there were some posters from our inaugural RAS GCSE Poster Competition — sponsored by Winton. We had a good turnout for this competition. The three you saw were the winners selected by the panel. We have small prizes to give to the winners. I would like, in reverse order, to make the presentation. In third place we have Daniel Leboff of JFS school, with his poster, 'Transit photometry'. Would he come up, so I can present him with his certificate and book token. [Applause.] In second place we have Meg Savage of Farlington School, with her poster, 'Cosmic topology: The shape of the Universe'. [Applause.] The first-place winner is on his way here at the moment, and hopefully he will arrive during the meeting, so I will defer that presentation until he turns up. I hope that several of you managed to view the posters that were on display in the library. Congratulations to all the students who took part.

Next, I need to inform you of the AGM, the Annual General Meeting, of the Society. The 198th AGM will take place here at 16^{h} 00^{m} on Friday, 11th of May 2018. Associated with that we are fast approaching the time for us to produce the annual report, which we are required to do, and, of course, the accounts, which we will present at the AGM.

You will recall that we appoint two Fellows, who are not members of Council, to be Honorary Auditors, who are directed by the by-laws to deliver a personal report on the resources, goals, structures, activities, conduct, and general health of the Society, but not matters relating to finance, law, or personnel. They present this report to the AGM. This year, Dr. Katherine Joy and Dr. Geraint Jones have agreed to undertake this role, and they welcome any input from members of the Fellowship. If you have any comments, even if you have any praise for the Society or the Councils, or (I cannot imagine it) any criticism, please submit it to them. I think their names are on the website with their contact details. Contact any member of the RAS staff if you are not able to find their contact details.

We now move to the regular programme. We start with the RAS Norman Lockyer Research Fellowship (2014–2017) Lecture. It will be given by Dr. Rowan Smith, of the University of Manchester. The title is, 'Filaments and dark gas: The environment of star formation in spiral galaxies'.

Dr. Rowan Smith. The process of star formation is an engine that drives how galaxies evolve. When massive stars die the resulting supernova explosions transfer energy to the gas in the galaxy and support it against gravitational collapse. Conversely, the large-scale dynamics and structure of galaxies determine where the dense gas needed for star formation is formed. Galaxy evolution and star formation are intrinsically entwined processes that should therefore be studied together. In this talk I present galaxy-scale simulations, using the magnetohydrodynamical code AREPO, that study the properties of the dense, cold, gas clouds where stars are formed.

The simulations model the response of gas to a large-scale gravitational potential representing that of a four-armed spiral galaxy. A simple chemical model is included that allows us to predict where molecular hydrogen and CO molecules are formed. This is crucial because the cold, dense, molecular clouds where stars form mainly consist of molecular hydrogen (H_2 molecules). Unfortunately, at the temperature of molecular clouds (about 10 K) no H_2 emission lines can be excited. This means that the H_2 molecules are invisible to observers. Fortunately, in addition to H_2, molecular clouds also contain trace amounts of other molecules that do have emission lines at these low temperatures, such as CO, which is used as the main gas tracer.

A further challenge when studying the formation of these molecular clouds is the huge range of spatial scales that must be modelled. Galaxy discs have sizes of tens of kiloparsecs, molecular clouds have sizes of tens of parsecs, and the individual gas cores in the cloud where stars are formed have sizes of 0·1 parsec or smaller. To resolve these scales simultaneously we introduced a refinement scheme into AREPO, where in one section of the disc the resolution was smoothly increased until a mass resolution of four solar masses was reached. In the dense gas this is equivalent to a simulation cell radius of about 0·3 pc, and so the substructure of the molecular clouds is resolved. It is crucial to resolve molecular-cloud substructure on this scale in order to get the gas chemistry correct and make good predictions for observations. As a test of our resolution and gas-chemistry model we confirm that our model naturally reproduces the known Milky Way value of the X-factor, the ratio of CO emission to H_2 column density.

With all these ingredients in place we are in a position to study the morphology of cold molecular gas on the galaxy scale. Unsurprisingly, we find that the spiral arms are rich in H_2 and CO gas; however, outside the arms we also see that in the space between the arms the galaxy is also threaded by long filaments of molecular gas, as hinted at by recent observations. However, there was a surprise when comparing the H_2 and CO distribution. It was found that the long filamentary clouds seen in CO were actually just the tips of the iceberg of larger H_2 filaments that extended hundreds of parsecs and would be invisible to observers!

Such H_2 gas with no CO emission in observations is called "CO-dark gas" and has been known about for some time. However, our simulations have shown that the filamentary morphology of gas in spiral galaxies encourages the formation of CO-dark gas. This is because CO is dissociated by the interstellar radiation field, and it is easier for this radiation to penetrate through the short axis of a filament than if the gas were distributed as a sphere. Using our simulation we are able to discover all the CO-dark gas in our spiral-disc model and we find that roughly 42% (allowing us to cite Douglas Adams) of the molecular gas is CO-dark and consequently invisible to observers. That is a substantial fraction of the Milky Way gas budget, but it has implications beyond that. We find that the thermodynamical state of the CO-dark gas is slightly warmer (~ 100 K) than that typical in molecular clouds with CO emission; however, it is still much colder than the rest of the interstellar medium (at least 10 000 K). Colder gas is much more easily compressed during cloud collisions or during spiral-arm passages. The existence of this large reservoir of CO-dark gas therefore means that it is easier to form new, dense, star-forming clouds *via* these mechanisms than might otherwise be thought.

So far we have concentrated on the filamentary morphology of clouds as a whole; however, we find that even within clouds such structures persist. To study this we also carried out simulations of individual turbulent molecular clouds without the galactic context. In this case the velocity field in the cloud is chosen from an idealized field that matches observed turbulent scaling laws. At present the galaxy-scale forces are not included.

Within the molecular clouds we quickly see that a network of sub-filaments is formed in agreement with observations. It has been known for some time that filaments become unstable above a critical mass-to-length ratio. Consequently, star-forming cores form along the unstable sub-filaments like beads on strings. In our simulations we find that those filaments' properties are closely linked to the turbulent field and that massive-star-forming cores are preferentially formed at the junction of such networks. Massive stars are incredibly important for understanding the evolution of the interstellar medium in galaxies due to the feedback they provide in supernova explosions. These small-scale simulations demonstrate that to understand where such massive stars form you also need to understand the structure and turbulence in molecular clouds. This is something we are now seeking to investigate in our galaxy simulations.

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

Reverend G. Barber. Would this scale up to even larger scales? In galaxy formation you tend to get filaments in galaxy clusters, filaments of galaxies.

Dr. Smith. Actually a lot of the filament-identification tools which I am using were developed from that cosmological context. It is actually slightly different, because in the galaxy case you are dominated almost purely by gravity, so those are filaments due to gravitational collapse. In those cases, we find that a lot of the structures come from other forces. In the galaxy, we are often looking at shear. You have a blob, and as it rotates, the differential rotation stretches it out. Within the clouds, what you are really looking at is the internal turbulence. One of the things that is really exciting, which I did not have time to go into, is that I think you can maybe relate the formation of these filaments to the actual velocity fronts moving through the cloud. It might even tell you something about the turbulent cascade. In the cosmological case, it is nice and clean, because you have only got one force. Within the ISM, there are many different forces, which unfortunately will all give you filaments.

The President. For the observational data, I didn't catch which facilities that you use.

Dr. Smith. I am a pure theorist. I leave that to the experts. Do not let me near data.

The President. You mentioned *Herschel*, for example?

Dr. Smith. *Herschel* was revolutionary, in that for the first time you could really see the dust emission properly. And you were not always doing background subtraction, which tends just to highlight the cores. When people suddenly looked at these clouds with *Herschel*, it was a bit of a game-changer, because suddenly you could see all of the threads and filaments, which had previously been subtracted out. It was really, really exciting. For the galaxy surveys, you are looking at any large CO survey. Something that is very exciting is *ALMA*. It now means that in nearby galaxies, you can actually go down to 10 parsecs, so even better resolution, which means that we can start to try and do some of the kind of work we have done on the Milky Way in external galaxies. That should really help us understand star formation.

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

Our second speaker is presenting the RAS Norman Lockyer Research Fellowship 2014 talk [*sic**], and it is Dr. Kelig Aujogue from Birmingham University, and his title is, 'Little Earth experiment: A journey towards the Earth's tangent cylinder'.

Dr. K. Aujogue. [No summary of this talk had been received at the time of going to press.]

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

Dr. G. Q. G. Stanley. I was wondering what would happen during the magnetic-field reversals? Would you see the vortices disappear and then reform? Would you have any idea of the time-scales involved?

Dr. Aujogue. I believe that the time-scale is far too long to be reproduced in the experiment. A funny anecdote on that question relates to the access to the 10 Tesla magnet. You can only work at night, because otherwise you put down the grid of the city, so I ended up with my supervisor working at night very late on that question. One morning we thought why not crash down the field and crank it up again? Because, although we cannot reverse it, we could eventually see what happens by doing such things to it. Then we did some calculations, and although it was rather early in the morning, we ended up with the conclusion that the time-scale was really wrong for us. The experiment was absolutely not designed on that time-scale unfortunately, because that is one of the natural questions that we have. But I have no answer.

Dr. Stanley. So from what you are saying, it is a good job you did not do that, because the city would have crashed.

Dr. Aujogue. It is a good job I did not do that during the day.

Dr. Stanley. Something to look forward to!

Ms. Yaling Xie. How many cylinders?

Dr. Aujogue. Only one cylinder.

Ms. Xie. What is the diameter?

*It was actually the RAS Patricia Tomkins Thesis Prize 2016.

Dr. Aujogue. It would be the diameter of the Earth's core — the solid seed.

The President. The facility you describe that you used, you said the measurements are made on the surface?

Dr. Aujogue. Those are made within the liquid, because we have a laser plane that goes through the liquid, so we observe that laser plane.

The President. And that makes it unique?

Dr. Aujogue. Yes, because what was done so far was using surface measurements. Well, not even of that configuration, but that is the uniqueness. What has been done in previous experiments was not to introduce a magnetic field.

The President. Thank you very much indeed.

We have the prize winner of the GCSE Poster Competition, so we should make the presentation now. Could I ask the first-place winner to come up — Zachary Place of Marlborough College with his poster, 'The solar dynamo of active regions'. [Applause.]

We now turn to the Eddington Lecture; one of the most prestigious of the named lectures of the society. It will be given by Professor Karin Öberg of Harvard University. The title is: 'Chemistry of planet formation and planetary habitability'.

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

The President. Thank you so much. We have a few minutes for questions or comments.

Reverend G. Barber. What happens in binary stars? Do you get interactions between the two protoplanetary discs, and does that lead to more complex chemistry?

Professor Öberg. That is an excellent question. I cannot say anything about the chemistry, because we haven't looked at that, but I can make some educated guesses based on what we see on the structure or the disc. One of the discs here was around a binary, just a very tight binary. If it is a very tight binary, then we don't see any difference in the disc structure or in the disc chemistry, as far as we can tell. If it is a wide-separation one, hundreds of astronomical units, then you get two individual discs. Again the discs are a bit smaller, but otherwise they are structurally the same, so I would guess chemically they are very similar too. But the intermediate case is the tricky one, which will be very interesting to look into, when they are roughly 10 AU. What is very typical is that one of the stars loses their disc pretty early on, and sometimes you do have a circumbinary disc in addition to the circumplanetary disc. This circumbinary disc is interesting because it is very far away, so it is fairly cold, but you have a lot of space between the stars and the circumbinary ring, so it might be quite exposed to radiation. If there is any place where you see very distinct chemistry it would be in these circumbinary rings.

Mr. M. Hepburn. I would like to challenge the notion of the habitable zone. The Earth's twin, Venus, has a surface temperature more than double that of the Earth. Its temperature is controlled by its atmosphere, and this could apply anywhere. So I think the whole thing is a totally unsatisfactory invention in the past that has lived on into our time simply because people have repeated it.

Professor Öberg. I will happily challenge that challenge. When we talk about the habitable zone, it should not be seen as a guarantee to have the right temperature. The way people typically define a habitable zone is that there are plausible atmospheres that would give you the right temperature. That means that the habitable zone around stars is much wider compared to where you would typically find a habitable planet, so there's some likelihood function.

We don't know that much about early atmospheres around exoplanets that are Earth-like yet. Those data are going to come in and will help us narrow what it means. So, the atmospheres matter a lot, but as far as I know no one has come up with an atmosphere that would keep water liquid much beyond Mars, for example, or not keep from vaporizing if you are much inside of Venus. It sets some boundaries for further investigation, and I think that is all it should be taken as.

Dr. Smith. So we have these complex organics in the disc. Do you know how well they would survive the process of planet formation, like growth through planetesimals? And would you expect a difference if you had planets formed with direct gravitational collapse, compared to a gradual build-up?

Professor Öberg. Yes. That too is an excellent question. I am going to have to answer it in different stages, because there are many 'if's and 'but's in there. If you form a planetesimal, we are pretty certain that the chemistry will survive, as long as the planetesimal does not differentiate. In the case of comets, we think that there is a good portion of the observed chemistry that survived comet formation rather than formed in the comet. If you form something that starts to differentiate, you will lose most of your chemical memory, except for the elemental ratios, which depend on the chemistry, but you will lose the actual molecular structures. You will have too much chemistry happening in the planet, whether it is a gas giant or a terrestrial planet. Then there is the third case, which I think is the most interesting one: the Earth probably received a lot of its volatiles from impacts of water-rich asteroids or comet-like bodies (depending on how you define comets). During those impacts, a very interesting question is how much survives them. That is going to vary by molecule. We just did a study on the cyanides, because we were interested in those, and the cyanide bond is so strong that it survives a big comet impact. But an amino acid is not going to survive. It is going to depend on which molecule you are looking at.

The President. Let me ask you a question. It is probably a dumb one, but I will risk it. When you were talking about the ice experiments towards the end of your lecture, it struck me, but does gravity matter?

Professor Öberg. It is not a stupid question, but it does not. At the scales we are talking about we have very, very thin ices, where its molecular interactions are much stronger than gravity. We typically run our experiments with ice being built up vertically. Some people do it horizontally; people do it differently only because of experimental reasons not because of gravity. I love the questions I can answer.

Dr. P. Wheat. When you were doing the experiments with a thin layer of molecules on a substrate, how can you be sure that the substrate does not have any catalytic effect?

Professor Öberg. The answer is you cannot; you have to test it. We do that in different ways. In most of the experiments, we first build up a compact water ice that is about 20 molecules thick on top of our normal substrate, because that is more what we have in space anyway (water being the most common ice constituent). There are times when we want to do things directly on the substrate, and what we then typically do is isotopically label different layers and see if we get different chemistry in the layer that is closest to the substrate, compared to higher up. Sometimes it does matter. For example, when we UV irradiate an ice and we have a metal underneath, you will get electrons into the ice that can travel for a little bit. So it then becomes very important to isolate what you are interested in from the substrate.

The President. Final question.

A Fellow. I would expect the electrostatic environment would make a huge difference in terms of what forms, how it forms, and how fast. I may have missed it, but is there any magnetic impact? The local magnetic environment — does that make any difference to chemistry that goes on?

Professor Öberg. That too is an excellent question, for which I do not have a fully satisfactory answer. Let me explain the caveats. Obviously ions will couple to the magnetic field and neutrals will not, so you might get a partial separation of neutral and ion reactants if you are in the presence of strong fields. The mid-planes of discs, which is where planets are forming, are actually very weakly ionized, which is a different problem when it comes to how they actually accrete/move material around. So there it is not going to matter. If it is going to matter anywhere, it would be closer to a disc atmosphere, where you do have a high degree of ionization, which means a lot of the chemistry is driven by ionization. A part of that question is that we know that grains get charged as well. They do get pretty weakly charged though, so I wouldn't expect it to matter there, but I am not sure it can be completely ruled out. Let us say we have bigger issues to tackle first, but it is not something that can be completely ruled out.

The President. The hands of the clock are 180 degrees apart, which is a sign for us to finish. So can we thank the Eddington Lecturer for a tremendous talk. [Applause.]

Just before we finish, it occurred to me this afternoon that the three winners of the Poster Competition prizes are probably amongst the youngest attendees we have had at our meetings in recent times. I would like to issue them with a challenge. The challenge is that you should come back within the next fifteen years to present a talk up here like those you have heard. Maybe a PhD prize lecture? And if you do, any one of you three, please remind us you were here collecting the GCSE Poster prize. I hope some of us will still be here to hear you speak. [Laughter.]

Can I remind you that we have our normal drinks reception across the way. Please do come and join us (starting right now). And finally, I give notice that the next monthly Open Meeting of the Society will be on Friday 11th of May. That will include the AGM. There is no meeting next month in April, due to EWASS-NAM being held then rather than in the summer.

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 262: HD 15013, HD 16082, AND HD 16197

By R. F. Griffin
Cambridge Observatories

Orbits are presented for three stars that all have right ascensions near 2½^h and are at northern declinations. The radial velocities obtained for HD 15013, which has already been recognized as a very close visual double star with nearly equal components, show it to have a period of 2533 days (6·94 years), determined with a formal uncertainty of only 5 days; that period is close to one of two quite disparate values that have been proposed by others from measurements of the system as a 'visual' double star. HD 16082 has been known as a composite-spectrum binary for 100 years; the writer gave a preliminary orbit for the late-type component in 1990 but now offers one in which the uncertainty of the ~7-year orbital period is reduced by a factor of 25. HD 16197 has been largely ignored in the literature until now, when it is shown to have an orbit of moderate eccentricity and a period of about 3·3 years, with a γ-velocity of nearly +60 km s^{-1}.

HD 15013

HD 15013 is an 8^m star in Triangulum, very close to the mid-point between the naked-eye stars δ and 15 Tri*. The *V* magnitude and colour index of HD 15013 have been given by *Tycho 2* as 8^m·02 and 0^m·73 respectively, and its spectral type (G5 in the *HD*) is listed by *Simbad* as G5V. It was recognized as a very close 'visual' double star by *Hipparcos*, and was found to have changed its position angle when it was re-observed by Horch *et al.*[2] in 1997. It had, however, already featured as one of six 'new *Hipparcos* binaries' for which orbits were initially given in 1995 by Balega *et al.*[3], who found its orbital period to be 6·85±0·05 years. Subsequently, Hönig & Tscharnuter[4], who seemed not to be aware of the Balega *et al.* orbit, published an erroneous orbit with a period of 11·15 years. They admitted an ambiguity between periods of about 6 and 11 years, which arose from the relative temporal isolation of the *Hipparcos* observation of 1991, and having recognized and briefly discussed the difficulty they were a bit unfortunate in making the wrong choice between the possibilities.

The star was placed on the radial-velocity observing programme of the Cambridge *Coravel* in the summer of 2006. For the first year and a half the traces appeared to be single-lined and the velocity change was very small. The first observation of 2008, however, was recognizably a double-lined blend and yielded twin velocities that were about 10 km s^{-1} apart. During that year the velocity separation progressively increased, reaching a maximum of about 20 km s^{-1}. By 2015 the system had been observed round a complete orbital

**Norton's Star Atlas*[1] confusingly shows an unidentified and actually non-existent second- or third-magnitude star in that area. It seems possible that it is a mis-plotted duplicate of ζ Persei.

TABLE I

Radial-velocity observations of HD 15013

All the observations were made with the Cambridge Coravel

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
2006 July 25·12	53941·12	−0·4		0·657	–	–
Aug. 30·15	977·15	−0·2		·672	–	–
Sept. 30·14	54008·14	−0·3		·684	–	–
Oct. 27·02	035·02	−0·3		·695	–	–
Nov. 29·02	068·02	−0·7		·708	–	–
2007 Jan. 20·84	54120·84	−0·9		0·728	–	–
Mar. 3·83	162·83	−0·8		·745	–	–
Sept. 15·13	358·13	−0·6		·822	–	–
Oct. 14·05	387·05	−1·0		·834	–	–
Nov. 14·95	418·95	−0·7		·846	–	–
Dec. 10·99	444·99	−0·9		·856	–	–
2008 Jan. 24·84	54489·84	−6·1	+4·4	0·874	−0·6	+0·1
Feb. 26·80	522·80	−6·2	+4·7	·887	+0·1	−0·4
Sept. 20·11	729·11	−10·2	+9·4	·969	+0·1	+0·2
Oct. 11·08	750·08	−10·6	+9·3	·977	−0·2	−0·1
Nov. 22·00	792·00	−10·2	+9·4	·993	+0·4	−0·1
Dec. 30·83	830·83	−10·4	+9·4	1·009	0·0	0·0
2009 Jan. 29·84	54860·84	−10·4	+9·0	1·021	−0·3	0·0
Aug. 28·15	55071·15	−5·5	+4·2	·104	−0·1	0·0
Oct. 9·11	113·11	−4·1	+2·7	·120	+0·2	−0·3
Nov. 20·94	155·94	−2·9	+2·0	·137	+0·3	0·0
Dec. 22·88	187·88	−2·6	+1·8	·150	−0·1	+0·6
2010 Sept. 15·11	55454·11	+1·3	−3·1	1·255	−0·6	+0·3
Nov. 14·96	514·96	+2·8	−3·9	·279	+0·2	+0·1
2011 Jan. 18·87	55579·87	+3·1	−4·9	1·305	−0·1	−0·3
Sept. 13·14	817·14	+4·3	−6·2	·398	−0·1	−0·3
Nov. 10·95	875·95	+4·6	−5·8	·421	+0·1	+0·3
2012 Feb. 1·80	55958·80	+4·7	−6·4	1·454	0·0	−0·2
Sept. 4·14	56174·14	+4·3	−6·1	·539	−0·1	−0·1
Nov. 10·98	241·98	+4·4	−5·7	·566	+0·2	0·0
2013 Feb. 2·84	56325·84	+3·8	−5·9	1·599	−0·1	−0·5
Sept. 3·16	538·16	+2·1	−3·8	·683	−0·3	0·0
Oct. 16·04	581·04	+2·2	−3·1	·700	+0·2	+0·3
Dec. 27·83	653·83	+1·1	−2·1	·729	−0·1	+0·5
2014 Sept. 8·16	56908·16	−2·9	+1·7	1·829	0·0	0·0
Oct. 10·11	940·11	−3·1	+2·6	·842	+0·5	+0·2
28·02	958·02	−3·7	+3·1	·849	+0·3	+0·3
2015 Jan. 28·84	57050·84	−6·2	+4·6	1·885	−0·1	−0·4
Oct. 10·11	305·11	−10·7	+9·5	·986	−0·2	0·0
2016 Feb. 3·78	57421·78	−9·7	+8·7	2·032	0·0	+0·1
Nov. 25·93	717·93	−2·3	+1·0	·149	+0·3	−0·3

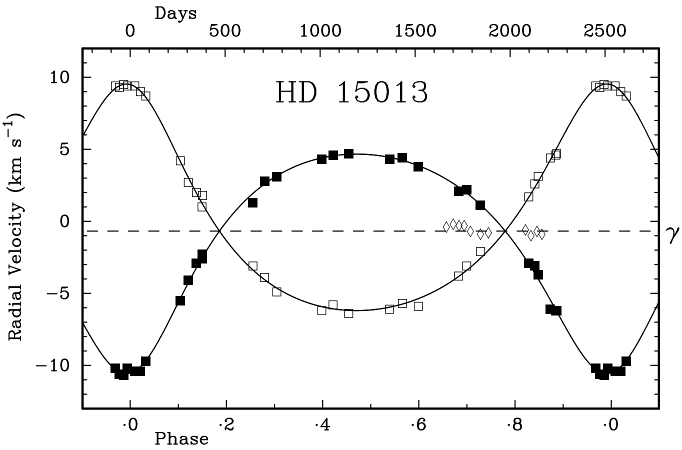

FIG. 1

The observed radial velocities of HD 15013 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations were made with the Cambridge *Coravel.* The filled symbols represent measurements of the primary star, open ones those of the secondary. Open diamonds plot measurements that were reduced as if the object were single-lined; they were not taken into account in the derivation of the orbit.

cycle; the 41 observed radial velocities (of which all except the first 11, obtained in 2006/7, have been reduced as double-lined) are set out in Table I and lead to an orbit, plotted in Fig. 1, which has a period of 6·94 years with an uncertainty of only 5 days*. In the calculation of the orbit, the velocities of the secondary star have been attributed a weighting of 0·8 in comparison with the primary. The complete elements are shown in the informal table here:

P	$= 2533 \pm 5$ days	T_1	$=$ MJD 54809 ± 9
γ	$= -0{\cdot}68 \pm 0{\cdot}04$ km s^{-1}	$a_1 \sin i$	$= 252{\cdot}9 \pm 2{\cdot}3$ Gm
K_1	$= 7{\cdot}61 \pm 0{\cdot}06$ km s^{-1}	$a_2 \sin i$	$= 261{\cdot}3 \pm 2{\cdot}5$ Gm
K_2	$= 7{\cdot}86 \pm 0{\cdot}07$ km s^{-1}	$f(m_1)$	$= 0{\cdot}1007 \pm 0{\cdot}0026\ M_\odot$
q	$= 1{\cdot}033 \pm 0{\cdot}005$ $(= m_1/m_2)$	$f(m_2)$	$= 0{\cdot}111 \pm 0{\cdot}003\ M_\odot$
e	$= 0{\cdot}300 \pm 0{\cdot}005$	$m_1 \sin^3 i$	$= 0{\cdot}430 \pm 0{\cdot}010\ M_\odot$
ω	$= 163{\cdot}0 \pm 2{\cdot}0$ degrees	$m_2 \sin^3 i$	$= 0{\cdot}416 \pm 0{\cdot}009\ M_\odot$

R.m.s residual (unit weight) $= 0{\cdot}25$ km s^{-1}

The very small standard error listed for the γ-velocity in the table above is only an internally determined one; no doubt the real (external) uncertainty is much larger. The same *caveat* applies to all seemingly unfeasibly small errors attributed to γ-velocities in this series of papers; the writer apologizes for not having excused them so explicitly every time the situation has arisen.

*Some of the other elements published by Balega *et al.*[3], notably ω, do not agree nearly so well with ours.

Since the actual masses of the two stars that constitute HD 15013 can be expected from their near-equality and joint spectral type to be nearly one solar mass each, the $m \sin^3 i$ values listed above can be viewed as indicating that $\sin^3 i$ must be close to 0·45, thus offering a rather accurate estimate of the orbital inclination as $\arcsin(\sqrt[3]{0{\cdot}45})$, which is 50°·0, in almost embarrassingly exact agreement with the astrometric value[3] of $50{\cdot}0 \pm 0{\cdot}9$ degrees.

HD 16082

HD 16082 is the late-type component of a system whose spectroscopically composite nature was evident more than a hundred years ago to Miss Cannon[5], who designated the star not only as HD number 16082, with spectrum G5, but also as 16083, A5. The system is to be found in Perseus, south-following by about 3° and 4½°, respectively, the remarkable eclipsing composite-spectrum systems τ Per[6] and γ Per[7].

The radial velocity of HD 16082 was measured three times at Mount Wilson in the 1920s, with the results first being published[8] as a mean value and long afterwards individually[9]. Those measurements appear at the head of Table II but have been zero-weighted in the solution of the orbit; the first one seems likely to be a measure of the A-type component whereas the others would pass for velocities of the late-type one.

The present writer put the star on the observing programme of the original radial-velocity spectrometer[10] at Cambridge 40 years ago, and has watched it almost ever since, accumulating a series of 145 measurements which are set out in Table II. About half of the writer's observations obtained in 1986–91, and most of those in 1992–98 (27 in total), were made with the Haute-Provence *Coravel* on a guest-investigator basis through the kindness of Dr. Mayor, who also communicated a comparable number of *Coravel* observations (32) that had been obtained previously by others with the same instrument and have been added to Table II. The last 61 Cambridge measures were made by the writer with the *Coravel*-type spectrometer that replaced the original one. A preliminary orbit was published[11] in 1990 on the basis of the first 56 radial velocities, but the data were not listed and the discussion was limited to just four lines of text. That text very succinctly addressed two points. One was that the large mass function showed that either the primary star is a supergiant (as was soon afterwards shown to be the case: it was classified as K0 II by Ginestet *et al.*[12]) or else the secondary must itself be double. The other point was that a conjunction, when an eclipse might occur, was to be expected in 1994; unfortunately the predicted date was in May or June, when nights in Cambridge are very short and the star scarcely accessible to the writer's telescope. Two subsequent opportunities, at less unfavourable seasons, were missed because the writer regrettably failed to remember the issue at the relevant times.

HD 16082, at 7th magnitude, is quite bright, and its declination is such that it passes within a few minutes of arc of the Cambridge zenith. It must have been those agreeable characteristics that encouraged the writer to make the unusually generous number of radial velocities that are listed here in Table II, though the fact that the star has been followed for well over three circuits of its 11-year orbit has also been a factor. The orbit derived from the velocities is illustrated in Fig. 2 and its elements are presented in the informal table on p. 200. If any irregularity is seen in the writer's thus taking a second bite at a cherry that he already tasted[11] 28 years ago, it might seem less reprehensible when a comparison with the new set of elements shows that the uncertainty of the period, for example, is now improved by a factor of about 25.

TABLE II

Radial-velocity observations of HD 16082

Date (UT)	*MJD*	*Velocity* *km s^{-1}*	*Phase*	*(O – C)* *km s^{-1}*
1920 Nov. 1·30*	22629·30	−13·2	$\bar{5}$·093	−23·7
1926 Sept. 29·44*	24787·44	−15·6	$\bar{5}$·644	+3·0
Oct. 28·35*	816·35	−16·7	·651	+2·2
1978 Sept. 23·10†	43774·10	−10·6	0·494	+0·6
1979 Sept. 28·92†	44144·92	−15·7	0·589	+0·5
Dec. 3·91†	210·91	−18·0	·605	−1·0
30·93†	237·93	−16·4	·612	+0·9
1980 Feb. 13·78§	44282·78	−18·1	0·624	−0·3
Aug. 27·08†	478·08	−21·9	·674	−2·2
Sept. 25·05†	507·05	−18·9	·681	+1·0
Oct. 10·05†	522·05	−20·3	·685	−0·3
Nov. 14·95§	557·95	−19·9	·694	+0·4
Dec. 7·93†	580·93	−20·0	·700	+0·4
1981 Jan. 30·75†	44634·75	−19·8	0·714	+0·9
Aug. 17·10†	833·10	−20·8	·764	+0·5
Sept. 15·12§	862·12	−21·3	·772	−0·1
16·13§	863·13	−20·9	·772	+0·3
19·04†	866·04	−21·1	·773	+0·1
23·00†	870·00	−21·0	·774	+0·2
Oct. 13·04†	890·04	−21·8	·779	−0·6
14·02§	891·02	−21·2	·779	0·0
Dec. 12·88†	950·88	−22·0	·794	−1·0
1982 Jan. 7·84§	44976·84	−20·1	0·801	+0·8
18·78†	987·78	−22·2	·804	−1·4
Mar. 5·82†	45033·82	−22·1	·816	−1·6
Aug. 25·13§	206·13	−18·5	·860	−0·4
Sept. 24·09†	236·09	−17·4	·867	+0·1
Nov. 26·15¶	299·15	−16·6	·883	−0·5
1983 Jan. 5·82§	45339·82	−14·0	0·894	+1·0
8·81§	342·81	−14·3	·895	+0·6
13·79†	347·79	−15·8	·896	−1·0
Sept. 18·12§	595·12	−5·4	·959	+0·3
20·11†	597·11	−4·9	·959	+0·7
21·08§	598·08	−5·6	·960	−0·1
Oct. 16·22¶	623·22	−5·7	·966	−1·3
Nov. 20·99†	658·99	−3·8	·975	−0·9
Dec. 26·85†	694·85	−0·4	·984	+0·9
1984 Jan. 17·85†	45716·85	−2·0	0·990	−1·6
Feb. 8·79†	738·79	+0·6	·996	+0·1
Sept. 2·01†	945·01	+7·6	1·048	0·0
Oct. 21·03†	994·03	+6·3	·061	−2·5
Nov. 4·04§	46008·04	+9·8	·064	+0·8
11·82§	015·82	+9·7	·066	+0·5
Dec. 3·20¶	037·20	+10·0	·072	+0·4
1985 Jan. 22·77†	46087·77	+10·4	1·085	+0·2
Mar. 19·81†	143·81	+10·4	·099	−0·3
Aug. 19·12§	296·12	+10·3	·138	−0·4
26·10§	303·10	+10·6	·140	−0·1

TABLE II (*continued*)

Date (UT)			MJD	Velocity km s^{-1}	Phase	(O – C) km s^{-1}
1985	Sept.	25·08§	46333·08	+10·6	1·147	+0·1
		27·01†	335·01	+8·8	·148	−1·7
	Oct.	20·03†	358·03	+9·7	·154	−0·6
	Nov.	11·96†	380·96	+9·9	·160	−0·2
1986	Jan.	25·81†	46455·81	+8·9	1·179	−0·3
	Feb.	13·81†	474·81	+9·1	·184	+0·1
		25·80§	486·80	+8·8	·187	−0·1
	Mar.	6·87†	495·87	+9·8	·189	+1·1
	Aug.	29·14§§	671·14	+6·6	·234	+0·6
	Sept.	19·12†	692·12	+4·4	·239	−1·3
	Oct.	12·05§	715·05	+6·0	·245	+0·7
		17·04†	720·04	+5·1	·246	−0·1
		18·02§	721·02	+5·5	·247	+0·3
	Nov.	11·98†	745·98	+6·2	·253	+1·4
1987	Jan.	3·82†	46798·82	+4·7	1·266	+0·9
	Feb.	28·79§§	854·79	+3·4	·281	+0·5
	Oct.	17·17§§	47085·17	−0·7	·340	+0·6
		29·96§	097·96	−0·8	·343	+0·7
	Nov.	1·07§	100·07	−1·6	·343	−0·1
		1·94§	100·94	−1·2	·344	+0·3
	Dec.	31·92†	160·92	−4·5	·359	−1·9
1988	Jan.	24·32‖	47184·32	−3·4	1·365	−0·4
	Mar.	11·78§§	231·78	−4·0	·377	−0·2
	July	25·10†	367·10	−5·9	·412	+0·2
	Oct.	25·95§	459·95	−7·0	·435	+0·6
		29·98§	463·98	−7·6	·436	+0·1
	Nov.	3·07§§	468·07	−7·9	·437	−0·1
	Dec.	12·89†	507·89	−7·9	·448	+0·5
1989	Jan.	12·81†	47538·81	−8·3	1·455	+0·6
	Mar.	14·79§	599·79	−10·3	·471	−0·4
		21·80§	606·80	−9·0	·473	+1·0
		24·81§§	609·81	−9·6	·474	+0·4
	Sept.	7·14†	776·14	−13·4	·516	−0·9
	Oct.	17·04†	816·04	−14·5	·526	−1·5
	Nov.	16·97†	846·97	−12·4	·534	+1·1
	Dec.	7·93§	867·93	−14·0	·540	−0·2
		13·92§	873·92	−13·7	·541	+0·1
		22·84†	882·84	−13·6	·543	+0·4
1990	Jan.	30·89§§	47921·89	−13·9	1·553	+0·6
	Aug.	28·14§	48131·14	−17·2	·607	−0·1
	Sept.	2·08§	136·08	−17·4	·608	−0·3
	Oct.	13·07†	177·07	−18·3	·619	−0·7
	Dec.	5·91†	230·91	−18·7	·632	−0·5
1991	Jan.	4·88§	48260·88	−17·6	1·640	+0·9
		9·81§	265·81	−18·7	·641	−0·2
	Feb.	3·84§§	290·84	−18·0	·648	+0·8
	Oct.	29·99§§	558·99	−21·2	·716	−0·4
	Dec.	17·88§§	607·88	−20·3	·729	+0·7
1992	Jan.	17·80§§	48638·80	−21·0	1·736	+0·1
	Mar.	3·12‖	684·12	−21·7	·748	−0·5
	Aug.	14·09§§	848·09	−21·3	·790	−0·2

TABLE II (*continued*)

Date (UT)		MJD	Velocity km s⁻¹	Phase	(O–C) km s⁻¹
1992	Oct. 27·98†	48922·98	−21·4	1·809	−0·7
	Nov. 11·99†	937·99	−20·3	·813	+0·2
	Dec. 21·95§§	977·95	−20·5	·823	−0·3
1993	Feb. 15·80§§	49033·80	−18·7	1·837	+0·8
	Mar. 18·78§§	064·78	−19·0	·845	+0·1
	July 12·11§§	180·11	−17·2	·875	−0·3
	Sept. 13·99§§	243·99	−16·1	·891	−0·8
	Dec. 25·90§§	346·90	−11·2	·917	+0·9
1994	Jan. 7·83§§	49359·83	−11·2	1·921	+0·4
	Feb. 19·85§§	402·85	−8·7	·932	+1·3
	Aug. 3·10§§	567·10	−3·6	·974	−0·4
	Dec. 12·85§§	698·85	+2·8	2·007	+0·5
1995	Jan. 3·83§§	49720·83	+4·2	2·013	+1·0
	Dec. 21·84§§	50072·84	+9·7	·103	−1·1
1996	Apr. 2·80§	50175·80	+11·0	2·129	+0·2
	Nov. 18·91‡	405·91	+8·5	·188	−0·3
1997	Jan. 25·81§§	50473·81	+7·8	2·205	0·0
	Mar. 6·81‡	513·81	+8·0	·215	+0·8
	July 20·10§§	649·10	+5·4	·250	+0·4
	Sept. 10·04§§	701·04	+3·6	·263	−0·5
	Dec. 21·86§§	803·86	+2·1	·290	−0·1
1998	July 12·12§§	51006·12	−1·0	2·341	+0·4
1999	Dec. 28·89	51540·89	−10·5	2·478	−0·2
2000	Feb. 21·76	51595·76	−10·6	2·492	+0·5
	Aug. 2·13	758·13	−13·5	·533	−0·1
	Oct. 6·08	823·08	−14·5	·550	−0·2
	Dec. 2·04	880·04	−15·2	·564	−0·2
2001	Feb. 6·92	51946·92	−15·6	2·581	+0·3
	Aug. 25·14	52146·14	−18·6	·632	−0·4
	Oct. 19·04	201·04	−19·4	·646	−0·7
	Dec. 21·96	264·96	−19·1	·663	+0·2
2002	Feb. 14·82	52319·82	−19·2	2·677	+0·6
	Aug. 29·16	515·16	−20·7	·727	+0·3
	Oct. 24·04	571·04	−21·0	·741	+0·1
2003	Jan. 7·05	52646·05	−21·0	2·760	+0·3
	Mar. 15·85	713·85	−21·2	·777	0·0
	Aug. 15·13	866·13	−20·6	·816	−0·2
	Oct. 18·04	930·04	−20·2	·833	−0·4
	Dec. 11·99	984·99	−19·1	·847	−0·1
2004	Mar. 1·86	53065·86	−17·6	2·867	−0·1
	Sept. 2·13	250·13	−12·3	·914	+0·2
	Nov. 14·02	323·02	−9·6	·933	+0·2
	Dec. 17·90	356·90	−8·4	·942	+0·1
2005	Jan. 22·00	53392·00	−7·5	2·951	−0·5
	Feb. 8·81	409·81	−6·3	·955	0·0
	Mar. 18·81	447·81	−4·7	·965	0·0
	Aug. 22·07	604·07	+2·3	3·005	+0·3

TABLE II (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2005 Sept. 17·12	53630·12	+3·2	3·011	+0·2
Nov. 5·07	679·07	+4·7	·024	−0·1
Dec. 10·89	714·89	+6·2	·033	+0·3
2006 Jan. 4·86	53739·86	+6·9	3·039	+0·2
Feb. 9·84	775·84	+7·5	·049	−0·2
Mar. 3·79	797·79	+8·0	·054	−0·2
July 25·11	941·11	+10·7	·091	+0·2
Aug. 30·16	977·16	+10·6	·100	−0·1
Sept. 21·13	999·13	+11·0	·106	+0·2
Oct. 27·02	54035·02	+11·0	·115	+0·1
Nov. 24·04	063·04	+10·5	·122	−0·4
Dec. 16·93	085·93	+10·9	·128	0·0
2007 Apr. 1·81	54191·81	+10·3	3·155	+0·1
Aug. 31·12	343·12	+8·0	·194	−0·5
Oct. 5·07	378·07	+7·4	·203	−0·6
Dec. 10·98	444·98	+7·4	·220	+0·4
2008 Nov. 25·99	54795·99	+0·8	3·309	−0·1
2009 Jan. 18·93	54849·93	−0·4	3·323	−0·3
Oct. 23·22	55127·22	−5·6	·394	−0·6
2010 Jan. 1·92	55197·92	−6·5	3·412	−0·4
Sept. 15·12	454·12	−10·8	·477	−0·6
2011 Jan. 31·83	55592·83	−12·8	3·513	−0·5
Sept. 14·13	818·13	−15·0	·570	+0·3
Nov. 27·93	892·93	−16·6	·589	−0·3
2012 Sept. 19·12	56189·12	−19·5	3·665	−0·1
Dec. 4·92	265·92	−19·7	·685	+0·3
2013 Feb. 19·85	56342·85	−20·6	3·704	−0·1
Sept. 5·16	540·16	−21·2	·755	0·0
2014 Nov. 1·03	56962·03	−18·3	3·863	−0·4
Dec. 13·88	57004·88	−17·2	·874	−0·2
2016 Jan. 15·83	57402·83	−3·2	3·975	−0·3
25·91	412·91	−2·7	·978	−0·2
Feb. 23·82	441·82	−1·7	·985	−0·5
Nov. 25·94	717·94	+8·2	4·056	−0·1

* Mount Wilson observation[8,9]; zero-weighted in orbit
† Observed with original Cambridge spectrometer; wt. ¼
‡ Cambridge *Coravel* in preliminary form; wt. 1
§ OHP *Coravel*, observed by others; wt. 1
§§ Observed with OHP *Coravel*; wt. 1
¶ Observed with 200-inch telescope; wt. 1
|| Observed at DAO; wt. 1
Unattributed 1999–2016: Cambridge *Coravel*; wt. 2

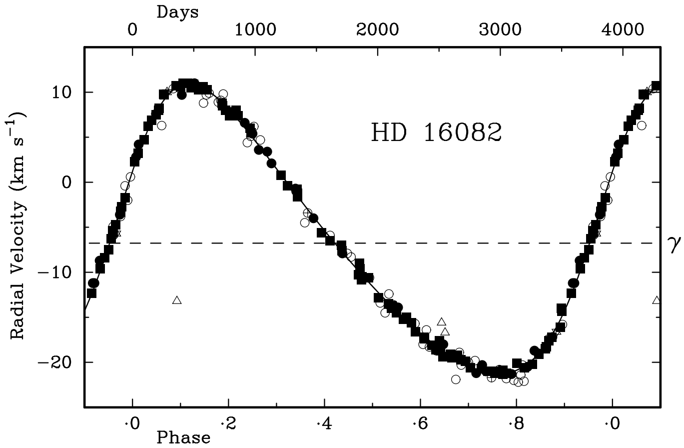

FIG. 2

The observed radial velocities of HD 16082 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The most reliable series of radial velocities is the one stemming from the Cambridge *Coravel* — 61 measurements, given double weight in the solution of the orbit and plotted with filled squares. Other series, attributed unit weight, are 27 obtained by the writer with the Haute-Provence *Coravel* (filled circles) and 32 made by others with the same instrument and kindly forwarded by Dr. S. Udry; also three obtained by the writer with the Palomar spectrometer (open stars, difficult to identify in the diagram) and two with the instrument at the DAO 48-inch telescope (circles with crosses in them). Small open circles plot the 49 measurements made with the original spectrometer in Cambridge and given weight ¼. Three velocities measured at the Mount Wilson Observatory nearly a hundred years ago are plotted as open triangles; one of them is conspicuously 'wild', so all three have been zero-weighted in the solution of the orbit.

P	$= 3914{\cdot}8 \pm 1{\cdot}8$ days	$(T)_2$	$=$ MJD 49670 ± 7
γ	$= -6{\cdot}77 \pm 0{\cdot}04$ km s^{-1}	$a_1 \sin i$	$= 839 \pm 3$ Gm
K	$= 16{\cdot}09 \pm 0{\cdot}05$ km s^{-1}	$f(m)$	$= 1{\cdot}538 \pm 0{\cdot}015\ M_\odot$
e	$= 0{\cdot}250 \pm 0{\cdot}003$		
ω	$= 293{\cdot}4 \pm 0{\cdot}8$ degrees	R.m.s. residual (wt. 1)	$= 0{\cdot}50$ km s^{-1}

HD 16197

This star, whose magnitudes are given by *Simbad* as $V = 8^{m}{\cdot}71$, $(B - V) = 1^{m}{\cdot}19$, spectral type K0, is to be found in the easternmost of the three north-preceding corners of Aries. It is about 2° following and slightly north of the 6^{m} star 13 Tri — in fact not far from the position plotted by *Norton*[1] for the non-existent bright star mentioned in the footnote in the section on HD 15013 above. *Simbad* lists only three references for HD 16197, all of them entries in large catalogues rather than individual observations of the star. Its radial velocity was first measured at Cambridge in 2002. A second measurement after a delay of more than two years disagreed; that led to a somewhat systematic observing campaign that has resulted in a total of 44 observations, which are set out in Table III and readily lead to an orbit whose elements are shown on p. 202.

Table III

Radial-velocity observations of HD 16197

All the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2002 Sept. 30·14	52547·14	+58·0	0·397	+0·1
2005 Jan. 14·83	53384·83	63·2	1·087	+0·1
Dec. 17·91	721·91	58·2	·364	0·0
2006 Oct. 3·12	54011·12	56·8	1·603	−0·2
Nov. 1·03	040·03	56·8	·626	−0·2
Dec. 2·94	071·94	57·5	·653	+0·4
2007 Jan. 1·93	54101·93	57·4	1·677	+0·2
Feb. 6·80	137·80	57·4	·707	+0·1
Sept. 8·14	351·14	60·1	·882	−0·2
Oct. 14·05	387·05	61·4	·912	+0·2
Nov. 11·97	415·97	61·7	·936	−0·2
Dec. 7·96	441·96	62·2	·957	−0·3
2008 Jan. 7·89	54472·89	63·5	1·983	+0·4
Feb. 12·82	508·82	63·8	2·012	+0·3
Sept. 20·13	729·13	60·8	·194	−0·1
Oct. 22·08	761·08	60·4	·220	0·0
Nov. 22·00	792·00	59·9	·245	0·0
Dec. 30·85	830·85	59·8	·277	+0·4
2009 Jan. 29·86	54860·86	59·0	2·302	0·0
Aug. 30·14	55073·14	57·4	·477	+0·1
Oct. 9·12	113·12	57·2	·510	0·0
Nov. 24·04	159·04	56·8	·547	−0·2
Dec. 22·91	187·91	57·0	·571	0·0
2010 Aug. 11·13	55419·13	57·7	2·762	−0·2
Sept. 15·12	454·12	58·0	·790	−0·3
Nov. 14·95	514·95	59·1	·840	−0·1
Dec. 18·96	548·96	60·3	·868	+0·4
2011 Jan. 28·82	55589·82	61·1	2·902	+0·2
Sept. 13·15	817·15	62·7	3·089	−0·4
Nov. 18·02	883·02	61·9	·143	−0·1
Dec. 14·93	909·93	61·4	·166	−0·1
2012 Feb. 1·81	55958·81	60·7	3·206	0·0
Nov. 6·10	56237·10	57·3	·435	−0·3
2013 Oct. 7·07	56572·07	57·3	3·711	−0·1
Nov. 13·01	609·01	57·7	·741	+0·1
2014 Jan. 27·78	56684·78	58·4	3·803	−0·1
Feb. 11·86	699·86	58·6	·816	−0·1
Sept. 8·18	908·18	63·0	·987	−0·2
Nov. 2·99	963·99	63·3	4·033	−0·3
Dec. 13·88	57004·88	63·7	·067	+0·3
2015 Feb. 17·80	57070·80	62·7	4·121	+0·2
Nov. 25·97	351·97	58·2	·353	−0·2
2016 Feb. 18·76	57436·76	57·6	4·422	−0·1
Nov. 25·94	717·94	+57·5	·654	+0·4

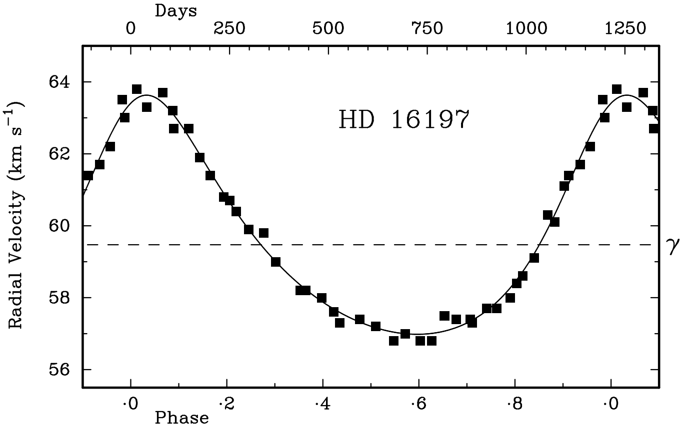

FIG. 3

The observed radial velocities of HD 16197 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations were made with the Cambridge *Coravel*.

P	$= 1214{\cdot}8 \pm 3{\cdot}4$ days	$(T)_3$	$=$ MJD 55709 ± 10
γ	$= +59{\cdot}47 \pm 0{\cdot}04$ km s^{-1}	$a_1 \sin i$	$= 53{\cdot}5 \pm 0{\cdot}9$ Gm
K	$= 3{\cdot}32 \pm 0{\cdot}06$ km s^{-1}	$f(m)$	$= 0{\cdot}00414 \pm 0{\cdot}00022\ M_\odot$
e	$= 0{\cdot}269 \pm 0{\cdot}015$		
ω	$= 339 \pm 3$ degrees	R.m.s. residual (wt. 1)	$= 0{\cdot}22$ km s^{-1}

The smallness of the mass function indicates that the companion star (which is not detected in the radial-velocity traces) is likely to be relatively faint, and/or that the orbit is seen nearly 'face-on'.

References

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THE IMPACT OF WORLD WAR I ON RELATIVITY PART III — THE AFTERMATH

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Neither the world nor science came to an end when the gunfire stopped on 1918 November 11 (close to 11 a.m. in some time zone), but neither would ever be the same again. Part I of this inquiry (**138**, 46, 2018) looked at the development of General Relativity under the rubric of Gerald Holton's "Only Einstein; only there; only then". Part II (**138**, 98, 2018) addressed the activities, relativistic, classical, and otherwise, of many (mostly) physicists who were interacting with Einstein, working on relativistic gravity, or, sometimes, against it, and leaving tracks that can still be followed. Part III considers some of what happened to Einstein, his theory of gravity, and related science after the war and, perhaps, because of it. A subset of the items will probably be familiar — the 1919 eclipse expedition and the founding of the International Astronomical Union the same year; Einstein's 1921 Nobel Prize (for the discovery of the law of the photoelectric effect). Others perhaps less so, including a flood of books about GR (pro and con) with the end of paper rationing surely playing a role; AE's 1922 trip to Paris, and the gory details, swings and roundabouts of gravitational radiation/waves and the cosmological constant. It is left as an exercise for the reader to decide which items are primarily scientific and which primarily political. The long-range issues of 'is General Relativity the right theory of gravity?' and 'do we have better wars?' come at the end. And I am going to start in a slightly improbable place.

Introduction

In the summer of 1921, a 26-year old, newly minted MD travelled by train from Moscow to Berlin, getting hung up briefly at the Lithuanian border. In Berlin, he conceived the idea of a peace-promoting project of publishing, in both the original languages and in Hebrew, two volumes of recent significant papers by European Jewish authors, one eventually devoted to Orientalia and Judaica, the other to Mathematics and Physics. This second volume of the *Scripta Universitates Atque Bibliotecae Hierosolymitarum* was partially edited by Albert Einstein; included the Einstein and Grommer 1922 paper[1]; and, as the rapidly-aging young man later explained, had been rather difficult to assemble, because many French savants did not care to be involved in a project in which there would also be German participants. There was, in fact, only one French chapter, by Hadamard (of the transform). Others came from Tullio Levi-Civita, Theodor von Karman, H. Bohr (not Niels, but his brother, a mathematician), S. Brodetzky (uncle of the late Leon Mestel), a Landau (not Lev) at Göttingen, a hyphenated Popper (not Daniel Magnes) at Vienna, a somewhat mysterious Loewy of Frankfurt (later metamorphed into Cornelius Lanczos of Dublin), and several others whose names I did not recognize.

The young man's father paid for the publications, out of rapidly-declining resources, and they thereby played a role in the establishment of the Hebrew University in Jerusalem, Einstein's visit to which you met in Part I, because the volumes could be exchanged (in what was then a common custom) for volumes published by other universities, giving the library a start.

The polymathic MD, who later practised as a psychiatrist, emigrated to the Palestinian Mandate in 1933 and to the US in 1939. From 1946 to 1955, he again interacted sporadically with Einstein in Princeton. Near the end of this period, he gave AE the first half of what would become his best-known and most contentious publication. Some of the more objectionable passages, to which AE took exception, were thereby removed before the volume in question saw light of print, though it was still sufficiently contrary to the known laws of physics to engage a distinguished Harvard astronomer in violent opposition, and to force a change of publishers to Macmillan, which had few technical books on its books and so could afford to annoy the scientific community. The Harvard pundit required a younger female colleague to provide a review of the book which was also very negative. Extensive correspondence between the polymath and Einstein, to which the latter eventually called a halt, was left in a disordered heap at the Institute for Advanced Study, Princeton, and had to be sorted out before depositing in the Einstein archives in Jerusalem. The 'out-sorter' has described the process as one of the vexations of science[1a].

If you haven't yet guessed that the pundit was Harlow Shapley and the younger colleague Cecilia Payne (Gaposchkin), please go to ref. 2 to identify the Einstein-mentored author. It was the 'Venus' section that Einstein had seen. I read the author's later volumes, *Ages in Chaos* and *Oedipus and Ahkenaten*, when they were new, but you are probably too young even to have heard of them.

Surprisingly at least to me, in his last, 1955 April, interview with I. Bernard Cohen, two weeks before his death, Einstein chose to address Velikovsky and *Worlds in Collision* (neither by name). He said that both book and person were "crazy" but not "bad," and regretted that the American scientific community had tried to prevent publication of the book.

I have not found a rational order in which to present the pieces of the 'aftermath' and so have grouped them under cutesy-poo section headings. Fig. 1 is the same one that appeared in Part I, with focus now shifted to the outcomes.

Fortune, films, and flood on folios

Actually the fortunes involved were very modest. As the war ended, the shortage of money and food mentioned in a number of the letters[3] did not immediately end. The Allies maintained their blockade and were slow in fulfilling a promise to prevent starvation (Doc. 664, 665, and notes thereto, early 1918 December). Einstein of course won the 1921 Nobel Prize in Physics (for "discovering the law of the photoelectric effect") given in 1922, but the money went to his divorced first wife as he had promised as far back as 1918 June (Doc. 562). Perhaps worth noting are that she would have control only over the interest, not the capital; that in case of her death or remarriage, the full sum would go to their sons; and that AE expected the Prize to be more than 40 000 German marks.

Luckily the prize was in Swedish krona, since the German mark went through dire inflation in the early 1920s, saved by Hjalmar Horace Greeley Schacht. You

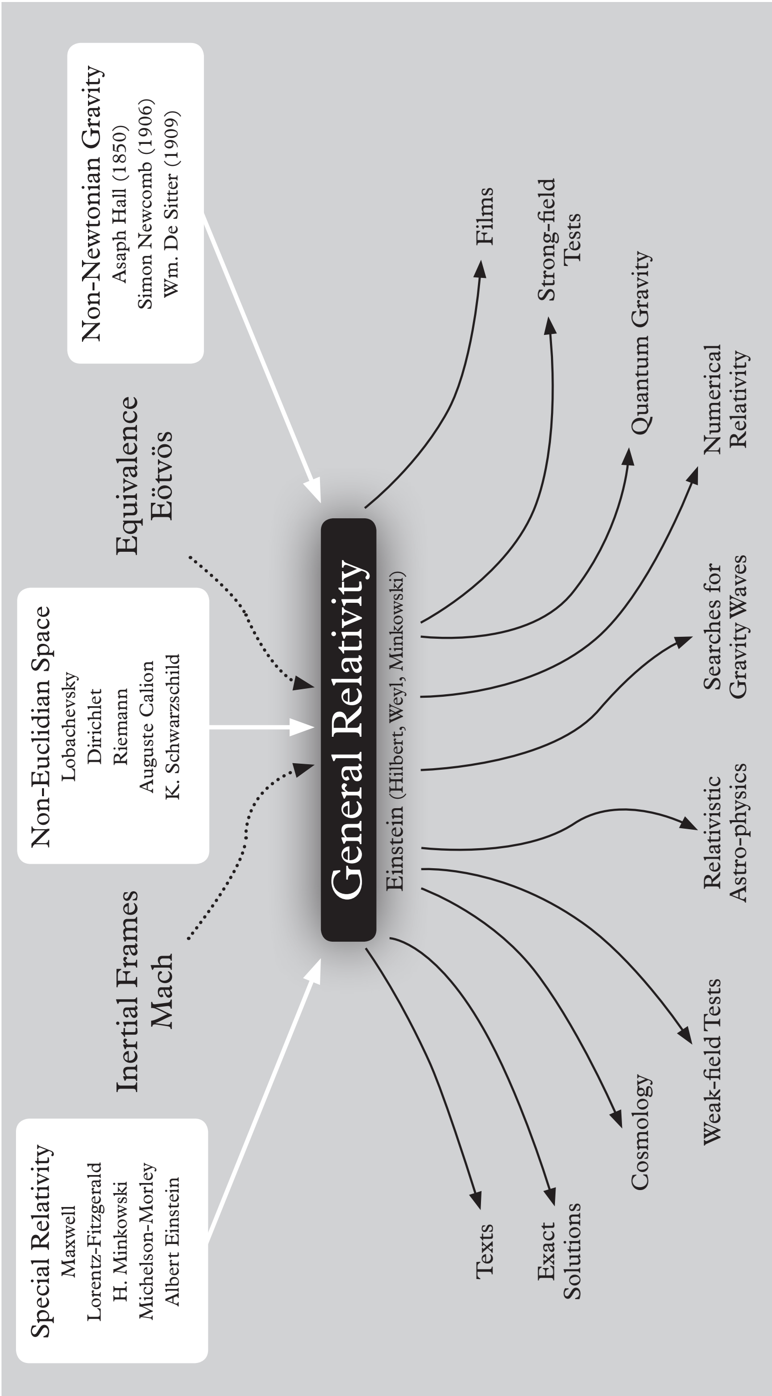

Fig. 1
The Origins and Outcomes of General Relativity

have to love the name, whatever you think of the person. His parents had been in the United States when Horace Greeley (of "Go West, young man," and he meant Pittsburgh) was the democratic candidate defeated by Ulysses S. Grant in 1872. Schacht also survived WWII.

Just how much was the Prize worth? In 1920, each was 134 100 Swedish crowns, down 10% or so from the pre-War value, the equivalent of US $36 250 or £8 252[4]. Circumstances have increased the recent prizes to of order a million US $. On the other hand, in 1915, a gallon of milk cost $0·36[5]. You could hire an unskilled laborer for $1 per day (Trimble family lore) and a skilled astronomer for $1 per hour.

Mileva Marić Einstein died in 1948 (after AE's second wife, Elsa, in 1936). Elder son Hans Albert became a successful engineer, fairly distant from his father, whom he outlived, as did younger son Eduard (d. 1965), who, however, spent much of his adult life in mental-health asylums.

Motion pictures intended to educate are not new (nor, it has to be said, typically very successful). In 1922, Hanns Walter Kornblum (1878–1970) produced a 2- or 3-hour German film explaining (mostly) Special Relativity, with bending of light at the end, though it was originally intended to cover all of Special and General Relativity. It had a large cartoon component and does not survive, though a 30 minute English-language version may[6]. A 1923 American cartoon, produced by Max Fleischer and intended to explain GR, can be found on YouTube, in my case by chance. Fleischer was also the producer of the Betty Boop cartoons, including "Betty Boop. Cinderella. Two-color" which takes less than 10 minutes to view, has better tunes than other Cinderella films, and is an excellent illustration of how two rather than three primary colors can produce attractive effects.

Some combination of enhanced fame after the 1919 eclipse results (see later section), the challenges of understanding what Einstein had done, and perhaps also a general quest for royalties in the wake of the war and subsequent economic turmoil, unleashed an enormous flurry of books about/for/against/explaining GR. Freundlich[7] led off in 1916. Einstein got into the act the next year[8]. In English we got Whitehead[9], Eddington twice over[10,11], Birkhoff[12], and Hermann Weyl in translation[13]. Ludwig Silberstein, who had tackled the Special theory in 1914[14] came back a decade later on the General theory[15].

There were more, naturally, in German. Goenner[16] and Gutfreund & Renn[17] have assembled a sizable list, surely not exhaustive. Here are just the years and authors:

1917 Moritz Schlick
1918 Wilhelm Wien, Werner Bloch
1919 Moritz Schlick, Jan Arnoldus Shouten (in Dutch)
1920 Hans Thirring, Max Born, Alexander Pflüger, Harry Schmidt, Max Hesse, Hans Reichenbach, Ernst Cassirer
1921 Felix Auerbach, Alexander Moszkowski, Max von Laue (two volumes), Hans Thirring, August Kopff, Wolfgang Pauli (encyclopedia chapter)
1922 Paul Gruner, Max Born, Ernst Richard Neumann
1923 Karl Vogtherr, Lorentz *et al.*[18]

There were also contemporaneous volumes harshly critical of relativity and of Einstein himself by Hugo Dingler (1921), Philipp Lenard (1920, 1921), and Johannes Stark (1922). It seems likely that Sten Lithigius, writing in Swedish[19a] would have had particular impact on the Nobel physics committee, but Friedman[4] devotes his whole Chapter 4 to "Einstein must never get a

Nobel Prize." And one cannot read ref. 17 or any other modern discussion of the history of GR without hearing repeatedly of the role of anti-Semitism in the German (and some other) reactions to relativity, and, for that matter, to quantum mechanics.

On the positive side, by 1922–24, Alexander Friedmann, Cornelius Lanczos, Enrico Fermi, and Eli Cartan were creeping into the journal literature with papers important enough to be cited by Misner, Thorne, & Wheeler[19]. Lest I forget to mention it elsewhere, Kasner[20] wrote in this same time frame to explain why you could not put a bunch of 4 (space-time) dimensional universes side by side in 5-dimensional space. In six, apparently you can.

Einstein's fame has never waned. *Time Magazine* declared him the Person of the Century (meaning the 20th), on 1999 December 31, primarily for relativity, though other topics were mentioned. He still inspires strange sorts of enthusiasm, being featured in the 2018 February issue of *1843* (an adjunct to *The Economist*) as a "sartorial role model who combines substance and style" in a piece called "best dressed"[20a]. The 'stylish' items were a brown leather jacket recently bought at auction for $149 700 and the absence of socks. And science historian Helge Kragh[20b] has created an imaginary, 1928 November, oral-history interview of Einstein by Kragh's imaginary uncle Carl Christian Nielsen (imaginarily 1887–1971) dealing primarily with cosmology. The chapter is accompanied by an apparently real photograph of AE on a park-like bench with Arthur Eddington, who was imaginarily interviewed by Nielsen on 1938 December 2.

Another PhD physicist named Frank Potter has put forward another set of imagined interviews with physicists of the past, available only on Kindle. Of the fifty, Einstein gets four, Galileo and Feynman only three each.

But the enthusiasm for General Relativity waned. In the fall of 1919, Charles G. Abbot (Home Secretary of the US National Academy of Sciences) told George Ellery Hale that everybody would be heartily sick of relativity by 1920 April. Indeed the Hale lecture that year was the Curtis–Shapley debate on 'The Distance Scale of the Universe', though Abbot had proposed the causes of the ice ages or some topic in zoology or biology. The short life of the IAU Committee on Relativity follows shortly. And the flood of GR books slowed to a trickle, only monographs by Otto Heckmann and Peter Bergmann appearing in the 1940s[20c,20d].

Einstein's own enthusiasms apparently also somewhat waned! W. W. Campbell, director of Lick Observatory, led a 1922 expedition to a solar eclipse in Australia[23]. He wrote in due course to Einstein, reporting their results (considerably more definitive than the 1919 numbers). A response came, which is preserved in the Lick archives*, expressing Prof. Einstein's "cordial gratitude and transmitting his admiration for the extraordinary diligence and accurateness of measurements taken". But it is signed "The Secretary", though Einstein had been writing enormous numbers of his own letters just a few years before.

Immediate sequels: the 1919 eclipse and the IAU

Arthur Stanley Eddington (1882–1944) was a Quaker and pacifist, who had several near-misses with trouble during the Great War while he had been Secretary of the Royal Astronomical Society[21,22]. In that capacity, he received letters and papers from Willem de Sitter (who appears in Part II and below, in

*Ms. Ilse Ungeheuer, of the current Lick staff, sent me a copy, and I confess to having found it surprisingly unenthusiastic.

connection with the cosmological constant). He was the only one of those you will meet in this section young enough to be at risk of conscription. Eddington was initially deferred because of the importance of his work, but called up in 1918, and he asked for conscientious-objector status (legal, but not regarded as honorable by most of his contemporaries). Intervention by the Astronomer Royal, Frank Watson Dyson, and others, kept him out of prison. Dyson and the others here all have entries in ref. 23.

Eddington and Dyson both recognized that an eclipse was coming on 1918 May 29, when the Sun would be projected against the star-rich Hyades cluster. They were the primary organizers. The Royal Observatory expedition (observers Charles R. Davidson, 1875–1970, and Andrew Crommelin, 1865–1939, born in Northern Ireland) went to Sobral, Brazil. The Cambridge expedition under Eddington went to Príncipe Island off the coast of Africa. Dyson's RO had lost 36 members of staff to active duty during the war, and work fell behind, though he hired retirees, refugees from Belgium, conscientious objectors, and *women* in their places.

Getting the plates home, measuring them, and deciding what the star positions meant all took time. There have been sporadic fusses about whether the published data were completely honest, but the announcement of results equal to the prediction of General Relativity by Dyson, Eddington, and Davidson[24] led to headlines splashed across the *New York Times* and elsewhere, and made Albert Einstein a superstar. The accuracy of their result does not matter to our present understanding of gravity, for the observations have been repeated many times optically at many other eclipses (down to the 2017 August 21 one in the US[25]). Radio astronomy took over when it was noticed that strong compact sources 3C 273 and 3C 279 would pass behind the Sun each October, and the bending of both light and radio waves is as close to the GR value as technology can make it[26].

The founding of the International Astronomical Union, whose centenary is fast approaching, was also a direct outcome of the Great War. For its story let us turn to Adriaan Blaauw[27] (1914–2010), one of the founders of the European Southern Observatory, the first chair of the Board of Directors of *Astronomy and Astrophysics*, and the president of the IAU (1976–1979), who shepherded the return of the People's Republic of China to membership without loss of the astronomers from the Republic of China (Taiwan) with a rubric, "one nation, two adhering organizations", adopted afterwards by others of the International Council of Scientific Unions (ICSU).

George Ellery Hale[28,28a] was the founder of three observatories, each in its day with the world's largest telescope, Yerkes, Mt. Wilson, and Palomar Mountain. He was also co-founding editor of the *Astrophysical Journal*, and in 1903–1904 he wrote to a number of "men of science" interested in solar research[29], inquiring whether they thought some sort of international organization on the topic would be useful. Acting upon their positive responses, he arranged to be chair of a committee of the US National Academy of Sciences (NAS), and, in that capacity, wrote to 17 national academies and scientific societies inviting them to send representatives in 1904 to the St. Louis Exposition. Sixteen sent representatives, Prussia refusing, but some Germans came from the German Physical Society.

They agreed to meet again in Oxford in 1905 September and to establish an International Union for Cooperation in Solar Research. This Solar Union was approved in 1907 by the International Association of Academies (held up perhaps by the Prussians). The IAA last met in 1913 in St. Petersburg. The Solar

Union again convened in 1907 in Paris (Meudon), in 1910 in Pasadena (and at Mt. Wilson, where participants were duly impressed by the 60-inch telescope), and where they agreed to expand their remit to include stellar research, especially astrophysics (meaning, in those days, spectroscopy).

The last fully international astronomical meeting before the First World War was still called the Solar Union for short, and happened in Bonn in 1913 from July 30 to August 5. Then there was a war. Well before it ended, indeed before the United States entered, the NAS offered to organize the scientific resources of the country in preparation for war. Woodrow Wilson ("He kept us out of war" having gotten him re-elected that same year) accepted the offer, and the National Research Council (NRC) came into being in April with Hale as chairman (as well as Foreign Secretary of the Academy). It included representatives of educational and research organizations, industrial and engineering research, technical bureaus of the Army and Navy, and government representatives. Hale regarded the NRC as a sort of model for an international organization to be established after the war ended. He never seems to have much doubted the outcome.

Following a great deal of to-ing and fro-ing (mostly letters and telegrams, but some sea voyages)[27], there took place the First Inter-Allied Conference on the Future of International Organizations in Science, at Burlington House, London, in 1918 October 9–12, followed by a second conference in Paris during November 26–29. Participants came from Belgium, Brazil, France, Great Britain, Italy, France, Portugal, the United States, and Serbia.

Several points in the resolutions adopted at these conferences echo down to the present. First that the nations at war with the Central Powers withdraw from the existing conventions relating to international Scientific Associations … as soon as circumstances permit. Second, that the new associations be established without delay by the nations at war with the Central Powers with the eventual cooperation of neutral nations. Third, that certain associations, such as the Metric Convention, be taken into consideration during the peace negotiations (a sample of these follows shortly).

At the Paris meeting, the name International Research Council (IRC) was accepted, and it acquired a council with Picard (France) as president, Schuster (Britain) as general secretary, and Hale (USA), Lecointe (Belgium), and Volterra (Italy) as vice-presidents. Astronomy was clearly well represented. The first formal assembly of the IRC took place in 1919 in Brussels from July 18 to 28. Represented were Belgium (about half the participating scientists), France, the US, Great Britain, Canada, New Zealand, Poland, Rumania, and Serbia, again with many astronomers. Additional countries from the Allied side immediately entitled to join the IRC and Unions under it were Australia, Brazil, South Africa, Greece, Japan, and Portugal. The founding IAU members were Belgium, Canada, France, Greece, Italy, Japan, United Kingdom, and the United States[30]. The neutral countries invited at Brussels to join the IRC and then the various unions were China, Siam, Czecho-Slovakia, Argentine Republic, Chile, Denmark, Spain, Mexico, Monaco, Norway, Holland, Sweden, and Switzerland.

The early additions to the IAU were Mexico (1921), Czechoslovakia, Denmark, Norway, Poland, Rumania, Spain, and the Netherlands (all 1922 at the 2nd General Assembly), Switzerland (1923), Portugal (1924), Egypt and Sweden (1925), Argentina (1927), Vatican City (1932), China, USSR, and Yugoslavia (1935), South Africa (1938), and Australia (1939). And then, as you might just barely recall, there was another war. After 1996, all the former republics of the USSR were deemed to have inherited her right to membership, if they could pay the dues*, while the Yugoslavian right went to Croatia; and Serbia (with Herzegovina) did not adhere until 2003.

Hungary, Germany, Austria, and Turkey (chronologically) all belong to the post-World War II period, along with a number of other countries (somewhat fluctuating) as and when they felt the need to support their indigenous astronomers and had the ability to pay the dues. The US share in 1948 was 2500 gold Francs or about $748. It is more now.

Treaties, conventions, and agreements allowed to survive the Great War

These appear in Articles 282–287 of the Versailles Treaty (my copy of which once belonged to a certain Frank M. Mason). These are about 36, and a few of them are subject to Germany fulfilling certain stipulations. You must go to the original document to see the complete list, but here are a few of my favourites, some of which have echoes down to the present, and violations of some of which occurred during the lead up to WWII (each has attached dates, 1857–1913, most in the 80s and 90s; and places where the agreements were signed, *e.g.*, Vienna, Washington, Rome, St. Petersburg, Lisbon): Protection of submarine cables; sealing of railway trucks subject to customs inspection (Lenin not mentioned); unification of commercial statistics; guaranteeing free use of the Suez Canal; suppression of nightwork for women (oops, there go our astronomers); suppression of white phosphorus in matches; suppression of the White Slave Trade (oops, there go our ...); unification and improvement of the metric system (kilogram still to be sorted out in 2018 or later); unification of pharmacopaeial formulae for potent drugs (still an issue!); concert pitch; precautions against phylloxera (save our wine!!); protection of birds useful to agriculture (bees not mentioned); Postal Union and Telegraphic Conventions; fisheries in the North Sea outside territorial waters (again still an issue in many places!).

Of course the new arrangements did not go through unopposed. Kapteyn objected initially to any exclusion of neutrals, and when they were invited in he tried to discourage the Dutch Academy from adhering for as long as Germany was excluded[27]. Be grateful he failed on that one, since Jan Oort was an enormously valuable officer and member for many years! He has by far the largest number of index entries in Blaauw's history.

The most bitter objections came from German astronomers[32], Struve ending his 'On the development of German astronomy' with "*Per aspera ad astra*". The Astronomische Gesellschaft (AG) had been in the habit of thinking of itself as "the" international astronomical society, and with some justification. From its 1863 founding through 1918, 60% of the astronomers who passed through as members were from outside Germany, including many from the US, UK, France, Italy, Poland, Russia, and so forth. These included (with years of membership, 'd' indicating that was also the year of death): George Ellery Hale himself (1893 d. 1938), Eddington (1913 d. 1944), W. W. Campbell (1891 d. 1938), F. W. Dyson (1906 d. 1939), E. C. Pickering (1877 d. 1919), Kapteyn (1887 d. 1922), both Curtis (1910 d. 1942) and Shapley (1925 d. 1945) of the Great Debate, de Sitter (1909 d. 1934), also Georges Lecointe of Belgium (1908–1921) and Vito Voltera of Italy (1898–1921), founding vice-presidents

*You will have to take my word that I am now typing these, in an order determined mainly by geography, not any alphabet, from memory. Lithuania, Latvia, Estonia; Belarus, Moldova, Ukraine; Armenia, Georgia, Azerbaijan; Kazahkstan, Kirghistan, Tajikistan, Turkmenistan, and Uzbekistan; and, of course, Russia.

of the IRC, Eduard Benjamin Baillaud (1877–1921) founding president of the IAU, and Svante Elis Strömgren, founding head of the IAU Central Bureau for Telegrams (1900–1945). If you care to go back further, you will also find John Couch Adams (also Galle who did find Neptune, but he was German) and Simon Newcomb. Karl Schwarzschild (1896 d. 1916), many of the astronomers Hilmar Duerbeck identified as having served for Germany, some killed in WWI, were also AG members, as was Albert Einstein (1921–1933), and our old friends Baron Lorand Eötvös (1898 d. 1919) and Erwin Fritz Finlay-Freundlich (1913–1926).

About 50% of the (smaller number of) members who passed through the AG in 1919–1945 were still from other countries, Sweden and the US dominating. But this dropped to about 15% after the Second World War and has remained low. If you sum Russia and the USSR, they have contributed the largest number of foreign members, followed by the US and Sweden. An alternative sum of Austria plus Hungary plus Austria–Hungary actually wins with close to 9% of the integrated membership. The female representation started to grow from near zero around 1920 and is now a smidge more than 10%.

In the event, some of the astronomical responsibilities that had resided in Germany before WWI, including portions of the *Carte du Ciel* and the central telegraph bureau, were moved elsewhere. Variable stars, the compiling of minor-planet data, and the maintenance of the astronomical bibliography were not relocated until after the Second war[27].

It has sometimes been written, somewhat incorrectly, and probably even by me, that the death of Hale's Solar Union and the establishment of the International Astronomical Union occurred under the Treaty of Versailles. In fact the only astronomical item there (yeah, I read the whole thing) is in article 131, which says: "Germany undertakes to restore to China within twelve months from the coming into force of the present Treaty all the astronomical instruments which her troops in 1900–1901 carried away from China, and to defray all expenses which may be incurred in effecting such restoration, including the expenses of dismounting, packing, transporting, insurance and installation in Peking." I had very much doubted that this ever occurred, and hadn't quite realized that the removal was part of a much larger looting of Chinese possessions in the wake of the Boxer Rebellion. In fact, Prof. Lu Lingfeng of the University of Science and Technology in China e-informed me that the instruments, probably eight, were returned. They were things like armillary spheres, sextants, quadrants, sun dials, and celestial globes (but no telescopes), all large, bronze, mostly supported by dragons (also bronze), and partially dating back to the 1600's when Jesuit astronomers were in China. They are now in the Beijing Ancient Observatory, which has a web presence.

The International Astronomical Union began its life with many traces of Hale's Solar Union, including triennial General Assemblies, more than one official language (English and French, German having been dropped from the Solar three), and committees, later commissions, to focus on specific territories and tasks. The last new one in the Solar Union had been classification of stellar spectra. The proposal to broaden from the Sun to other stars is generally credited to Karl Schwarzschild, but the topic had been on the agenda before the meeting started, and was introduced by Hugh Frank Newall of Cambridge. The formal motion came from Schwarzschild in German, immediately after he claimed his English was not good enough for the purpose*.

*The proceedings of all five assemblies of the International Union for Cooperation in Solar Research are on-line in four volumes (scanned from the University of Michigan library); I found and read them all, but would not undertake to do so again.

The IAU also began its life with 32 Committees[27], each with a president from one of the founding nations. Four were solar-orientated (though Hale was president of only one). And Committee Number 1 was Relativity (ah!!, here we are back on topic) under A. S. Eddington. It voted itself out of existence at the 1925 General Assembly in Rome, and Relativity did not reappear at the IAU until the 1970 General Assembly at Brighton (UK), where Commissions 47 (Cosmology) and 48 (High Energy Astrophysics) were blessed and established.

Other Solar Union relics included, in 1919, nations and their academies and societies as the adhering organizations. Individual human beings as members finally appeared in revised by-laws in 1958 (the Solar Union considered this step, but firmly rejected it), and we now outnumber the national adhering organizations 100:1 or thereabouts. And in the latest iteration of Divisions and Commissions, it is not entirely clear where General Relativity belongs.

Scientific issues that lingered

There are (at least) three of these: the reality of what Einstein wrote as lowercase λ and we write as upper case Λ, the cosmological constant; whether gravitational waves (radiation) can carry energy; and is GR the right theory of gravity? We think we know the answer to all three: yes, yes, and no, but here are some additional steps on the paths from the early days. The relevant chapters from Gutfreund & Renns are (5) 'The Genesis of Relativistic Cosmology' and (6) 'The controversy over gravitational waves'.[17]

Lambda has a history something like the American folk dance, *The Hokey Pokey* ("You put your left foot in, you put your left foot out, you put your left foot in and you shake it all about. You do the hokey pokey and you turn yourself around; that's what it's all about." Try singing this with 'lambda' instead of 'left foot'.). If you have already heard some version of the story and are tired of it, feel free to skip to a later section. If you would like to know more, but not from me, ref. 33 has an expert discussion.

Einstein's well-advertised original motivation for introduction of the extra term in his field equations[34] was the desire for a static universe. At various times he also noted, as you have surely been told, that it could be thought of as the second integration constant of a second-order differential equation (Hubble's H being the first). In principle, there are two such static solutions, called spherical (where all geodesics will pass through two poles) and elliptical (where the geodesics intersect only once). Because one must not think of the latter as looking like a three-dimensional ellipse (Doc. 300), it is perhaps better not to think of it at all. The two differ by a factor two in volume for a universe with a given value of density or Λ. AE explains this most clearly in Doc. 300 to Freundlich, who had drawn his attention to that sort of geometry. Felix Klein enters the story with Doc. 319[3]. Other participants in the exchanges included de Sitter and Weyl.

Both Einstein's initial cosmology and the empty 'De Sitter hyperboloidworld' emerge in extended debate-by-letter among the four (see p. 351–372 and the associated letters in ref. 3). De Sitter space did not have the singularity Einstein 'accused' it of (merely an artefact of coordinate choice). But Einstein's static universe really is unstable, and collapses or expands in response to any perturbation. Various sources credit several different contributors for demonstrating this instability. But I started with a more serious worry — aren't systems generally perturbed from outside? Not to worry. Tolman (sect. 159 of ref. 34) shows the basic calculations and then tells his readers that, if free radiation condenses into matter or freely moving particles get captured by condensation, the model will start to expand. Conversely, if matter transforms into radiation (stars do a lot of this) the model would start to contract. We can, therefore, turn with a clear conscience to Friedmann and Lemaître.

Alexander Alexandrovich Friedmann[35] (1888–1925), whose father, also Alexander Alexandrovich Friedmann, was a ballet dancer and musician, interrupted masters-level study to serve in WWI in aviation units of the Army on the northern and southern fronts. Soviet scientists were able to catch up on western European scientific advances only after the end of the war and their revolution, at which point Friedmann set out to study General Relativity[43]. The first Russian survey of the topic came from AAF's friend and colleague V. K. Frederiks (a joint volume[42] appeared only after AAF's death; but there had been a 1923 book *Theory of Relativity* (sorry, my typewriter doesn't speak Russian) by Yakov Ilyich Frenkel (father of the middle author of ref. 35)).

Can we still connect up with that period? Yes, if 'we' are quite old! Vladimir A. Fock, who led the Russian delegation when they walked out of the meeting of GR6 in Copenhagen in summer 1971, had been part of a seminar group with which AAF discussed cosmological ideas; and George Gamow (1904–1968) had just started work on cosmology with AAF when the latter died, and so Gamow completed a 1928 thesis on what we would now call barrier penetration in alpha decay. The last chapter of ref. 35 makes clear just how unpopular cosmology was in the Soviet Union until about 1962. One wonders whether a longer life for Friedmann, and Gamow's remaining in Leningrad, could have made a difference. It is usual to blame the decline of cosmology there on Lev Landau (I've done so myself), but Tropp *et al.*[35] point out that Landau and Lifshitz "gave an exemplary presentation of Friedmann's cosmology in their famous *Course of Theoretical Physics*".

Just what was that cosmology? Friedmann showed that there are solutions of the Einstein equations for a homogeneous universe, both with and without Λ, that can either expand or contract, as different functions $a(t)$ depending on relative values of density of mass–energy and of Λ[36,37]. Does all this contradict whatever you might have previously heard about evolutionary cosmologies violating materialistic principles of Communism? Never mind. The 'antis' put all the blame for an expanding universe on the "reactionary scientists Lemaître, Milne, and others." (p. 223–224 of ref. 35).

So what then of Georges Henri Joseph Édouard Lemaître (1894–1966)? He also interrupted his studies (at the Catholic university in Louvain, Belgium, in engineering) when called to serve as an artillery officer. Post-war, he completed a first degree in mathematics and physics, wandered among Cambridge (UK), Harvard, and MIT, writing a thesis in French that included a form of what we now call the Tolman–Oppenheimer–Volkoff equation of state (useful for neutron stars), and receiving a 1927 PhD from Louvain. Meanwhile, however, he had enrolled at the seminary at Malines, Belgium, and was priested in 1923. This was not, present Louvain astronomers tell me, a reaction to the Great War, but something he had always planned.

Lemaître's pioneering paper[38] definitely favoured an expanding universe with a non-zero cosmological constant and a very dense state at its origin. He demonstrated the instability of Einstein's static universe, used Slipher's galaxy redshifts to estimate what we now call the Hubble constant at 600 km/sec/Mpc, interpreted Λ as a vacuum energy density, described the early Universe as a "primeval atom" (meaning the mass of a few billion galaxies all at nuclear density), and suggested that cosmic rays were a remnant of that primordial state[46]. Though we would now disagree with some of the details, one really has to agree that the Abbé was the "father of the Big Bang"[40,41]. Unfortunately the 1927 paper appeared in a Belgian journal not much read in the UK, the US, or Russia, and the version of his paper published in *Monthly Notices*[45] had the expansion-constant calculation removed, with his own acquiescence, as being of no "actual" importance, a confusion in meaning between French *actuel* ('current') and the similar-sounding English word.[46]

In later years, there was some Soviet work, described as deriving from the Friedmann solutions[35]. I mention only a few names of mathematicians and physicists who might be familiar to you in other contexts: Matvei Petrovich Bronshtein (one of many executed in 1937), O. D. Khvolson (who as Chwolson published the very first gravitational-lensing paper[47b]), A. A. Belopolsky (who influenced Gerasimoch and so Ambartsumian indirectly) and, of course, Landau & Lifshitz, who explored both sign conventions — positive ds^2 = time-like (my choice) and space-like (ref. 27).

We bid temporary farewell to Einstein, who had described Λ as something to be determined by observations of the distribution of stars and such (Doc. 325 from 1917 in ref. 3) and on another occasion as the second integration constant (Doc. 591). Famously, he backed away from Λ when he accepted that the Universe expands, somewhere around 1931 April[47]. The same year, Einstein worked out his own expanding model, which never got published, but has been treated in detail in ref. 47[a].

Erwin Schrödinger (1887–1961) pops in here, before turning to his equation and his cat. He had been called up into active service as an artillery officer for three years and then was transferred to meteorology[48]. Often the greatest risk was boredom, and he filled large notebooks with calculations, but also received a citation "for his fearlessness and calmness in the face of recurrent heavy enemy artillery fire". Back on civilian soil, he turned his attention briefly to relativistic universes and came out in favour of the cosmological constant[48] and held by it to the end[50,44]. He outlived Einstein by about six years, and their disagreements (more often about unified theories but also about Λ) continued throughout their lives.[44]

Was Λ ever without an astronomical supporter? Eddington held the fort until 1944; Schrödinger until 1961; Lemaître until 1966. Soon after that, Gerard Henri de Vaucouleurs (1918–1995) maintained that a value of the Hubble constant near 100 km/sec/Mpc required a cosmological constant to make the Universe old enough for its contents[52,53] pretty much until his death, when large-scale-structure folks[54] took over.

You know how the story turns out — with the 2011 Nobel Prize in Physics going to Perlmutter, Riess, and Schmidt for discovery of cosmic acceleration (that is, significant non-zero Λ) and the current best-buy universe having 70% or so of its energy density (positive, though the pressure is negative) in Λ or dark energy, or quintessence, or whatever you want to call it. And we can bridge the gap from the last of those who held on beyond Einstein to 'Universe-2018'. One of Neta Bahcall's early studies of very-large-scale distribution of galaxies[54] pointed out that the data were easier to understand with the help of a cosmological constant. A plodding review of all possible DM candidates as understood in 1987[55] included a cosmological constant as a dark mimic so that $\Lambda \neq 0$ could provide $\Omega = 1$ without dark matter. G as a function of length scale was the other mimic. And the third bridge seems to have left no paper trail.

One of the symposia that was part of the IAU General Assembly in Kyoto in 1997 concerned cosmology and ended with a panel discussion on the cosmological parameters. This did not make it into the proceedings but is high on my list of memorable events, because the organizers recognized at the last minute that they had empaneled eight men and so added me. A couple of the panelists, including 'Chip' Arp, were not subscribers to the conventional hot Big Bang universe and so declined to choose parameters. But leading off for the conventional view was J. P. Ostriker of Princeton, who said that H was about 75, the Universe flat, and about ⅓ of the mass–energy in matter of some sort and ⅔ in the cosmological constant. When my turn came, I said I agreed with Jerry, except that my H was a bit smaller (disciple of Sandage!) and my Λ a bit larger. And a majority of the panelists agreed that some cosmological constant was needed to make the Universe older than its oldest stars for any likely H and to model most successfully the formation of large-scale structure. None of us received Nobel Prizes for this!

The reality and properties of gravitational waves/radiation

The two words mean the same thing in this context, though 'radiation' is perhaps firmer in saying that they carry energy. But it is one of those scary words, like nuclear (especially when pronounced "noocooler"), and the billion-pound gorilla, *LIGO*, declared that they are gravitational waves, preferably not to be confused with gravity waves, which happen in places like the Earth's atmosphere and have gravity as the restoring force (in contrast to sound, which has pressure as the restoring force).

Within Newtonian gravitation, information is propagated instantly. If the Sun vanishes, we fly off immediately, not after 8 minutes. But as early as 1905, Henri Poincaré[56] pointed out that the Lorentz transformation required ("… *la propagation de la gravitation n'est pas instantaneé, mais se fait avec la vitesse de la lumière*"), that gravitation travel at a finite speed, that of light. Next on the field was Max Abraham (who appears briefly in Part II), whose own theory of gravitation was once regarded by Einstein as a viable alternative to GR, but later repudiated. Abraham wrote[59] that gravity could have no analogue to electromagnetic waves because a gravitational dipole would have the sum of the inertial masses and the acceleration equal to zero. That is, waves might be valid solutions of the field equations, but there would be no way to generate them.

Einstein's first statement on the subject dates also from 1913 (*Collected Papers*, Vol. 4, no. 18, p. 229), and was a response to a question from Max Born about how fast the effect of gravitation propagates. At the same speed as light, AE said, for infinitesimal disturbances of the metric. The next person to ask was Karl Schwarzschild (whom you also met in Part II), writing from the Russian front to ask about waves in Einstein's theory (he had already correctly calculated the perihelionic precession of Mercury), in a communication that does not survive. Einstein's response (Vol. 8, Doc. 194), was that relativistic gravitation would have no waves analogous to electromagnetic ones. But his first paper on the subject[57] came within the same year.

Lest we once again do the *Hokey Pokey*, this time sticking our right hands in and out, let me refer you to Chapter 7 of ref. 17 for some of the details, though they seem to have missed the denial of reality from Levi-Civita[60] in 1917, even before AE's more comprehensive discussion[58]. It is perhaps not a coincidence that he was president of the IAU Committee on Relativity when it voted itself out of existence.

From 1918 to 1937, Einstein was apparently not interested in gravitational waves, or anyhow not interested enough to publish on the subject. Arthur S. Eddington (of the eclipse), stepped up to the spinning cricket bat[61,62], defended the reality of the waves and their ability to carry energy, and provided the factor of two needed to correct AE's quadrupole formula. He did not, however, reach a firm conclusion on whether the orbit of a pair of masses would decay owing to the emission of gravitational waves.

The difference between Eddington's spinning rod and his binary star is that the former has forces and energies that are not due just to gravitation. That difference remained key to the reality disputes that continued beyond 1923 and, believe it or not, have still not quite ended.*

Einstein pops back into our story in 1937 with the then young Nathan Rosen (1900–1995), in an encounter with the publications process that has since become modestly famous. Kennefick[64] provides the most complete version, but here is a precis. The paper as originally written claimed that there could be no energy-transporting waves in GR. They submitted it to *Physical Review*, in which AE had already published since coming to the United States. The editor (Tate) sent the paper to a reviewer, later revealed as H. P. Robertson (1903–1961), of the Robertson–Walker metric. Robertson found serious errors in the calculations and relayed them to the editor who informed Einstein that the paper could not be accepted in its present form. AE was deeply angered, writing that he had sent the paper to be published, not criticized, and withdrawing it. Back at Princeton, he discussed the calculations with Robertson (who was there until 1947), who was able in person to persuade Einstein (and Rosen, who was, however, just then in the Soviet Union), to correct the calculations and revise the paper. But *Physical Review* never saw hide-nor-hair of AE again, and the paper[65] appeared in the *Journal of the Franklin Institute of Philadelphia*, still in 1937.

Rosen wrote an additional gravitational-wave paper from the Soviet Union and another after he had relocated to Israel (cited by Weber[63]), on some of the technical difficulties with sources and propagation. Later in life he turned to non-GR, bimetric theories of gravitation[66], and was the president of the International Society on General Relativity and Gravitation the year (1974) we met in Israel.

Rosen could possibly hold some record for length of time from first to last paper on a topic, from 1937 to 1993, when he and a young colleague showed carefully that, for a cylindrical gravitational wave in empty space, the energy and momentum densities were positive and "reasonable"[66a]. He had noted this back in 1958, promised further details, but was slow in providing them for reasons, he wrote, that he had long forgotten.

Leopold Infeld (1898–1968), of Einstein, Infeld & Hoffman, carried on with anti-wave (or at any rate anti-energy-transport) papers from the 1930s at least until 1960 as he moved from the US to Canada and back to Poland where he had been born (well, it wasn't Poland then, but you know what I mean).

*A sphere of uniform density or density varying only with radius is a monopole. We have lots of approximate mass monopoles in the Universe and indeed live on one. The expansion or contraction of a monopole yields no radiation whether the sphere is charged or massive or both. A uniform sphere of magnetic north, or a point, would be a magnetic monopole; we find none of those, and the lowest order EM radiation is dipole, when the distribution of charges changes in some more complex way than expansion or contractions of a sphere, for instance a plus and a minus charge dancing the *Hokey Pokey*. Weber[63] assures us in his Eqn. 7.36 that the lowest-order multipole gravitational radiation is quadrupole. You are supposed to remember that most functions can be expanded in multipoles, and to save you from having to look it up, below is Eqn. 7.36. Another way to say it is that for an isolated oscillating system, the dipole moment vanishes as a consequence of conservation of linear momentum, which is equivalent to what Abraham wrote. And yet another verbal version from Gutfreund & Renn[17]: "Gravitational waves are produced in leading order by a mass source changing along two perpendicular directions, for instance a weight-lifter doing squats".

$$\int T_{ij}\, d^3x = \tfrac{1}{2}\left[\int T_{00} x^i x^j\, d^3x\right]_{,00}$$

The early papers were single-author, some later ones had student co-authors (including the fairly well known Plebanski, Schild, and Michalska-Trautman)[66,67].

Improbable as it may seem, 'wave denialists' have persisted not only past the discovery and analysis of PSR 1913+16 (the Hulse–Taylor[68] binary radiator), but even beyond the *LIGO* announcements[69]. Each press release from the latter has provoked a 'no such thing' response from A. Loinger and T. Marsico of Milan, starting with ref. 70.

But to return to the mainstream*, revival of interest in 'existence and nature' of gravitational radiation paralleled that of the revival of General Relativity in general. Significant events were the 1955 Bern conference[71] which had been intended to honour Einstein on the 50th anniversary of his 'miraculous year', but ended up mourning him; the Chapel Hill conference[72] in 1957, organized by Bryce and Cecile DeWitt, which counts as GR1; and the 1959 Royaumond Conference[73]. At this last, Peter Bergmann said it would be unfair to vote on the reality of the radiation in the absence of Leopold Infeld (who had been at Bern, and spoke against). He also said it would be a major advance if anything came of the "schemes" of Joseph Weber.

Names connected with gradually-improving calculations, leading to gradually-increased confidence that the energy and momentum content of the waves was positive and, as Infeld said, "reasonable", include Hermann Bondi, William Bonnor, Felix Pirani, Ivor Robinson, and John A. Wheeler and Joseph Weber[74]. Particle physicists attach a good deal of importance to an argument from Richard Feynman which they call "beads sliding on a wire", but this clearly has non-gravitational forces and so does not respond to the difficulties perceived by the late denialists, and, indeed, by Bill Bonnor himself.

Let's see if we can sort out what was being argued about. The continuing problem was that, although Einstein's equations have wave solutions, a pseudotensor† for energy and momentum was zero (I don't know whether this is the same objection as that of Loinger, that particles all follow geodesics and so cannot be carrying energy in waves). At the Chapel Hill conference, Infeld[74a] expressed his on-going objections. In the summary talk, Bergmann wrote that Weber and Wheeler[74] concur that waves don't carry any energy in the case of cylindrical waves. He wasn't sure whether there would be spherical wave solutions, let alone how you could generate them from oscillating quadrupoles. Equally unclear was whether an orbiting pair of point masses would lose energy at a rate given by the square of an amplitude.

But this is the wrong way to look at the problem. Weber & Wheeler note in passing that a closed universe has total energy undefined, but that does not mean that the curvature is zero, and, what is more, that electromagnetic radiation would seem non-existent because it wiggles a test particle one way and back again to the same state, so that no energy was absorbed. No, because the wiggling charge itself emits EM radiation — the radiation or back reaction — and so drains the passing waves. One should look at gravitational waves the same way. A test particle is moved by the passing wave, and the invariant space–time interval between two test particles is changed. They in turn send out gravitational information as a radiation reaction, so energy has been drained from the wave.

* *Revenons à nous moutons* suggests either that we all follow the scientific leaders like sheep, or like Handel's sheep, all go astray.

† That bothersome pseudotensor appears somewhere in Landau & Lifshitz; in R.C. Tolman *Phys Rev*, **35**, 875, 1930; a paper by Chr. Møller; and elsewhere.

This approach leads rather naturally to thinking of test masses as detectors and expressing the result of passing waves as the ratio of change in separation to that separation, $\Delta s/s = h$. The radiation appears only in a third approximation to exact solutions, with 'advanced' potentials in the calculation, and the motion of the test particle(s) is transverse to the passing wave. The proper description, therefore, is not "ripples in space time" but "transverse shear strains of the spacetime metric"[75]. My take on how it all played out appears at greater length in ref. 67.

Is General Relativity the right theory of gravity?

"No, because it is not a quantum theory and cannot be made into one" is the answer one has heard for many years. Very crudely, the issue is that, if you try to renormalize GR in the way that Quantum Electrodynamics deals with electric charges and their interactions, you can hoke up finite answers in the first-order corrections ('one-loop' approximation), but the others all come out larger, not smaller, so the procedure blows up instead of converging.

Einstein himself expected that, just as GR had supplemented or supplanted Newtonian gravitation and mechanics, GR itself would someday be superseded by a better, more complete theory (ref. 3, Doc. 323)*. Even at that time, he probably had in mind some unified theory of gravitation and electromagnetism, though his first paper moving in that direction came five years later. Meanwhile, he at least expressed interest in the upcoming 1919 solar eclipse (ref. 3, Doc. 486), as an additional GR test.

Has such an improved theory turned up so far? No, or you would have heard about it. Conversely, you may or may not have read items claiming that there is no necessity, since relativistic and quantum-mechanical effects appear in such different contexts (so wrote Freeman J. Dyson a while back in *New York Review of Books*). The very early Universe, boiling away of primordial black holes, and near the centers of other black holes would seem to be counterexamples, but I have not visited any of those.

Recent support and tests

Does gravitation travel at the speed of light? The first answer to this came from the advance of the perihelion of Mercury. For which 'getting the right answer' says that $v_g = c$ to within 5% or so. There was a brief flurry of worry that some neutrinos were faster than light[76] which almost as quickly as light went away. Or perhaps light was faster than gravity[77], which, said the authors, would solve the 'horizon' and 'causality' problems of standard Big Bang cosmology with no need for inflation. If this were right, then the slope of the spectrum of

*AE wrote, on 1917 April 4, to Felix Klein: "No matter how we draw a complex from nature for simplicity's sake, its theoretical treatment will ultimately never prove to be (adequately) right. Newton's theory for ex. seems to describe the gravitational field completely with the potential φ. This description proves to be insufficient, the $g_{\mu\nu}$ functions take its place. But I do not doubt that the day will come when this approach will also have to give way to a principally different one for reasons that we do not anticipate today. I believe that this process of securing the theory has no limits. I am sending you my last paper together with these lines. The gist of its content is in particular, that the size of the universe seems to be linked to the mean density of matter. It is not at all out of the question that in the foreseeable future the statistics of fixed stars will confirm or refute the theory."
And to David Hilbert on 1915 November 15 "…since I often racked my brains to construct a bridge between gravitation and electromagnetism …. I am tired out and plagued with stomach pains besides" (Doc 144).

primordial density fluctuations would be 0·96478 (*versus* 1·0 for the Harrison–Zeldovich spectrum). The authors asserted that adopting their proposal would "inform quantum gravity". But, we can now skip directly to the *LIGO* binary-neutron-star event (of 2017 August 17), with gamma rays arriving 1·7 seconds after the gravitational-wave burst[78]. This sets the two speeds the same to within 10^{-15} and the mass of the graviton at less than 10^{-54} gram[79]. We are still far from the Fritz Zwicky limit of 10^{-63} gram, which follows if there is no higher-order clustering of galaxies[80]. Confidence that the speed of gravity is close to that of light, or anyhow much larger than the speed of earthquake waves through ground and soil, is such that it has been proposed to use the waves radiated by shifts of ground as an early-warning system for quakes[81].

How precise is the equivalence principle? That is another topic to which the *LIGO* double-neutron-star event has made and will make further limits possible (ref. 78 and references therein). Meanwhile, the weak equivalence principle is tested by dropping Galileo … no, wait, dropping massive objects of different mass and composition in a vacuum to see whether they land at the same time (in air they do not, but you can approximate the real experiment either with two pendula of identical length and different bob masses or by dropping a sturdy book, held with a smaller piece of paper on it so the air can't get to it). The *MICROSCOPE* experiment[82] used a hollow platinum-alloy cylinder centred inside a hollow titanium-alloy cylinder in space. First results say that inertial and gravitational masses are equal to one part in 10^{14}. The goal, with additional data to be analyzed, is one part in 10^{15}.

The strong equivalence principle, also held by Einstein to be essential to his theory, says that the part of the mass of an object that is due to its own self-gravitation should also have inertial and gravitational masses equal. Most terrestrial objects (even your department head), have modest self-gravity, but nature has given us pulsar PSR J0337+1715, with one white dwarf in close orbit with it, and another white dwarf further away. If the pulsar and its close companion (having different percentages of self-gravitational mass–energy), fell at different speeds toward the distant WD, this would show up as a precession of the orbit, and a periodic change in the pulsar timing. None has been seen[83] to within about 2 parts in 10^6.

If it bothers you that the constraint on the strong principle is weaker than the constraint on the weak principle, please pause for a glass of Cinzano Bianco (ice, no lemon, please, in mine), and rejoin us for the miserable collection of ideas in the next section.

Indeed, GR is now flourishing outside the Milky Way, with strong galaxy–galaxy lensing by ESO 325–G004[84] showing that the amount of spatial curvature produced per unit mass is the same out there at 150 Mpc as it is here.

Alternative theories of gravitation and cosmology

The number of these has been countably infinite, some predating or contemporaneous with GR, with brief appearances in Parts I and II, a sprinkling from the 1920, 30s, 40s, 50s, and so forth, with no end in sight, even if you ignore ideas that start with strings, branes, self-reproducing inflation, and other ideas part of modern theoretical physics. Steady State or its modifications is probably best known[85]. I suppose it will vanish with the last of its founders and supporters, the youngest of whom is slightly older than I. There are also alternatives associated with the names of P. A. M. Dirac, E. A. Milne, Hannes Alfvén, Irving Segal, Roland Omnes, Oskar Klein, M. Milgrom, Jacob Bekenstein, and people best remembered for other contributions, even the much-lauded Arthur S. Eddington*. Many recent alternatives have among their goals the elimination of the need for dark matter.

Keep an eye out (perhaps that third one on the tops of our reptilian heads), for ref. 86, a chapter for which I was invited to provide, but couldn't manage to reach agreement with the CEO on how many theories to include. I, of course, wanted very many, at least in a table with dominant properties, rather than extended examination of a few.

So, by way of compensation, you get here only two very recent ones. First Donald Lynden-Bell (whose passing in 2018 February I mention with deep sorrow) and S. M. Chitre asked in these very pages[87], "Does viscosity turn inflation into the cosmic microwave background and Λ?" The answer "yes" yields a total volume for the Universe of 55777 $(c/H_o)^3$ or about $2{\cdot}25 \times 10^{34}$ pc^3.

Second, Andre Maeder of the University of Geneva has proposed[88] 'A new model, based on the dynamical effects of the scale invariance of the empty space: the fall of dark matter'. Dark matter is replaced by a slight effect of scale invariance on Newton's laws; inflation is replaced by the effect on Einstein's equations. And "the scale invariance of the empty space is also present in the fundamental theory of electromagnetism".

The test of a new theory remains, however, the ability to reproduce all the good features of the previous theory while still making new predictions or accounting for old observations that were previously puzzling. From that point of view, the situation has not changed since the years of refs. 89 and 90, when one had to admit that General Relativity has passed all the tests thrown at it, better than various competing theories, including some intended to lead the way to quantum gravity and superunification.

What became of Albert Einstein?

Well, like the hero of every biography, he dies at the end. But let's look at a few items along the way, beginning with the paper trail as he moves away from the quantum ideas he pioneered and eventually away from the mainstream in other ways. Here are my favourite five:

(*i*) The Einstein A and B coefficients[91], the derivation of the relationship among which was a mainstay of qualifying exams in the days when physicists were supposed to think about atoms. You are too young to remember this, but it was one of the very few items on my first, failed, three-hour oral qualifying exam that I got right.

(*ii*) His generous, surely unprecedented and rarely-followed reading, editing, and submitting of papers by Satyendra Bose, containing what we now call Bose–Einstein statistics[92].

(*iii*) The provocative question, "Can Quantum Mechanical Description of Physical Reality be Considered Complete?"[93]. Their answer was "no", and may well in some deep sense have been the right answer. But quantum mechanics has in common with General Relativity that, if you follow the rules and do a calculation, the results always agree with experimental and observational data. Whether this counts as 'understanding' is up to you.

(*iv*) One of many attempts at understanding motion in General Relativity, sometimes mentioned as AE's last 'useful' paper[94].

*The Eddington universe, with $M = E$ from Special Relativity, and the Pauli exclusion principle from quantum mechanics, attempts to construct quantitative predictions of α and the number of particles in the Universe. It appears in a review of a 1949 book by Edmund T. Whittaker by Peter Bergmann, and you may know it as Eddington's *Fundamental Theory* (1944), the first mistake in which, according to Richard Feynman, occurs on page 7, after which he quit reading.

(*v*) An attempt to use kinetic energy of moving point masses to prevent the sort of collapse that Oppenheimer and Snyder[95] had reported[96]. This feels to me like a sort of flying off the handle upon encountering something one doesn't like. I've done it; perhaps you have too. Not being Einsteins prevents us from having our loose screws appear instantly in high-repute journals. Email and online sites allow us to be foolish even faster.

Moving forward, Einstein's scientific endeavours increasingly focussed on attempts to unify gravitational and electromagnetic forces, even after the recognition of a nuclear force. He said[97] that it was his experience with the theory of gravitation that determined his expectations. That is, a long struggle with moments of despair and rejoicing was to be expected, leading to eventual success. Erwin Schrödinger also spent many of his later years hunting for some theory that would unify the forces[44], but with equal lack of success.

The number of people working on various forms of unified field theory, or theory of everything, now greatly exceeds two. It is not 100% certain that their collective scientific creativity exceeds that of Einstein + Schrödinger, but they have much more powerful tools of strings, branes, and multiverses at their disposal. It is, however, pretty much guaranteed that any unified field theory that might emerge and triumph will be a quantum one, which would presumably have pleased Erwin but not Albert.

The events of 1922–23

There have been whole chapters and books written about Einstein's 1922 April trip to Paris[98,99]. This was the second half of a two-part visit originally arranged for 1914 by Paul Langevin, whose lab had worked on sonar during WWI. The first part came off pleasantly. The 1922 part included a public pairing of talks, variously described as a discussion or debate, between Einstein and Philosopher Henri Bergson (1859–1941)*.

Walther Rathenau was a strong advocate for Einstein making the trip in hopes of mending relations among European scientists; not all his Berlin colleagues agreed. And Langevin had had to work very hard to make the Paris side of the visit come off†.

The speakers genuinely disagreed about the nature of time. Their dialogue is published in the 1922 July issues of *Bulletin de la Société Française de Philosophie*. AE maintained that there were only two sorts of time, psychological (like his remark about 10 minutes spent sitting on a hot stove *versus* 10 minutes next to a pretty woman), and the time of physics, hosted in equations. HB maintained that there is also philosophical time, to which AE said, "*Il n'y a donc un temps des philosophes*." Topper and Canales agree that the two didn't understand each other very well. Jimena Canales is scheduled to speak on 2018 October 3 at the American Center for Physics in College Park, Maryland on 'The trouble with Einstein's time' in the Lyne Starling Trimble Lecture Series (yes, my father).

My answer to "what time is it?" is "about half past 2·725 K," and high time I finished Part III. This answer has now been available, with increasing precision,

*Bergson was the son of a Polish–Jewish father and British–Jewish mother. He became president of the British Society for Psychical Research in 1913. He wrote in his 1937 will that he thought Catholicism was an appropriate complement to Judaism, but did not convert because he didn't want to be seen to be escaping the events befalling Jews. The Vichy government offered him exemption from having all his offices and titles taken away from him, but he resigned these rather than accepting.

†The visit and its meaning appear *in extenso* in the relevant volumes of the Einstein Papers Project, which can now be searched at http://einsteinpapers.press.princeton.edu/

since 1965. I have no idea how Einstein would have reacted to it, but Prof. Canales apparently doesn't find it satisfying, or she would not still be lecturing about the topic.

Einstein and Bergson agreed about the merits of attempting European scientific reconciliation, and served together on a League of Nations international commission on intellectual cooperation (chaired by Bergson, and including Marie Curie[100]). They disagreed about religion and the role of government, Einstein having written to Rathenau (ref. 3, Doc. 305) that the only proper roles of nation-states were to look after hospitals, universities, the police, and so forth, for which some of the Swiss cantons were too small, but most European nations far too large.

The Nobel Prize events also belong to 1922–23. Of 32 nominations for 1921, 14 were for AE (Friedman, ref. 4 p. 129). Many of the scientists entitled to enter nominations did not. The Swedish Academy voted not to award the 1921 prize. In 1922 they voted for Einstein for 1921 and Bohr for 1922, with the ceremony to take place in 1922 December in Stockholm.

Einstein was in Japan (he picked up his prize in Gothenberg in 1923, lecturing on relativity, though the prize was for the photoelectric effect). His trip was in response to a request from a Japanese publisher for lectures on relativity in 1922 June, and somewhat motivated by death threats he had received after Rathenau's assassination. En route back, the Einsteins stopped in Palestine, where he spoke at the site that was to become the Hebrew University, beginning in Hebrew, continuing in French, and ending in German. Details of the trip appear in the recently published *Travel Diaries*[101] reviewed in *Science* (**360**, 722, 2018) by Andrew Robinson.

Also newly to hand is the latest Volume 15: *The Berlin Years: Writing & Correspondence June 1925–May 1927*. I haven't read it yet, but a review[102] mentions how very active Einstein was, interacting with colleagues on scientific and organizational issues. He "applied for grants, refereed papers; administered funds and institutions; grappled with personal issues; and was bored in meetings".

The letters, documents, and all have become so numerous that the paper publication has many items only in a Calendar of Abstracts. I pluck out one item, because it leads us directly to the next and last section. "The 1925 Locarno Treaties renewed Einstein's optimism in the prospects for European reconciliation."

Remember Great War hostilities ended in a 1919 June Treaty of Versailles (the Allies and Germany, the US signing through never implementing its commitment therein to the League of Nations). Over the next year, similar 'agreements' took in Austria–Hungary, Bulgaria, and Turkey, none with the US as a party (though there were subsequent US–Central Powers treaties), and Turkey refusing to sign off on hers.

The 1925 Locarno (Switzerland) Treaties (there were seven) aimed at solidifying the borders of France and Belgium with Germany (with the Ruhr by then back on the German side), Great Britain and Italy acting as guarantors. The price was leaving the eastern borders with Poland and Czechoslovakia relatively unprotected.

Long-term impact

Do we have better science? Certainly we have models, explanations, unexplained data, covering a much wider range of phenomena than did our scientific great grandfathers of 1914–18. It is much less obvious that there is more, or even equal, space for individual geniuses, to the point where the awarders of Nobel, Kavli, Breakthrough, Dan David, Gruber, Ambartsumian, and similar prizes have begun to recognize entities like 'A, B, C, and the D Team', though the Nobel holds its fortress at three. War, near occasions of war, and fear of war have unquestionably funded and driven many of these expansions. Martin Harwit[103] has worried that vitally significant science may somehow have been missed as a result of this process, though he gave no examples of, for instance, near misses.

The gravest result of WWI and its settlement was, of course, World War II, and some modern historians have suggested that the whole thing should just be described as the 31-year war, Part 2 starting at the flimsy boundary left at Locarno. Do we have better wars? Perhaps, at least different in the sense of being so far self-limiting, like common colds compared to the Black Death, and restricted in area involved compared to WWII, though 73 years is not very long in the great scheme of things.

As for impact on General Relativity, three very important outcomes of WWII were radar giving rise to radio astronomy, German rocketry giving rise to X- and gamma-ray astronomy from space, and (counting the lead up, the war, and the aftermath) massive relocations of physicists.

Radio astronomy has given us not just better measurements of light deflection by the Sun and large numbers of discrete sources that could be counted to rule out the Steady State, but also the cosmic microwave background radiation (absolute time in the Universe), binary pulsars, and the first quasars. X-ray astronomy gave us binary systems with black-hole components, whose behaviour has on the whole confirmed the Schwarzschild and Kerr solutions of Einstein's equations. Various combinations of X-ray, gamma-ray, and radio data (plus long-suffering optical astronomy, some using adaptive optics developed for military purposes) have told us that most massive galaxies have black holes at their centres with masses a bit less than 10^{-3} of the stellar mass, and that black-hole birth and accretion are accompanied by relativistic jets that can point at various angles to the line of sight.

As for the relocation of people, Einstein, Weyl, and Peter Bergmann to Princeton; Bondi and Gold to England; and Schrödinger and Lanczos to Ireland are the golden tip of an iceberg. The founders of the Texas Symposia on Relativistic Astrophysics, Ivor Robinson, Alfred Schild, and Engelbert Schucking, were all born places other than Texas, indeed places other than the US*. Leopold Infeld was described in one of the web sources I encountered as, in his day, Canada's greatest theoretical physicist. Aspects of the Cold War sent him journeying again, along with Nathan Rosen, David Bohm, and Bernt Peters, a cosmic-ray physicist who had worked with Oppenheimer and ended up in Denmark.

Newspapermen used to speak of "the Afghanistan effect", meaning that three million people killed in an earthquake someplace distant and obscure would get fewer column inches than a lost dog in the neighborhood. Growth, indeed overgrowth, of instantaneous communication has reduced this effect, leaving us all far more aware of battles, of other places, and other peoples. No one quite knows what will be the weapons of World War III. But World War IV will be fought with stones, so said Einstein in 1949. This is already beginning to happen on the border of Israel and Gaza, which he had once hoped might be a homeland for both the peoples who claimed it.

*Wolfgang Rindler, who was at both First Texas (though not a founder) and the 50th anniversary gathering, reached Texas from Austria *via* England and Cornell.

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HISTORICAL OBSERVATIONS OF STEVE

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Recent work by MacDonald *et al.*[1] has highlighted the valuable work carried out by sky watchers and auroral enthusiasts in obtaining high-quality digital images of rare and unusual auroral structures. A feature of particular interest, which has been nicknamed 'Steve', typically takes the form of a short-lived arch, beam, or narrow band of light in the sky. MacDonald *et al.* have established that the phenomenon is characterized by a range of optically-visible low-magnetic-latitude structures associated with a strong subauroral ion drift. Respecting its nickname, they have dubbed the phenomenon STEVE, an acronym for Strong Thermal Emission Velocity Enhancement. Here, we draw attention to earlier observations of similar structures, showing that some previously unidentified atmospheric, meteoric, or auroral 'anomalies' can now be recognized as examples of 'Steve', and therefore as part of a broad spectrum of occasional auroral features that may appear well below the region of magnetic latitudes represented by the traditional auroral oval. This highlights the contributions of 'citizen scientists' dating back hundreds of years, and the importance of reassessing historical reports of rare auroral luminosities for a full understanding of the range of solar activity over millennia.

The 'Steve' phenomenon

The discovery of 'Steve', exemplified by puzzling observations of a visually bright, very thin east–west aligned auroral-like luminosity typically positioned south of the zenith in the northern hemisphere rather than towards the north, as would usually be the case, first became widely known through an article in the *New York Times* by Fortin[2]. Images and descriptions of the phenomenon can be found there and elsewhere in both the popular and scientific press, and on the Internet[1–7].

Key characteristics of 'Steve' are that it is usually seen: (*a*) as a bright, rather stable luminosity ranging in duration from a few minutes up to an hour or more; (*b*) closer to the equator than a normal aurora and potentially visible over a wide geographical area; (*c*) as a narrow, finely structured band, arch, or elongated patch of light, often passing close to the zenith; (*d*) orientated in an approximately east–west direction, sometimes showing a large angular extent and ranging up to hundreds or thousands of kilometres in length, occasionally showing a slow, coherent motion towards the south or north; (*e*) as grey or white in colour to the naked eye, sometimes with tinges of other luminosities such as yellow, pink, mauve, or purple, rather different from the reds and greens of a normal aurora; (*f*) occasionally accompanied by streamers or by a green, rapidly evolving 'picket-fence' structure aligned nearly perpendicular to the line of the arch; and (*g*) invariably associated with normal polar auroral activity.

In referring to 'Steve', we note that there is an alternative, strongly held view[8,9] that 'Steve' is not new, that it has been observed for at least 50 years, and is still not sufficiently well understood to merit the acronym suggested by MacDonald *et al.* According to that view, the phenomenon should be given a broader label, namely a Sub-Auroral Arc (SAA). In this work, we use the term 'Steve' because it was that which first drew our attention to the phenomenon, and this may be true for others, and because it provides a convenient and scientifically neutral moniker to describe a wide range of poorly understood, but distinctive and morphologically similar visual auroral luminosities. Older descriptions of the aurora borealis (*e.g.*, ref. 10) often distinguished two types of auroral phenomena: one (which we identify with 'Steve') appearing uniformly between magnetic ESE and WSW in the form of a luminous arch and shining with a steady and more or less vivid light; and the other (which we identify with the more frequent 'normal' auroral phenomena) usually appearing closer to the magnetic pole, and often shining with a diffuse green or sometimes red light, showing striae and 'curtains' with very rapid movements and variability.

The key features noted above serve to distinguish 'Steve' from other auroral structures, for example the proton aurora, caused by precipitation of protons rather than electrons into the lower thermosphere and mesosphere, and characterized by a broad, diffuse structure and emissions largely invisible to the naked eye; the discrete classical electron auroral arcs (*e.g.*, ref. 11), which have different colours from 'Steve' and usually occur poleward of the proton aurora, which itself occurs poleward of 'Steve'[1]; the Sub-Auroral Red (SAR) arc, caused by energetic electrons from the magnetosphere and normally characterized by largely monochromatic red emissions at a wavelength $\lambda \sim 6300$ Å, produced by neutral oxygen atoms energized by the precipitation of electrons at heights greater or much greater than 150 km and seen close to the auroral oval; and the Sub-Auroral Ion Drift (SAID) phenomenon, which MacDonald *et al.* suggest is similar in some respects to 'Steve' but with a significantly lower temperature, higher minimum electron-density, n_e, and lower drift velocity, v.

The visual appearance of 'Steve' thus seems to be produced by optically thin thermal emission from a narrow, spatially confined region comprising a high-velocity flow ($v \sim 6$ km s^{-1}) of high-temperature ($T \sim 6000$ K), low-density ($n_e \sim 10^4$ cm^{-3}) ionized gas[1], though its precise origin in the ionosphere remains unresolved. It is noteworthy that there may be a seasonal variation in the frequency of observations of 'Steve', showing biannual equinoctial peaks similar to that of the wider auroral phenomenon, and a suggestion[5] that it may appear only during the northern summer months March to September inclusive.

Interest during the 1890s

The work by MacDonald *et al.* highlighting the 'Steve' phenomenon struck a chord, reminding us of a late-19th-Century description of what had been described as 'a rare phenomenon'[12,13]. This had been seen from Scotland and Norway on the night of 1891 September 11 and on the same evening by Dreyer at the Armagh Observatory and Wilson at the Daramona Observatory, both in Ireland[14,15]. In a review[16] of Wilson's observations from Daramona, the phenomenon is characterized as 'a rapidly moving comet'. It is noteworthy that the same phenomenon was seen from London and other places in England[17,18], and a similar feature was seen from Scotland two weeks later[19].

Copeland remarked that according to a letter[20] published in *The Scotsman* on 1891 September 14, a similar luminosity, slightly tinged pink at its eastern end near the horizon, had been observed from south-west Scotland the previous evening (1891 September 10), while Dreyer noted that a comparable structure had been observed[21] during the early evening of 1890 October 27 from Grahamstown, South Africa, and described as a comet. Copeland also drew attention to an apparently similar phenomenon recorded by Barrell[22], seen from Sutton at Hone, Kent, on 1717 March 30 (O.S.).

While some of the observations discussed here feature descriptions only partially matching the seven main characteristics (*a*) to (*g*) of 'Steve' outlined above, either because they are not detailed enough or because they focussed on other features, many of them describe phenomena that align with our understanding of 'Steve' very well indeed. To take a good example from the end of the 19th Century, there were numerous reports of what was described as a 'curious light' seen on the evening of 1896 March 4 (*e.g.*, refs. 23–28). It was observed in Oxford, Malvern, Cambridge, Dunsink, and Wolverhampton and was visible for a significant amount of time, characteristics (*a*) and (*b*), at least 20 minutes and perhaps up to an hour or more, and vanished in a manner "quite inconsistent with the idea of the light disappearing by setting rather than fading". Its appearance was described as resembling the tail of a very bright comet in the west barely 1° wide. This matches characteristics (*c*) and (*d*) very well. The light was white or 'ordinary pale yellow', characteristic (*e*), with no streamers observed. Later that night, 'auroral light and streamers were seen in the north', which matches characteristic (*g*). As is clear from the ordinary meeting of the RAS at the time, the authors — and indeed many others who observed the phenomenon — could not come to a definite conclusion as to its cause: was the light produced by a particularly strange and condensed zodiacal light or a very unusual comet, or was it — as discussed by Ellis[29] — auroral? To the modern eye, the observations clearly match descriptions of 'Steve', as it fulfils all the required criteria. From the amount of space in the astronomical journals of the day dedicated to this peculiar event it is evident that interest in such phenomena was very high at the time.

Historical reports

Observations of peculiar sky glows, streaks, arches, columns, beams, and slowly moving disc-like patches of light, lozenges, or luminous bands in the sky have been reported intermittently, but consistently, by numerous observers over at least three hundred years. Sometimes these phenomena appear — and indeed subsequently turn out to be — cometary (*e.g.*, ref. 30), and sometimes they resemble a meteor train, a faint misty patch similar to the Milky Way or zodiacal light, or a very high, slowly moving sunlit cloud (*cf.* visual observations of Comet C/1983 H1 IRAS–Araki–Alcock[31]).

There are many cases, however, when the phenomenon fails to show the characteristic very slow motion of a comet, which if bright is invariably visible for at least several nights, or the rapidly evolving snake-like appearance of a wind-driven persistent meteor train (*e.g.*, refs. 32, 33), but instead is associated with — although apparently separate from — an active aurora. Early-19th-Century examples include those described by Dalton[34] and Longmire[35], namely the aurorae of 1814 April 17, 1814 September 11, 1819 October 17, 1825 March 19, 1826 March 29, and 1827 December 27. Later instances include those of

1831 January 7, 1833 September 17, 1847 March 19, 1858 March 14, 1863 April 9, 1870 October 14, 1871 November 2, 1875 May 16, 1882 November 17, 1895 March 13, 1896 March 4, 1898 September 10, and 1899 March 15 (*e.g.*, refs. 36–54).

While Groneman[36] inclines towards his own meteoritic hypothesis for the origin of the phenomenon, his article is noteworthy due to the inclusion of an illustration of the arch seen on 1871 November 2 from Groningen, The Netherlands. The 'curious light' seen at Oxford and elsewhere on 1896 March 4, initially reported by Turner[23], was extensively reviewed by Ellis[29] who concluded that it was neither cometary nor a manifestation of the zodiacal light but 'certainly auroral'. Corliss[55] provides a compendium of many such auroral 'anomalies'. Examples from the early 20th Century include those of 1903 August 21[56–58] and 1908 May 25[58], the 'immense arc or ribbon of light' observed on the night of 1916 August 28 by Satterly[59] from Jackson's Point, Lake Simcoe, Canada, and a 'strong narrow ray' some 150° long and 1° wide observed on 1937 April 27 by Bobrovnikoff[60].

Older examples include the aurorae of 1715/16 March 6 O.S.[61–63], sometimes nicknamed 'Lord Derwentwater's lights'[64,65], 1725 September 26 O.S.[66], 1726 October 8 O.S.[67–72], 1731/32 February 29 O.S.[73], 1736 August 25 O.S.[74], 1738/39 March 18 O.S.[75–77], 1749/50 January 23 O.S.[78], 1765 October 12[79], and 1769 February 26[80].

Less certain identifications include observations associated with the aurorae of 1705/06 March O.S.[81]; 1707 April 3 O.S.[82], 1707 November 16 O.S.[83], 1764 March 5[84], 1899 February 11[54], and 1908 May 25[58]. Further possibly related auroral features, for example the 'meteor' seen at Oxford on 1760 September 21[85], the unusual nocturnal arches seen on 1729 November 16, 1787 June 20, and 1788 June 17 from Portugal, Brazil, and Spain, respectively, and discussed by Carrasco *et al.*[86], and the 'fluctuating clouds' associated with the aurora of 1909 May 15[58], appear to be 'Steve'-like but are so far unexplained. Drawings of the peculiar 'meteors' reported by Swinton[85,84,79] are discussed by Olson & Pasachoff[87].

The frequency of recorded aurorae has fluctuated significantly over historical time-scales, broadly reflecting observed changes in solar magnetic and sunspot activity, and changes in the position of the Earth's magnetic pole and hence the auroral oval[88]. 19th-Century sources, for example the extensive review of the aurora borealis by Loomis[89], show that whereas observations of relatively stable auroral features such as broad auroral arches, pillars, beams, *etc.* are comparatively rare, they were seen sufficiently often by early observers to enable an assessment of their general properties. For example, the height of the arch phenomenon was estimated sometimes to be as low as around 100 km, with the apparent arch (a perspective effect) usually extending from a point towards the east, peaking either north or south of the zenith and ending towards the west. The azimuthal extent was often less (but occasionally more) than 180°, with one arm of the arch located in a direction either slightly north or south of true east or west and the other in the opposite general direction dependent on the arch's overall azimuthal extent. Similarly, any motion or translation of the arch towards the north or south was found to occur much more frequently in the direction north to south in the northern hemisphere, though not exclusively so, the ratio depending on the observer's latitude.

The morphologically similar characteristics of a bright, slow-moving, sharply defined beam, column, or patch of generally white luminosity with a duration most frequently less than a few minutes but occasionally ranging up to tens of minutes and rarely up to an hour or more, and with an arc-length on the sky ranging from a few degrees up to 70° or more, and occasionally passing the zenith, are also suggestive of the 'Steve' events described by MacDonald *et al.* Observations of these similar structures, with colours ranging from white to grey, pale-yellow or straw, and less often reddish or sometimes crimson or blood-red, may provide insight into the more general phenomenon, although one must take care not to stretch the definition of 'Steve' too far, with the attendant risk of blurring possibly important distinctions between different types of rare auroral phenomena.

Our review of earlier observations of such 'Steve'-like phenomena has uncovered a large number of probable and possible examples, some of which are summarized in Tables I–VIII. Of course, assessing the likelihood that a particular observation does, in fact, correspond to an instance of 'Steve' or a closely related phenomenon inevitably involves an element of subjectivity and it is possible — perhaps probable — that others would come to different judgements in particular cases. Nevertheless, our assessment shows that the earliest 'modern' description of 'Steve', or a 'Steve'-like event, appears to be the phenomena reported by Derham[82,83], for example the aurorae of 1707 April 3 O.S. and 1707 November 16 O.S.; or if not these then the rare luminosity associated with the aurorae of 1715/16 March 6 O.S. and 1716 April 2 O.S. (*e.g.*, refs. 61, 62), all of which occurred around the end of the Maunder Minimum conventionally dated between 1645 and 1715. A still earlier possible example might be the observation reported by Wallis[90], who regarded the 'meteor' seen during the early evening of 1676 September 20 O.S. as probably a small comet that happened to pass close to Earth.

Further early-18th-Century examples would be those described by Maunder[91] and Halley[92], reporting the aurorae of 1719 November 10 and 11, the latter of which was described as similar to the luminosity seen on 1715/16 March 6 O.S.; the report of an aurora from Dublin on 1719 November 24 O.S.[93]; and that by Cramer[94], observed from Geneva on 1730 February 4 O.S. Several early-19th-Century examples (*e.g.*, those of 1825 March 19 and 1826 March 29[34]) appear to be associated, although not exclusively so, with the increase of solar activity around the end of the Dalton Minimum conventionally dated between approximately 1790 and 1830. Dalton provides an estimate for the height of these rare auroral arches of approximately 160 km.

In Table VII, the entry for 1833 September 17 is notable for being associated with a period of major auroral activity, which was reported not just from Britain and Ireland[37,38,95,96] but across Europe[97] and the USA[98]. This suggests a very high worldwide level of solar activity at the time perhaps comparable to the 1859 Carrington event. It is interesting to speculate that it was the bright aurorae observed during 1833 mid-September and mid-October (*e.g.*, ref. 99) that inspired the Irish novelist William Carleton to include a very detailed description of an aurora borealis in his work *The Priest's Funeral*, published the following year[100].

In the same table, the entry for 1858 March 14[39] is notable for being possibly the only ground-based instrumental response from this period suggestive of short-wavelength radiation originating from this type of aurora, presumably produced by soft X-rays or near-UV radiation from the hot 'Steve'-like region itself, which in principle could be heated to even higher temperatures than the currently observed 6000 K. The extent to which short-wavelength radiation from an exceptional solar flare, aurora, or 'Steve'-like event could pose a health risk to those on the ground remains to be explored. However, it is noteworthy

TABLE I

Examples of Possible Pre-Eighteenth-Century Observations of 'Steve'.
Dates are given Old-Style (O.S.). S denotes 'Probably Steve'; P 'Possibly Steve'.

'Steve'?	*Date*	*Location*	*Notable Characteristics*	*Source*
P	218 BC	Italy	At Rome in the winter of 218 BC, "a spectacle of ships gleamed in the sky".	114, p. 82
P	204 BC	Italy	"at Setia a torch was seen to be stretched out from the east to the west".	111, p. 89
P	173 BC	Italy	In 173 BC, "at Lanuvium a spectacle of a great fleet was said to have been seen in the sky".	114, p. 83
P	100 BC	Italy	In 100 BC, probably at Rome, "a circular object like a round shield, burning and emitting sparks, ran across the sky from west to east at sunset".	114, p. 83; 111, p. 92
P	687/688 Feb	England	A comet rose out of the west, and with great brightness went to the east.	116, Vol. 1, p. 78.
P	992/993 Jan 7	Germany	On the 7th of the Calends of January, at one o'clock in the night, suddenly light shined out of the north like midday; it lasted an hour, but the sky turning red, the night returned.	116, Vol. 1, p. 92.
P	1101	England	Was seen as a flying fire from the east toward the west, like no small City.	116, Vol. 1, p. 106; 117, p. 131
P	1177 Nov 30	England	November the 30th, a light shone from east to west. This light and redness like burning fire flew with the wind in England; some affirmed they saw a fiery dragon at the same hour with a crisped head.	116, Vol. 1, pp. 125–126; 117, p. 144
P	1254 Jan 1	England	A prodigious, large ship was clearly and plainly seen in the air. After some time, it seemed as though the boards and joints were loosed, and then it vanished.	116, Vol. 1, p. 149; 117, p. 156
P	1559/60 Jan 30	England	Burning spears	61
P	1564 Oct 7	England	A frightful meteor or aurora borealis. The northern quarter of the sky was covered with flames of fire that reached the zenith and then descended west. Although there was no Moon, it was as light as full day. Terrible lights and fiery meteors had often been seen the previous winter as well, sometimes standing still, other times suddenly darting streamers; they continued all summer and the beginning of next winter.	116, Vol. 1, p. 228–229; 117, p. 222
P	1650 Nov 30	England	About sunset, the sky opened in a fearful manner in the SW over Standish, five miles from Gloucester. A terrible fiery shaking sword appeared, with hilt upward and point downward, long and of a blue colour. At the point was a long flame of fire, sparkling and flaming to the fear and wonder of the spectators. At last the sky closed, the sword vanished and the fire fell to the ground.	116, Vol. 1, p. 327
P	1676 Sep 20	England	Seen in most parts of England between 7 and 8 o'clock at night. A sudden light appeared equal to that of noon-day, so that the smallest pin or straw might be seen lying on the ground. Above was seen a long appearance as of fire, like a long arm with a great knob at the end of it, shooting along very swiftly. It might have been an ordinary meteor, except that it was seen in most parts of England at or near the same time, suggesting a very high-altitude phenomenon such as a comet.	90

TABLE II

Examples of Early-18th-Century Observations of 'Steve'.
Dates are given Old-Style (O.S.).
S denotes 'Probably Steve'; P 'Possibly Steve'.

'Steve'?	*Date*	*Location*	*Notable Characteristics*	*Source*
S	1705/06 Mar 20	England/ France	A glade of light like the tail of a comet, but pointed at the upper end.	81
S	1707 Apr 3	England	After sunset, a long slender pyramidal appearance perpendicular to the horizon with base near the Sun, then below the horizon. Initially a vivid rusty red colour. Similar to the white pyramidal glade of light seen March 20 the previous year.	82
P	1707 Nov 16	Ireland	Mr Neve's observations reported by Derham. A strange light in the north, as bright as a Full Moon rising. Streams or rays like the tails of comets, but broad below and ending in points above, extended nearly perpendicular to the horizon. The motion of the dark and lighter parts ran strangely through one another, sometimes east and sometimes west. It continued for at least 15 minutes.	83
S	1715/16 Mar 6	Off NW coast of Spain/ England	A clear cloud to the east not far from the zenith from which emerged rays of light like the tail of a comet of such great length that it reached the horizon. A body of light appeared towards the NNE, continuing almost as bright as day till after midnight. Halley and Cotes describe an exceptionally brilliant aurora the same night, initially emerging from a dusky cloud low in the NE with edges tinged with a reddish yellow colour. From this 'cloud' arose luminous rays or cones perpendicular to the horizon, rather like candles on a cake, while its base moved swiftly along the northern horizon towards the WNE. The whole event, with many rays and streaks, soon produced a bright corona. The rays or beams were like erect cones or cylinders resembling long cometary tails, some of which lasted minutes, others just appeared then died away, while others moved from east to west under the Pole. Around 9 pm a series of very thin vapours arose from the east, ascending at lightning speed so as to pass between 15° and 20° north of the zenith, leaving a momentary dilute and faint whiteness. Around 10 pm two very bright streaks, about a degree broad, were seen lying parallel to the horizon towards the NE. Towards the end of the display, which lasted most of the night, a very bright obelisk of a pale whitish light greater than any previously seen was observed moving from E to W, disappearing towards the NW.	62, 61, 63
S	1716 Apr 2	England/ Ireland/ France	On March 31 and April 2, Dr Taylor saw appearances of the same kind as those of March 6. They began soon after sunset and continued until after midnight. Both 'clouds' were centred around 10°–15° westward of north, with an azimuthal extent of around 80°. Martin Foulks, from London, saw a bright ray of very white light suddenly appear in the ENE, resembling the tail of a comet. While this suddenly disappeared, it was replaced by another such beam, not exactly in the same place but in the same situation. After remaining stationary for nearly 10 minutes it moved slowly westwards, while growing fainter and after a further 10 minutes or so disappeared towards the WSW.	62

TABLE III

Further Examples of Early-18th-Century Observations of 'Steve'.
Dates are given Old-Style (O.S.).
S denotes 'Probably Steve'; P 'Possibly Steve'.

'Steve'?	*Date*	*Location*	*Notable Characteristics*	*Source*
S	1716 Jul 25	England	A cord of light of a pale colour, running from north to south, about 10 yards long.	116, Vol. 1, p. 483
S	1717 Mar 30	England	Around 11 pm, a long, narrow streak of light extending east and west, initially shining very bright but fading after 8 or 9 minutes. Its motion (if any) was southward. After a further approximately 7 minutes the eastern part of the streak became visible again, though dim, and it disappeared after a further 4 or 5 minutes.	22
S	1725 Sep 24–26	Ireland	A series of bright aurorae. About 9 pm on the 26th, one of the frequent irregular arches of light reached the zenith, with its lower points towards the ENE and WSW. This was observed for at least a quarter of an hour. The lower part was a constant fixed light, equal to the edge of a white cloud in daytime when the Sun shines on it. As it rose higher, it was somewhat weaker, with pillars or beams of light that moved after each flash of the aurora. Higher still, the flashes were like explosions of great guns, showing faint colours of red, green and yellow. After these, there remained a thin, duskish vapour in and near the zenith, and all along the arch from east to west. This undulated and moved like a stormy sea, the motion coming from the SSE. At the same time, another thin cloud, with a similar appearance arch-ways was noticed to the southward, presumably the remnants of another auroral arch.	66
S	1726 Oct 8	England and elsewhere	An exceptional auroral display, including a luminous arch extending across the sky from near sunset to moonrise, rising above the horizon about 25°, and from which emerged a great number of rays and luminous streams about 10° above it. Langwith describes a stream of light, almost due west and up to 8° broad, extending upwards to about 40° and inclined slightly towards the south. The stream was dusky red on its northern side, but pale on the other side and seemed to have other colours too. There was another stream of pale-coloured light towards the NE. This moved with a slow regular motion towards the west and about 8 pm suddenly expanded in every way. The brightness increased substantially, and the arch was edged by colours as full and strong as the brightest rainbow, showing red, yellow and a dusky bluish-green. Huxham describes a vast fiery red-coloured 'obelisk', which shot from the west to a height of 30–40° and remained for at least 15 minutes. Hallett describes a great light extending over the zenith from east to west. Derham describes a long narrow cloud extending from WSW to ENE at about 8 pm, which emitted streams and within a few minutes disappeared. Hadley describes a hazy arch low to the southward, fainter but steadier than that to the north, while Derham also notes a report at around the same time (c.7.30 pm) of a slightly curved arch, resembling a narrow, yellow rainbow, extending from roughly east to west and which remained for around 15 minutes. The whole auroral display lasted at least 3 to 4 hours.	67–71

TABLE IV

Examples of Mid-18th-Century Observations of 'Steve'. Dates on or before Wednesday 1752 September 2 are given Old-Style (O.S.); those on or after Thursday 1752 September 14 are given New-Style (i.e., following the modern Gregorian calendar). S denotes 'Probably Steve'; P 'Possibly Steve'.

'Steve'?	*Date*	*Location*	*Notable Characteristics*	*Source*
S	1731/32 Feb 29	South Atlantic	Reported by James Montgomery, Commander of 'The Monmouth' from approximately 3000 km west of Cape Town. The moon being nearly full, a very bright light, like a comet, rose in the west and after about 5 minutes passed from west to east between the Moon and our zenith and southward of Spica, carrying a stream of light after it about 40° long and between 1·0° and 1·5° wide.	73
S	1736 Aug 25	England	In a review of a 1739 book by J. Huxham. Between the hours of 9 pm and 11 pm, there appeared a narrow, but very bright band, which extended entirely from west to east, like a great rainbow.	74
S	1738/39 Mar 18	England	Mortimer describes a bright column seen near the ENE around 7.30 pm and reaching up to a point a little south of the zenith. It had a uniform steady light, but sometimes vanished for a few minutes then reappeared. At around 8 pm the column grew much wider, extending beyond the zenith towards the horizon in the WSW. Martyn describes a broad red band extending slightly north of east, apparently fixed, neither radiating nor fading, the band or arch bounded on the north by streams of greenish blue extending northwards. Later, there was a great brightness close to the zenith but declining to the SW. Neve notes that the 'aurora australis' lasted for about an hour and a half, and spread with a variety of colours all over the horizon. It faded as it moved slowly towards the north.	75–77
S	1743 Oct 4	England	A clear night with great shooting of stars between 9 and 10 pm, all shot from SW to NE, one like a very large comet in the meridian, like fire, with a long broad train of fire after it, which lasted several minutes; after which was a train like a row of thick small stars, for 20 minutes which dipped north.	116, Vol. 2, pp. 313–314
S	1749/50 Jan 23	England	About 5.30 pm a reddish light towards the SSW, shining with such extreme brightness that the constellation of Orion was almost effaced. Looking NNE there was a very broad band of crimson light, like that seen a decade earlier (1738/39 March 18) but this time much darker red. A very deep crimson band or arch was observed, about 15° broad and passing just above Canis Minor and ending towards the west, near Venus, which was then about 20° high. The whole event lasted a little over 2 hours.	78
S	1760 Sep 21	England	Dark cloud, like a pillar or column of thick black smoke, and perpendicular to the horizon, appeared around 6.40 pm in the NW, pushing gradually forward towards the zenith, until at last it extended almost to the opposite part of the heavens in the NE. Several degrees in width. Exterior limb of the arch was tinged with a pale yellow, the lowest part black, and other parts white.	85

TABLE V

Examples of Late-18th-Century Observations of 'Steve'.
S denotes 'Probably Steve'; P 'Possibly Steve'.

'Steve'?	*Date*	*Location*	*Notable Characteristics*	*Source*
S	1764 Mar 5	England	Bright, white column of light, with a base some 20 to 30 degrees above the horizon. It rose nearly 30°, passing to the south of the zenith. Much narrower at the top than the base, giving a pyramid-like appearance.	84
S	1765 Oct 12	England	A broad luminous arch in the northern sky, extending from east to west almost terminated by the horizon. The upper or exterior limb of the arch was white and resplendent. Lasted about an hour.	79
S	1769 Sep 9	England	A bright luminous arch extending roughly E-W slightly northwards of the zenith, lasted about 20 minutes. In several respects similar to the event of 1737 December 5. The colour was red; the brightness nearly equal to that of the full Moon on a cloudy night.	80; cf. 116, Vol. 2, pp. 115–117, 215
P	1781 Mar 27	Eastern USA	Auroral arch stretching from nearly due east towards the WNW.	89
P	1787 Jun 20	Brazil	A white, rainbow-like arch, visible for about an hour and extending from WSW to ESE and drifting in a poleward direction.	86

that among the most famous north-Norwegian beliefs about the aurora was its potential to cause harm[101,102]. In Alaska and the Faroe Islands, for example, children were advised to avoid going outside or to wear a hat in the presence of an aurora in case it would scorch their hair, and in Sweden people were warned against having a haircut during auroral activity[101].

Many earlier examples of possible or apparent 'Steve'-like luminosities exist, for example, some of those in Table I, but the nature of the reports is such that the older they are the more difficult it is to be sure of the precise nature of what was observed without further investigation on a case-by-case basis, drawing on primary sources. What is certain, however, is that the range of celestial phenomena — and of space weather and solar activity more generally — that has been experienced by humanity over thousands of years must be much greater than that which has been scientifically recorded over just the last three hundred years, covering what one might call 'modern' astronomy.

Discussion

Observations of Sun-like stars, that is, slowly rotating G-type stars with surface temperatures in the approximate range 5600–6000 K and rotation periods in the range 10–20 days or more, have revealed the existence of so-called 'superflares' with energies in the range 10^{26}–10^{29} J, roughly corresponding to the high-illuminance X-ray-flare classification X100–X100000. (For comparison, the famous Carrington flare of 1859 September 1 had an estimated energy corresponding to around X30.) From statistical analyses of these super flares on other stars it is found that events greater than X1000 occur once every approximately 800 years, and the larger X10000 flares every 5000 years or so[103], that is, within a time-period covered by recorded history. It is also possible, in

TABLE VI

Examples of Early-19th-Century Observations of 'Steve'.
S denotes 'Probably Steve'; P 'Possibly Steve'.

'Steve'?	*Date*	*Location*	*Notable Characteristics*	*Source*
S	1814 Apr 17	England, Ireland	A similar arch to that seen on 1814 September 11.	35
S	1814 Sep 11	England, Scotland, Ireland	A very beautiful meteoric object in the shape of an arch, initially around 7.30 pm increasing its length from W to E as if it had been slowly projected in that direction, and finally extending from slightly north of east to slightly south of west. The colour was greyish white, resembling that of the white parts of clouds when the Sun shines on them. It had a weak lustre, through which stars could be seen, and during the time of observation moved southward. At 8.20 pm the arch disappeared at the eastern end, and at the western end around 8.25 pm. After the arch disappeared, several large clouds of faintly luminous bodies occasionally passed over to the south. The height was estimated to be around 15 km. It differed greatly from common meteors, from solar and lunar bows, and from the common aurora borealis.	35
S	1819 Oct 17	England/ Scotland	A singular and beautiful phenomenon about 8 pm. It was a bow or arch of silvery light stretching from east to west, and intersecting the meridian a few degrees south of the zenith. After remaining very bright for around 20 minutes, dark blanks were first observed to take place here and there, and then after expanding a little in breadth and shifting a short way further southward, it disappeared. It was strikingly different from any of the usual forms of the boreal lights, which too were seen very vivid that evening.	34
S	1826 Mar 29	England/ Scotland	Immediately after the fading of the evening twilight, at 8.15 pm, a bright luminous ray was seen to rise from the eastern horizon, gradually extending itself towards the zenith and thence towards the western horizon, presenting, when completed, the appearance of an arch of silvery light, similar to that seen on 1825 March 19. It soon evinced a decided motion towards the south; the direction very nearly at right angles to the magnetic meridian. The arch continued its motion towards the south, and in 15 minutes passed through about 20°. The light became gradually fainter, and at length disappeared.	34
S	1827 Dec 27	England	A luminous arch, first seen around 6.10 pm, stretching from east to west and passing through the zenith. It was broadest in the zenith, and more condensed in the eastern extremity than in the western. A second, parallel arch appeared about 20° north of it, of rather less intense light. After around 10 minutes, the arches both moved approximately 20° towards the south. The total appearance lasted about half an hour.	34
P	1830 Dec 7	Sweden	A very bright patch, twice the size of the Moon's disc, moved with great velocity behind the common auroral beams.	36

principle, for the Sun to generate a sufficiently large sunspot within a few solar cycles that could lead to superflares in the X1000 class[104].

Support for adopting a 'long-term' perspective as to the likely range of solar activity over hundreds or thousands of years comes from the so-called Miyake

TABLE VII

Examples of Mid-19th-Century Observations of 'Steve'. S denotes 'Probably Steve'; P 'Possibly Steve'.

'Steve'?	*Date*	*Location*	*Notable Characteristics*	*Source*
S	1831 Jan 7	Germany, Britain	A bright yellow streak seen above the western horizon, rising upward with a common cloud-velocity, passing 30° north zenith distance, and forming an arch from W to E, beginning to disappear from the west end, almost at the same time that it reached the eastern horizon. A moving cloud as bright as the Milky Way passed from east to west in five minutes.	36, 37
S	1833 Sep 17	England	A very peculiar luminous stream or streak of apparently phosphorescent light in a direction about WSW. Visible for about 50 minutes from approximately 9.15 pm. Was similar in general appearance to the feather of a quill, but not so wide in proportion to its length. The central part at least four or five times as bright as the Milky Way. A very bright aurora was seen worldwide about the same time.	38, 95, 97, 98
S	1847 Mar 19	England	A brilliant band of light suddenly appeared, extending from the western horizon upwards across the zenith to at least 20 or 30 degrees beyond. It was a whitish colour and appeared to be moving southward. The width was nearly 3° and it lasted for around 45 minutes.	29
S	1858 Mar 14	Ireland	An aurora of more than average brightness. At 11 pm it showed an arch extending from W to ENE, which emitted a few yellow streamers; and the sky above it was covered with diffused light, over which brighter portions flickered like waves extending several degrees beyond the zenith.	39
S	1863 Apr 9	Eastern USA	Auroral arch in the early evening, stretching from east to west inclining about 15° towards the south. The apex comprised a line of short streamers, presenting the appearance of a row of comet tails all parallel to each other. It gradually moved to the south at a rate of around 10 degrees in 20 minutes. The whole phenomenon lasted about an hour.	40
S	1870 Oct 14	Scotland	At 9 pm, besides some ruddy aurorae, chiefly in the west and north, a band of light very similar to that of 1871 November 2. It stretched all the way across the sky from west to east, and continued for some time without much apparent change in figure or locality.	53
S	1871 Nov 2	The Netherlands/ Germany	A strange, brilliant arch, striped parallel to its well-defined sides and changing its curve during its two hours of existence. It began like an elliptic patch of light around the Pleiades. It disappeared slowly, beginning at the east end. See image in Groneman (1883).	36
S	1875 May 16	Freemantle, W. Australia; Adelaide, S. Australia	Bright white light 7 or 8 degrees wide, extending from WNW to ESE about 20 degrees north of the zenith, resembling a lunar rainbow, lasting around 45 minutes. Its light was that of a very bright white cloud; its form like that of an elongated feather without any shaft.	41

event[105] seen in the ^{14}C tree-ring record around 775, which can be understood by postulating a powerful but not inexplicably strong solar-energetic-particle event[106]. We note that several of the inferred 18th- and 19th-Century 'Steve'-like events occurred after periods of prolonged low solar sunspot activity,

TABLE VIII

Examples of Late-19th-Century Observations of 'Steve'.
S denotes 'Probably Steve'; P 'Possibly Steve'.

'Steve'?	*Date*	*Location*	*Notable Characteristics*	*Source*
S	1882 Nov 17	England and elsewhere	A very brilliant streak of greenish light about 20° long appeared in the ENE, and rising slowly, passed nearly along a parallel of declination, a little above the Moon, disappearing after two minutes in the west. A spindle-shaped beam of glowing white light, quite unlike any auroral ray, formed in the east. It slowly rose towards the zenith, gradually crossing apparently above the Moon, and then sank into the west, slowly lessening in size and brilliancy as it did so, fading away as it reached the horizon. The peculiar long spindle shape, slow gliding motion and glowing silver light, and its isolation from other parts of the aurora, made it a most remarkable object. A white, cloud-like object, in shape like a fish-torpedo or a weaver's shuttle, was observed to cross the heavens from east to west. Its length was about 30° and its width about 4°. Its surface had a mottled appearance, its colour white, its motion slow; it was visible, horizon to horizon, upwards of 50 seconds.	43, 44, 52
S	1890 Oct 27	South Africa	A comet was seen at 7.45 pm and observed until 8.32 pm, when the last trace faded towards the SE. It travelled from nearly due west around the western and southern horizon at an altitude from about 20° to 25°, and disappeared in the SE. At its longest it was fully 90° in length, while in width less than 0·5° except where it became very faint and slightly spread out at its posterior extremity. The preceding portion was a point in cometary form, but no nucleus could be discerned. The Moon was full.	21
S	1895 Mar 13	Germany	An appearance very similar to that of 1896 March 4, in the WNW, taken to be auroral.	29
S	1896 Mar 4	England	Around 8.55 pm, a splendid 'comet' plunging head foremost into the distant trees exactly in the axial line of the zodiacal light, against a faint, clear sky.	23, 24, 26, 27, 29
S	1898 Mar 15	Yerkes Obs., USA	Twice a brilliant and enormously long irregular ray of light about 1° or 2° broad stretched across the sky south of the zenith and perpendicular to the meridian. This had a slow motion to the south and was sinuous. A white, comet-like ray – perfectly resembling a comet – extending from near the east horizon through Jupiter, remained stationary for upwards of an hour. Patches and wisps of nebulous light appeared in all parts of the sky. In the beginning, before a third arch broke up, bluish white masses of intense light appeared on the arch and moved very rapidly to the right.	54
S	1898 Sep 10	Yerkes Obs., USA	A magnificent and superb display of an aurora, the most striking feature of which was a great comet-like mass of intense light with head to the southwest of Orion, and stretching across the sky slightly south of the zenith, to the west horizon. It was some 20° wide and very much resembled some of the photographs of Brooks' comet of 1893. It moved slowly to the SE, and faded after about 10 minutes. So bright was the aurora that at times the light in the north cast a distinct shadow of a person across the ground.	54
P	1899 Feb 11	Yerkes Obs., USA	One-side arch, a singular occurrence.	54

such as the Maunder and Dalton minima, and it is perhaps relevant to note that sunspot records of the last two or three solar cycles suggest that we may now be approaching another grand minimum, although with magnetic energy presumably continuing to build up below the Sun's visible surface.

In the 17th and 18th Centuries, the project to disentangle the physically diverse but morphologically similar 'meteorological' phenomena illustrated by these kinds of observations ultimately led to the gradual overthrow of the then prevailing Aristotelian dogma[87] and to a separation — which continues today — between meteorology in the modern sense of the word and 'meteoric' phenomena, which we now understand are produced by processes in and sometimes far beyond the Earth's upper atmosphere. At the same time, from the perspective of the meteorologist, the scientific advances that led to increased 'professionalism' in the measurement and reporting of meteorological data led to a decrease in the frequency of reports of rare or unusual meteoric events and 'prodigies' in the professional scientific literature[65], although relevant observations — largely reported by citizen scientists — can still be found in a wide variety of miscellaneous journals and newspaper articles. Nowadays, not only is the phenomenon of climate change and 'space weather' drawing astronomy and meteorology back together, but there is growing interest in the effects of exceptional space-weather events on our modern, but technologically sensitive, global economy (*e.g.*, ref. 107), with global costs for a Carrington-level event estimated to be trillions of US dollars[108].

An issue of growing importance, therefore, is how best to interpret the broad spectrum of occasionally vague and sometimes unreliable historical records in terms of phenomena that we would now recognize as (for example) 'atmospheric', 'stellar', cometary, meteoric, or auroral. The existence of 'Steve'-like phenomena among the latter, occupying a morphologically central position between comets, bright meteors, aurorae, and the zodiacal light, exacerbates the problem of definitive identification. But the increasing interest in all aspects of space weather, particularly its magnitude, range, and time-variability[109], provides an additional strong motivation to obtain, if only statistically, a sound interpretation of the full range of natural phenomena that have been experienced by humankind over thousands of years. Many rare and unusual events will by their very nature have occurred unexpectedly and have been witnessed by people with little or no formal education and knowledge of 'meteorology' let alone modern astronomy. For this reason, many historical reports are likely to be inherently inaccurate, perhaps even misleading, and their substance therefore veiled in the historical record, but the observations on which they are based should not be lightly ignored or dismissed as fanciful.

Conclusion

Our principal conclusions are the following:

(*i*) Historic observations can add significantly to our understanding of 'Steve'. They show that it has been observed many times in association with certain active auroral displays and is not a new phenomenon. Nor is it limited to the northern-hemisphere summer months March to September (Tables I–VIII). During the 18th and 19th Centuries, it was seen as early as January (*e.g.*, the aurora of 1831 January 7[36,37]) and February (*e.g.*, the aurorae of 1730 February 4 O.S. and 1749/50 January 23 O.S.[94,78]) and as late as November (*e.g.*, the aurorae of 1871 November 2 and 1882 November 17[36]) and December (*e.g.*, the aurora of 1827 December 27[34]). Similarly, the colour — whether white, red, yellow, green, blue-green, crimson, blood-red, or deep purple — provides clues as to the source of its luminosity, for example its temperature, ionization state, and height in the atmosphere, as well as the origin of the energetic particles that ultimately drive the processes that produce the observed physical structures and emission. So far as the curious light seen around 9 pm on 1896 March 4 is concerned, Herschel[26] remarked that the axial colour had a ruddy tint, the rest being ordinary pale yellow, a colour confirmed by observations by Newall from Cambridge[24], while Monckton[27], observing from Wolverhampton, noted that the phenomenon lasted more than an hour after he first saw it.

(*ii*) The scientific literature contains references to a wide range of rare and unusual astronomical and meteorological phenomena, which if anecdotally reported nowadays might for various reasons receive less scientific attention than in the 18th and 19th Centuries. However, such observations should not be dismissed simply because they are not professionally made or seemingly inexplicable or inconsistent with the current prevailing paradigm. This applies particularly to reports found in historic documents dating back hundreds or sometimes thousands of years. For example, the existence of well-documented historical sources enabled Willis *et al.*[110] to identify the earliest known conjugate sightings of northern and southern aurorae. Excellent articles, books and compendia include those by Barrett[111], Stothers[112–114], Ramsey[115], Janković[65], Short[116], Hetherington[117], Kronk[118], Valle & Aubech[119], Chatfield[120], and Mr. X[121], all of which provide references to numerous primary sources.

(*iii*) The advent of affordable digital cameras, telescopes, and home computers, together with access to the Internet, has tipped the balance of discovery back towards citizen scientists, stimulating a range of highly productive 'Pro–Am' collaborations in certain areas of science. The increasing trend towards specialization in modern science means that professional scientists are sometimes no better informed than educated amateurs once they move significantly beyond their individual specialisms. This can give an edge to the work of capable amateurs and well-informed citizen scientists, who — although not always professionally trained — may have more time to investigate the most informative elements among the historical records of 'Steve'.

(*iv*) The appearance of 'Steve' is often associated with pre-midnight auroral activity and has sometimes been confused with, or is reminiscent of, either the tail of an exceptional but hidden comet or the zodiacal light (*e.g.*, refs. 50, 24–27) or the passage of a bright comet (*e.g.*, refs. 73, 21), or the train of a bright meteor, fireball, or stream of interplanetary dust (*e.g.*, ref. 36). We suggest that 'Steve'-like phenomena may also include slowly moving disc-like patches of bright light, lozenges, or other rare auroral shapes and features (*e.g.*, ref. 55). Historically, their brightness has sometimes been likened to that cast by the full moon or even broad daylight.

(*v*) Careful re-reading of early records of anomalous or unusual 'meteorological' phenomena and sky glows may help to resolve more of these rare luminosities into different aspects of the wider auroral phenomenon, providing new insight into their underlying frequency and cause. Data mining this cultural heritage, much of which is now on-line, illustrates the value of 'citizen science' observations dating back hundreds of years and more. It provides an exciting opportunity for today's citizen scientists to make new contributions to knowledge by recording and researching old and often puzzling observations in the light of modern understanding, at the same time opening a new window on the impact of such phenomena on humanity over thousands of years.

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CORRESPONDENCE

To the Editors of 'The Observatory'

On the Velocity of Gravitational Waves — further thoughts.

My sincere thanks to Jonathan Thornburg for his considered response[1] to my previous letter[2] on this subject. I should say immediately that it was in the hope of prompting precisely such discussion that that original letter was written, and that I do, indeed, agree with almost everything Dr. Thornburg says. That in turn prompts some further thoughts and clarifications which I believe are worth stating.

In reference to J.T.'s first and last paragraphs, I should re-emphasize that it is not the truth, *per se*, of the *result* $c^{\star} = c$ — either as arising from mathematical analysis in General Relativity or as an empirical fact of recent observation, neither of which I take to be in serious doubt — with which my suggestions were primarily concerned. Rather, those suggestions were an attempt at something which appears to be lacking in the existing literature, a clear, first-principles *explanation* for this feature of fundamental physics recently put under the spotlight by the dawn of gravitational-wave astronomy. While both the theoretical analysis and the observations compel belief in the mind of anyone competent to appreciate them, neither conveys any direct physical understanding of the necessity of the result. Maybe in the end no such direct, first-principles explanation proves possible and this is a case of Einstein's dictum that everything should be made as simple as possible, but not simpler. But that is no reason for not first making the attempt.

I am entirely persuaded by Thornburg that the argument based on the proposed thought-experiment is, in fact, incomplete. That argument rests on a point of view to which Einstein† himself seems to have inclined, that the observed invariance of the velocity of light is itself a direct consequence of the Principle of Relativity, in which case that implication would necessarily apply with equal force to the propagation of gravitational waves. A logical counterexample exists, however: the Ritz Emission Hypothesis of 1908, in which the velocity of light is source-invariant rather than observer-invariant, is equally consistent with the relativity principle, so the latter form of invariance of the signal-velocity cannot simply be assumed, either for light, or for gravitational waves. Therefore, the propositions "c = Lorentz invariant" and "$c^{\star}$ = Lorentz invariant" *not* both being consequences of the relativity principle, they could be true or false independently of each other, and the proposed argument fails.

So has anything been achieved? Actually, I remain convinced that it has, for two reasons. Firstly, as Thornburg points out, the uniqueness argument does prove that the observer-invariant signal velocity is unique — if c and $c^{\star}$ are any two such, then $c = c^{\star}$ follows. This is certainly not trivial and surely should be included in any rigorous development of relativity from first principles, yet a straw poll of the 15 books on the subject immediately to hand on my shelves, from 1921 down to 2005, failed to find any acknowledgment of that basic point. Secondly, for that reason, the proposed argument does at least provide one of the only two steps required to demonstrate that $c^{\star}$ for gravitational waves must equal c. That then focusses attention on the second step, that of proving the Lorentz invariance of $c^{\star}$: isn't it possible to find a simple argument which does for gravitational waves what de Sitter's 1913 double-star argument did for Ritz's hypothesis about light? Or a more general argument which deduces a contradiction from the proposition that remote signals may exist *not* having the invariance property, alongside others (light) which do have it, all within the same framework of physical law? Surely there must be a principle of 'democracy of media' among such means of observing the physical world? It certainly isn't self-evident that the answers to both of these questions must be 'no'.

One secondary point where I do take issue with Thornburg's critique is his invoking of neutrinos. The moment that ν's are allowed non-zero rest-mass their velocity becomes completely undefined by the laws of nature, as they are now ordinary material particles whose velocity is arbitrarily variable on the interval $(0, c]$, unlike light, gravitational waves, or radiation transmitted by any other

†Which is to say, regarding the numerical value of c, as derived from Maxwell's equations as $c = 1/\surd(\mathrm{e}_0\mu_0)$, as being a law of nature and therefore subject to the relativity-principle. There are a number of hints of this in his writings and Einstein did not at all give the prominence to, for instance, the Michelson–Morley experiment which is such a feature of accounts of Special Relativity in the English-speaking world. (In any event, the one thing which that experiment did not test directly, countless statements in subsequent textbooks notwithstanding, is the Lorentz invariance of 'c'!) Such an argument would apply equally, *mutatis mutandis*, to wave-propagation in the gravitational field because, whatever the mathematical details of the relevant theory and the corresponding value it predicts for $c^{\star}$, that result would logically have exactly the same status as a law of nature as does Maxwell's result for c.

long-range interaction independent of a material medium, all of which must propagate at velocities — whatever they are — uniquely fixed by the relevant field-equations, *i.e.*, by the laws of physics†. It was for precisely this reason that I excluded 'transfer of material particles' in my original letter: as for neutrinos, so for house-bricks.

If in the end, however, any attempted classical proof of $c^\star = c$ from first principles even in the weak-field case proves to be impossible, can we fall back on a *quantum*-physics argument along the following lines? In quantum field theory, electromagnetism is an exchange-force mediated by transmission of virtual photons; for that to be of infinite range, the $\Delta E.\Delta t \geq \hbar$ form of the Heisenberg Principle requires the photon's rest-mass to be zero and therefore, by Special Relativity, its velocity to be exactly c; a pulse of real electromagnetic waves is, simply, a packet of photons and so must be visibly transmitted at that same velocity. Therefore, *if* gravity can be similarly quantized (perhaps a big 'if', after 50 years of trying?), exactly the same argument must apply, with 'gravitons' substituted for photons, and $c^\star = c$ immediately follows‡.

The relation of this discussion, on the other hand, to classical ideas of the 'propagation' of gravity itself, as in the gravitational-aberration argument (Thornburg, para.3), is, I suggest, a very moot one at best, notwithstanding these two issues being so frequently equated. The aberration argument, that any finite velocity of 'propagation' of gravity would result in a small aberrational offset of the force of attraction from the line of centres in the simple Kepler problem, so causing a secular acceleration of the mean motion, goes back explicitly at least as far as a 1776 memoir of Laplace§. Such arguments, ancient or modern, are unconvincing on the most basic conceptual grounds however, as they seem to imply a mechanistic view of gravity wholly alien to, and in no way implied by, either Newton's model of the phenomenon or Einstein's. Laplace, for instance, in order to introduce into his derivation the possibility of any physically meaningful velocity attaching to gravity itself, was driven to adopt a Le Sage-style 'explanation' for attraction as the effect of corpuscular impacts. Such nuts-and-bolts mechanisms for gravity are logically redundant and profoundly unconvincing even in Newtonian philosophy, let alone in GR.

† See footnote on p. 246.

‡ This is a special case of a more general argument going back at least to Hideki Yukawa's 1935 theory of the strong nuclear force; see H. Yukawa, *Proc. Phys.-Math. Soc. Jap.*, **17**, 48, 1935 and, especially, G. C. Wick, *Nature*, **142**, 994, 1938, in which he deduced the likely rest-mass of his proposed mediator from the range of that force. Both electromagnetism and gravitation, by contrast, are customarily described as being of infinite range but that, of course, is pure assumption strictly speaking. The objection is not relevant, however, as it would apply with at least equal force to the photon itself, as to the graviton: the recent *LIGO*, *et al.*, detections show that the range of the radiation-field for gravity is broadly comparable with the greatest distances from which light has been detected, and the observational evidence for the static (non-radiative) gravitational field acting at cosmological distances is actually far stronger than that for electromagnetism. Such cosmological distances are to all practical purpose infinite on the quantum scale and the only slightly novel feature of the deployment here of this long-established argument is its extension from virtual quanta to real energy-carrying ones.

§ See C. C. Gillispie (ed.) *Dictionary of Scientific Biography*, New York 1978, vol. xv, pp. 288–9. Laplace deduced a lower bound for this 'velocity' of $7 \times 10^6 c$ from the absence of any such effect in the lunar orbit and later went on to refine this in 1805 in his *Mécanique Céleste* to $1 \times 10^9 c$ by applying the argument to the Earth's heliocentric mean motion. In Newtonian dynamics it is not even necessary to appeal to astronomical observation, however: in such a two-body system a finite 'velocity of propagation' of gravity provides no possible mechanism for coupling of the orbit to any other dynamical degree of freedom, so conservation of angular momentum rigorously forbids any such secular acceleration, thus immediately requiring that hypothetical 'propagation' to be truly instantaneous. That, surely, is just another way of saying that 'propagation' isn't occurring in the first place.

Proponents of the idea of the classical gravitational field itself being transmitted or propagated — at any velocity — need, logically, to confront the following questions: (*i*) Why introduce such a notion, so at variance with the essentially reciprocal nature of the phenomenon, in the first place? Gravity is fundamentally a property of the *relationship between* bodies, not an inherent attribute pinned to the individual bodies. The force arises from that reciprocal relationship, something which cannot, in principle, be localized in space. (*ii*) How can such a notion be introduced anyway? That is, how, logically, can the 'velocity of propagation' of gravity be defined? What, exactly, is supposed to be propagating here? Certainly not energy, as a moment's consideration of the case of two attracting masses at relative rest demonstrates. And if not energy, then nothing material which can be said to possess a defined position in space and, thus, in principle, a velocity. There is a fundamental logical distinction between the clearly-defined transmission *by* the field of spatially localized material energy in wave propagation and any alleged transmission *of* the field itself: I have never seen any attempt at a coherent definition of the latter and seriously question its possibility. (*iii*) The clear distinction between these two things is brought into particularly sharp focus by *the self-defeating black-hole paradox*: gravitational-wave energy being propagated at c, any such originating within the event-horizon of a black hole is trapped there, just as light is — nothing paradoxical in that; but if gravity itself is 'propagated' at c in the simplistic sense often implied, the black hole would swallow its own static gravitational field as well and so could not be a black hole. This is something far worse than a mere physical inconsistency, a logical contradiction, a *reductio ad absurdum* which shows that the possible existence of black holes is incompatible with any naïve notion, at least, of gravity 'propagating' at c. Proponents of 'propagating' gravity must, then, define that notion clearly in such a way as to evade this paradox¶. Never having seen these questions even raised in the literature, let alone convincingly answered, I cannot take the idea seriously, for any alleged numerical value: to this student of such matters, 'the velocity of the gravitational field' firmly belongs in the same category of pseudoconcepts as 'the velocity of the aether'.

In any event, there is no need to invoke such a questionable construct in this discussion of the nevertheless well-defined velocity of gravitational waves, whose motivation was simply to attempt to bring simplicity and transparency to a foundational issue where none currently seems readily available.

Yours faithfully,
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¶This, on the face of it, appears to apply to the 'graviton' Q.F.T. model of gravity mentioned above, but the issue is not so clear-cut there as quantum tunnelling might possibly evade the difficulty. If not, on the contrary, perhaps this just proves that quantization of gravity is impossible in the non-linear régime?

Erwin Freundlich (Finlay-Freundlich) — Unlucky yet very Fortunate

In her substantial review of *The Impact of World War I on Relativity*[1,2], Virginia Trimble devoted a page (p. 102, June issue) to the work of Erwin Freundlich. He had attempted from an early stage to secure observational data that would test Einstein's Theory of Gravitation, and Trimble noted that Freundlich was remarkably unlucky in that regard. However, he was very fortunate in being appointed to the first Napier Lectureship in Astronomy at the University of St Andrews, Scotland, with effect from 1939 March 1, thereby being rescued together with his family from the Holocaust. Trimble's comment that Freundlich "resigned the Napierian Professorship in 1951" is not correct. Freundlich was *promoted* to the Napier Professorship in 1951 in reward for his work to establish the Observatory and Department of Astronomy at St Andrews, and for directing the manufacture of the world's first Schmidt–Cassegrain telescope. Subsequently, he sought to make a second Schmidt–Cassegrain telescope with a primary mirror of 37-inches diameter, and the delays and cost over-runs of that venture certainly tested the patience of the University Court. Freundlich suffered a heart attack in 1953 but recovered to go on a planned solar eclipse expedition to Sweden in 1954 with his refurbished 1929 equipment, but was 'clouded-out' — unlucky again. By the end of 1956, at the age of 71 years, Freundlich asked the University Court to find a replacement for him and offered his resignation, a request that was accepted, although he remained formally as Observatory Director until 1959. It was his successor, D. W. N. Stibbs, appointed from 1959 October 1, who directed the completion (in early 1962) of the second telescope, named the *James Gregory Telescope* (*JGT*).

As a former Director of the Observatory at St Andrews (1990–2006), it is a pleasure for me to record that the *JGT* was remarkably well constructed since it is still fully operational 56 years later, a credit to the team of designers and technical staff who built it. The *JGT* has been equipped with CCD cameras since 1992, and is almost entirely under computer control by the astronomer in a comfortable warm room — a very different type of observing experience from that of the 1950s and 1960s. Further information about the Observatory and its history may be found on the website maintained by the current Director (Dr. Aleks Scholz) at www.observatory.wp.st-andrews.ac.uk, which includes a link to my e-book[3] on that history in the History section.

Yours faithfully,
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REVIEWS

Dynamical Astrochemistry, by David A. Williams, Thomas W. Hartquist, Jonathan M. C. Rawlings, Cesare Cecchi-Pestellini & Serena Viti (Royal Society of Chemistry), 2018. Pp. 290, 24 × 16 cm. Price £159 (hardbound; ISBN 978 1 78262 776 0).

This excellent textbook provides an introduction to, and summary of, a field that was until recently on the fringes of astronomy, but now sits most definitely right in the middle of the mainstream. It is written by *the* key leaders in the field (Williams practically single-handedly invented the field). Molecules were first detected in space some eighty years ago, and the first molecules to be detected were CH and CN (not CO, as many astronomers believe). However, the advent of mm-wave radio telescopes around fifty years ago totally transformed the field, and at around the same time a relatively small band of interested chemists began modelling networks of molecular reactions in interstellar space, thereby creating the field of astrochemistry.

The significance of the word 'dynamical' in the title of this book is that the interstellar medium is of course not a static environment, and dynamical changes, such as cloud–cloud collisions, or gravitational collapse to form a star, can occur on time-scales shorter than the chemical-reaction times. Furthermore, changes in the chemical make-up of the gas can, in turn, affect the dynamical evolution of a cloud, if, for example, the ionization fraction changes and alters the interaction between the gas and the magnetic field.

This book analyses both of those aspects, with a couple of chapters on the effects of turbulence and shocks on the chemistry, followed by a long chapter on the effects of the chemistry on star formation, which essentially forms the 'meat' in the centre of the book. The equations of single-fluid hydrodynamics are derived, followed by the equations of magneto-hydrodynamics in both the single-fluid and multi-fluid cases. But don't be put off. There is plenty of explanatory text, some diagrams, and even a few pretty pictures, to illustrate the physics and chemistry that is being described.

A very broad range of topics is covered, from low- to high-mass star formation, post-main-sequence evolution, and even planet formation. Naturally, therefore, some topics are covered only relatively briefly, but there is extensive referencing at the end of every chapter for the reader to pursue topics of interest in greater detail.

This book will no doubt stand as the definitive work in this field for some time to come. If you have even a passing interest in the interstellar medium, either in the Milky Way or in other galaxies, you should read it. Furthermore, you will be able to give it to every future PhD student on their first day and say 'start here'. — DEREK WARD-THOMPSON.

Isaac Newton and Natural Philosophy, by Niccolò Guicciardini (Reaktion Books), 2018. Pp. 268, 22 × 14 cm. Price £14·95 (hardbound: ISBN 978 1 78023 906 4).

I enjoyed reading this book, and feel that Niccolò Guicciardini has provided a very fine and very accessible account of one of science's outstanding figures. It is published as part of a series entitled 'Renaissance Lives', placing Newton in a context of cultural history, along with Michelangelo, Rembrandt, Pascal, and John Evelyn.

Very importantly, Newton's life is unfolded within a rich historical context, including much more than just the optical and gravitational science which immortalized his name. In particular, I like the preliminary 14-page 'Introduction. Images of Newton' section. This section and Chapter 1 introduce the reader to Newton's world and the leading cultural currents of the 17th Century. These include the complex national and international politics of the age, the centrality of religion, the still very viable cultures of alchemy and magical philosophy that were taken seriously even by the most learned, the importance of Biblical prophecy and interpretation, and how they all related to what was emerging as experimental and observational science.

In short, what was 'truth', and how did one best go about elucidating it in 17th-Century Europe? Even within the wider scientific community, indeed, there was the problem of how the mathematical, mechanistic science of René Descartes related to the experimental science of the early Royal Society. Was it the pure intellect, or hands-on 'putting nature to the torture' through trial and error and physical observation, that would supply the golden key?

For this was the world of 'natural philosophy': a world within which Isaac Newton lived and thought from his Grantham schooldays onwards. Professor Guicciardini, an academic at the University of Bergamo, Italy, with two major Newton studies already to his credit, is very well placed to deal with the technical aspects of Newton's achievement, especially in optics, mechanics, and gravitation theory, all of which he treats in considerable detail, and with great lucidity.

Professor Guicciardini also does a good job of placing Newton alongside his scientific contemporaries. Yet while he devotes several pages to the work of Robert Hooke, I feel that he is inclined to follow the fashionable line in seeing Hooke as "occupying . . . an intermediate positon between the world of artisans and that of natural philosophers" (p. 81). For while Hooke, the Westminster School and Christ Church, Oxford, graduate, was indeed deeply 'hands-on' and a powerful advocate of the experimental method in science, he nonetheless had a formidable international reputation as a *gentleman* of broad learning; a Gresham College Geometry Professor and FRS who dined with Archbishops and noblemen, as well as with the conspicuously upwardly-mobile artisans such as Thomas Tompion.

Niccolò Guicciardini packs a great deal of very readable science and history into the 231 pages of his main text. The book is also fully referenced and well-illustrated. I warmly commend it as an excellent guide to Sir Isaac Newton and his historical and scientific world. — ALLAN CHAPMAN.

Giovanni Domenico Cassini: A Modern Astronomer in the 17th Century, by Gabriella Bernardi (Springer), 2017. Pp. 186, 24 × 16 cm. Price £23·99/$39·99 (hardbound; ISBN 978 3 319 63467 8).

This new biography of Giovanni Domenico Cassini (1625–1712) — or Cassini I as he was later known, in order to distinguish him from other astronomers of his dynasty — is to be welcomed. In addition to providing us with an insightful life-history including details of Cassini's early life in Perinaldo, Genoa, and Bologna (where he was appointed Professor of Astronomy) in a country that is now called Italy, we learn more about Cassini's family and his astronomer-nephews, the Maraldis (whose rarely seen portraits are reproduced). The case for Cassini's modernism as a 'European scientist' is stated as resting upon his rigorous scientific achievements, diversity, internationalism, and management skills.

The book rescues many details of Cassini's daily life from obscurity, and presents many newly discovered facts. The author displays very good judgement in assessing his various scientific contributions. Cassini's early work in Bologna was not limited to astronomy, for he was also Superintendent of Public Waters, and carried out investigations as a naturalist as well as several assignments for the Pope. Using a telescope by Campani, Cassini made an accurate estimate of the length of the Martian day, as well as observations of Jovian satellite shadows and the Red Spot (or an earlier incarnation of it). Some poetry he composed is given in the Appendix.

Louis XIV certainly made an inspired choice when he enticed Cassini to Paris. The latter became a naturalized Frenchman, taking the Christian name Jean Dominique. Cassini is remembered for his involvement in the design and subsequent directorship (from 1671) of Paris Observatory. An observer of considerable skill with the long 'aerial' telescopes of his day, it was from Paris that he discovered the major division in Saturn's rings as well as four of its satellites and the fact that the two hemispheres of Iapetus differ greatly in albedo. (By the way, Cassini even recorded a transient brightening of the planet's equatorial zone in 1683.) A map of the Moon followed. This is reproduced by Bernardi, but not the beautiful original drawings (which I had the pleasure of seeing a few years ago) upon which it was based. Cassini created a Dynasty in Paris, and was the first of four Directors of the Observatory to bear the family name.

This book ends with a number of interesting Appendices, including a chronological table of the astronomer's life and works, and a useful Bibliography. Springer is not noted for the excellence or detail of their Indexes, and in this case the Index is conspicuous by its absence. But there is a short table of contents at the front. Proof-reading of this book has been a little poor in places. It is well illustrated, containing some unusual and rare subjects, though it lacks reproductions of many of Cassini's own drawings. Given that his astronomical notebooks have long been on display to visitors to the observatory that he founded, that is rather a pity. Nevertheless the book is a very interesting read, and is certainly to be recommended. — Richard McKim.

What is Life? On Earth and Beyond, edited by Andreas Losch (Cambridge University Press), 2017. Pp. 316, 26 × 18 cm. Price £110/$140 (hardbound; ISBN 978 1 107 17589 1).

The definition of life, its origin on the Earth, and its possible existence elsewhere in the Universe are age-old questions which are addressed in the present volume. It is a collection of essays arising from a workshop, and is divided into three approximately equal sections — Science, Philosophy, and Theology — with fairly porous boundaries. The difficulty of defining life is brought out in several contributions. In hers, Maurel gives references to compilations of several-hundred definitions of life before continuing to consider origins and evolution. She contrasts the gradual view of evolution with punctuated equilibrium, long periods followed by brutal variations, and also introduces another recurring question: are viruses living creatures? After biochemistry, we have astronomy: Krissansen-Totton and Catling give a thorough and up-to-date account of the search for habitable planets, chemical bio-signatures, and SETI. Hofmann then surveys the morphological signatures of ancient microbial life in rocks. Fossil remains of vertebrates, invertebrates, and eukaryotic unicellular organisms have long been studied, but individual prokaryotic organisms have little chance of ending up as easily recognizable fossils. Those that grow in filamentous forms and/or excrete a slime-like sticky substance, however, can provide morphologically distinctive remains. Filamentous microbes can form colonies, resulting in streamers that can be fossilized and produce macroscopic build-ups having a characteristic texture: bio-fabrics. Hofmann provides striking illustrations, many in colour, of streamers and fabrics. He goes on to survey common types of morphologies preserved in rocks, including stromatolites, and discusses the distinction of biogenic and non-biogenic morphologies. The scientific section of the book is completed with a historical survey by Lazcano of the ideas of the origin of life running from vitalism (Dr. Frankenstein)* to the 'RNA World' *via* Lamark, Darwin, Oparin, and many others. Taken together, these contributions provide a fine scientific introduction for the non-specialist.

The first two contributions to the philosophy section (Morange and Beisbart) return to the question of life, including viruses, and the difficulty of defining it. Next, Weidemann discusses the Chance hypothesis, that the emergence of life on Earth was so sensitive to precise and improbable conditions that it was a unique event, and concludes that the hypothesis should not be dismissed too quickly. He adds that it dissolves the Fermi paradox: if our Galaxy is teeming with (intelligent) species, where are they? An alternative solution to the paradox is offered in the next contribution by Ćirković, who, in the spirit of broadening the discourse, quotes the science-fiction author Karl Schroeder's novel *Permanence*: because intelligence is significant only insofar as it offers an evolutionary advantage, it is bound to disappear once the selective advantage disappears, so that intelligent species degenerate. The final contribution in the section is rather different: Schneider discusses the likelihood of post-biological intelligent life, super-intelligent artificial intelligence (SAI). She follows the argument that, once a society creates the technology that could put them in touch with intelligent life on other planets, there is only a short window before they change their own paradigm from biology to AI, so that it is more likely that any aliens we might encounter would be post-biological.

In the theological section, Massmann moves away from Cartesian dualism and avers that where there's life, there's mind. In his contribution, Peters proposes a layered definition of intelligence and explores the continuity between human intelligence and that in other life forms. He also makes the point that if astrobiologists limit their search for bio-signatures, they may miss non-biological intelligence. Marrufo de Toro tackles the implications of the discovery of intelligent life elsewhere for the core Christian belief of Incarnation: was it unique to the Earth or were there many? — and settles on Deep Incarnation for all reality. The focus in this section is on Christianity, which seems restrictive. It would be interesting to know how Jewish and Islamic theologians view the prospect of finding (intelligent) life elsewhere, let alone scholars of other religions, including those that believe in reincarnation.

All the contributions are well written and extensively referenced. They fit together well and give the impression of careful editing. At the end, do we really know what Life is? In his Introduction, the editor quotes the NASA working definition, "life is a self-sustained chemical system capable of undergoing Darwinian evolution", and in his excellent Conclusion writes that the evolution of the special relation of its constituents might be the key to understand it. If we did find traces of life beyond Earth, we might learn more about the beginnings of its evolution here. — PEREDUR WILLIAMS.

*Mary Wollstonecraft's father had been a friend of Humphry Davy, one of the founders of electrochemistry, which may be the origin of the monster's electrical enlivening.

Gravity! The Quest for Gravitational Waves, by Pierre Binétruy (Oxford University Press), 2018. Pp. 245, 22·5 × 14·5 cm. Price £19·99 (hardbound; ISBN 978 0 19 879651 0).

This volume does not make the common mistake of describing cosmological redshifts as Doppler shifts. Instead we find Doppler–Fizeau effect, because the late author Pierre Binétruy and the colleagues who finished up this modified version of his 2015 *A la pursuite des ondes gravtationelle* are French. Another signature is the choice of short sayings at chapter heads, with Pascal, Proust, and Bergson, though Goethe and Shakespeare also appear. Bergson is perhaps least helpful, having written (in translation) "Time is invention or it is nothing" in 1922, the same year he and Einstein faced off in Paris, discussing the nature of time and related issues somewhat heatedly.

Can a reader learn about gravity and gravitational waves from Binétruy *et al.*? Yes, if said reader is not too fussy. The press conference that announced the first *LIGO* event on 2016 February 11 was said to have been sited at the National Science Foundation (in fact the National Press Building some miles away), and the agency director is called, both in text and index, Frances Cordova (she is France Cordova, an odd mistake for French authors). A black body is said to be one that reflects all electromagnetic radiation. Some numbers are written as 2·10–15. The spectrum of gravitational-wave frequencies is cut off at 102 Hz, with *Virgo* and *LIGO* in the equivalent of the ultraviolet, and no corner for cryogenic-bar detectors. Histories are simplified as usual: only Fritz Zwicky and Vera Rubin appear as part of the dark-matter story, and Richard Feynman is given full credit for the 'sticky bead' demonstration of the energy-transporting powers of gravitational waves at the Chapel Hill conference of 1957, something I would not have noticed except that the American Physical Society had a session on that conference at its April meeting in Columbus, Ohio, on April 17 (I am writing on the 20th).

Most of the illustrations are basic drawings, including Margie the cow, who discovers time dilation in cooperation with Albert Einstein, who is riding a train through her pasture. American cows are called Bossie, another cultural indicator. And we learn that vacua in Chinese tradition are much more dynamic than the western approximate equivalent.

Binétruy recommends three experiments for readers to conduct. The first involves smashing grandmother's last antique crystal glass, and I decided to skip it. The second is a really neat, cool (other adjectives of approbation) demonstration of what Galileo should have done at Pisa. First drop a book and a piece of paper separately. Book lands first; check. Now put the (smaller) piece of paper on top of the book held horizontally and drop together. Indeed they arrive at the same time, modulo the paper jumping off at the last second and flying under the desk.

We will now pause briefly while I rescue the cheque intended to recompense the colleague who taught my class while I was frivoling in Columbus (which British readers may think of as Nether Wallop or Little-Piddling-in-the-Marsh). Do try that one.

The third experiment begins, "You need a broomstick", which is a bit off-putting for female readers like your reviewer who are increasingly distressed by changes in their ages and appearance.

Speaking of appearances, only four biological entities appear in photographs. The contest for best-looking is a toss-up between Joseph Weber and a conch shell, presented "as a model of a horizon, within which tiny perturbations develop into a sound reproducing the surf". This appears in the chapter on inflation and is not quite the sea shell of one's childhood, which mostly showed that human hearing is remarkably sensitive. Indeed if you put the first *LIGO* event one astronomical unit away, you would receive about 10^{25} W m^{-2}, causing a strain $\Delta L/L$ of 10^{-6} (another item from Columbus). You won't feel or see this, but you might just hear it. And who were the other biological entities presented in photographic form? Albert Einstein and Abbé Lemaître together at the California Institute of Technology in Pasadena in 1933. — VIRGINIA TRIMBLE.

On Gravity: A Brief Tour of a Weighty Subject, by A. Zee (Princeton University Press), 2018. Pp. 197, 22·5 × 14·5 cm. Price £14·95 (hardbound; ISBN 978 0 691 17438 9).

This is a popular-science book on gravity, and as the title suggests, brief. The author, a professor of physics at the Kavli Institute for Theoretical Physics at the University of California, Santa Barbara, and author of several popular-science books and several university-level textbooks, writes that it is pitched between a typical popular-science book and a textbook, mentioning two of his own books[1,2] as examples. However, the level of this book is typical for popular-science books, or perhaps even a bit lower (as my history teacher used to say, just an observation, not a judgement), in which case his popular-science books must be very introductory. The book starts and ends with gravitational waves; many recent books on gravity of course (try to) take advantage of the recent detection of gravitational waves, even if neither the theory (which is not new) nor the *LIGO* detector is described in detail. The rest of the book covers what one might expect from a book at this level, with two exceptions: an appendix (more mathematical than the rest of the book) explains space–time, curved space, and curved space–time in an easy-to-understand way; and, unusually for such a book, the action principle is discussed extensively, not just as an alternative to but, in the opinion of the author, also as a better approach than equations of motion.

Although the material covered is similar to that in other introductory books about gravity, the presentation is somewhat different. First, although there are unnamed parts and named chapters and sections (some chapters and many sections being quite short), rather than being clearly organized, the book is more like one long essay. The conversational tone is reinforced by attempts at humour, always a matter of taste, of course — I found them somewhat corny and distracting. Second, a more serious complaint concerns digs at colleagues who see some things slightly differently; even if all of those are justified in some sense, they seem out of place in a book like this. Third, there is no mention (except for mentioning that they won't be mentioned) of the three classic tests of General Relativity, nor, except in passing, of such regular characters as Eddington. Fourth, Faraday, Maxwell, and Hertz — names normally not associated with gravity — are discussed in some detail, as part of the emphasis on fields, waves, and action. In a book of this length, one can't cover everything, and the somewhat different emphasis sets it apart from similar books at the same level.

Zee also departs from the traditional narrative in some respects. He often uses the term "Einstein gravity" rather than "General Relativity". (Interestingly, that was common in the early 20th Century.[3]) Zee says that relativity is "[p]robably the worst name ever"; while I wouldn't go that far, I agree that the term can be misleading; Zee also points out that it was first used by Alfred Bucherer in 1906, Einstein not having used it in his early papers. I'm also with Zee regarding the adoption of the traditional cosmological constant instead of 'dark energy', at least as long as there is no observational evidence that something more complicated than the cosmological constant is needed. However, that makes his criticism of those who prefer to have the cosmological constant on the left, 'geometry', side of the Einstein equation, instead of the right, 'mass–energy', side, somewhat confusing; usually, those who see the cosmological constant as something fundamental put it on the left side, while those who see it as another form of mass–energy put it on the right side along with the mass–energy tensor. That discussion goes back to Einstein and Schrödinger[4,5]. However, as Zee himself notes, his preference for the action formulation makes the choice moot.

As usual, the editing could have been better, although this book contains fewer typos and other blunders than most I have reviewed in these pages. I did notice two factual mistakes; both are rather common in the literature: Wheeler did not coin the term 'black hole', though he did popularize it[6], and Zwicky did not coin the term 'dark matter', which goes back at least to Kapteyn[7]. Several black-and-white figures are spread throughout the text, though strangely not all have the 'Figure' label. Confusingly, there are both footnotes and endnotes, with no apparent reason why some are one rather than the other. While I usually enjoy reading notes (especially the more convenient footnotes), this book contains too many. Some could be integrated into the main text; others are not really needed. The bibliography mentions about a dozen books by others and about half a dozen by the author, ranging from popular-science books to advanced textbooks. The 13-page small-print index is more than sufficient.

It's not clear who the target readership is. The sometimes too-breezy style might annoy those who are looking for something not found in similar books, while the discussion of action, curvature, *etc.*, might throw off those looking for an introductory discussion. It is thus not the 'if you read just one, this should be it' book. However, those with some basic knowledge of gravity can find introductory discussions of topics usually found only in more advanced works, while the colloquial style might appeal to some, perhaps other, readers. — PHILLIP HELBIG.

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(6) M. Bartusiak, *Black Hole: How an Idea Abandoned by Newtonians, Hated by Einstein, and Gambled on by Hawking Became Loved* (Yale University Press, New Haven), 2015.
(7) J. Kapteyn, *ApJ*, **55**, 302, 1922.

Gravitational Waves — Volume 2: Astrophysics and Cosmology, by Michele Maggiore (Oxford University Press), 2018. Pp. 820, 25·5 × 19·5 cm. Price £60 (hardbound; ISBN 978 0 19 857089 9).

This is the second of two excellent volumes on gravitational waves, following on from the successful first volume that covered theory and experiment. The second volume focusses more on the astrophysical and cosmological aspects, and the ten-year gap between the two volumes has very conveniently allowed time for the detection by *LIGO* of gravitational waves from the mergers of pairs of black holes and neutron stars. The publication is therefore perfectly timed. For anyone wanting to obtain a thorough understanding of gravitational waves, the combination of the two volumes is perfect. At the same time readable and rigorous, the book covers a lot of territory, setting the groundwork well to understand quite a lot of the details underpinning the analysis of gravitational-wave signals from coalescing binaries, since a fair amount can be understood mathematically without the use of numerical relativity solutions. This may be what draws many readers to this book, but it is much broader, covering gravitational-wave production in other astrophysical contexts, including from inflation, phase transitions, supernovae, and cosmic strings, and it shows how observations can constrain stochastic backgrounds of gravitational waves, for example, *via* pulsar-timing arrays or polarized microwave-background observations. A fair amount of theory is developed in this volume, but the book makes extensive reference to material in Volume 1, so having both on the shelf is recommended. It will appeal both to researchers in the field, and to a wider readership who want to understand gravitational waves at quite a deep level. To some extent, one can also get an overview of the subject, as the writing is quite accessible, but the book comes into its own for readers who are prepared to work through the mathematics to obtain a good grounding. For anyone wanting to get a thorough understanding of this field, or who wants a comprehensive resource covering essentially the entirety of this field, the two volumes are an exceptional resource, simultaneously delivering great depth and clarity. — ALAN HEAVENS.

Space Science and the Arab World: Astronauts, Observatories and Nationalism in the Middle East, by Jörg Matthias Determann (I. B. Tauris), 2018. Pp. 258, 22·5 × 14·5 cm. Price £59/$95 (hardbound; ISBN 978 1 78831 014 7).

In recent years my activities in space science and more general university collaborations and relationships have taken me to several Middle East countries. Behind the obvious headlines, it is a region both fascinating and challenging in many ways, but also, in my experience, welcoming and friendly to visitors. Consequently, I expected the subject of this book to be of particular interest to me and I was pleased to be sent it to review. On the other hand, I wondered how well the quite narrow subject area would work in this monograph format. The answer is, very well indeed! I had believed I knew quite a lot about this subject through my work, but this excellent volume has really exposed the breadth and depth of my ignorance.

Determann has made his exploration of the history and current politics regarding astronomy and space science a very accessible read. He covers the development of the subjects in modern history, spanning the last 150 years or so, referencing the important historical contributions made by Islam and the Middle East only briefly, but when appropriate and useful to the narrative. An important thread, running through the whole story, is the international nature of the work and how observatories and facilities came into existence to support the world-wide priorities such as eclipse and transit observations. More recently, the politics of space exploration has drawn the countries of the region into its grasp, and it is interesting to see how some have succeeded in their aspirations, while others have not.

Various chapters focus on the contributions of key individuals and influential roles played by US East Coast colleges and their off-shoots in the region. I was particularly struck by the problems faced through the turmoil of World Wars and political upheaval, which most of us in the UK have not had to face in the same way. How galling it must be to lose control of an observatory that you have built up and run over decades as a result of régime change, then have to see it decay through active neglect or even destroyed in a conflict, as happened to the Lee and Ksara observatories during the Lebanese civil war. Established research teams have broken up, as individuals were often forced to leave their countries and find new homes. Despite this, there are important contributions being made through the creation of new facilities such as *TRAPPIST* (*Transiting Planets and Planetesimals Small Telescope*), which made headlines with its discovery of the TRAPPIST-1 planetary system. Space science is also developing rapidly, particularly in the UAE with their Earth-observing satellites and a planned mission to Mars.

This book has been published by an independent publishing house, greatly to their credit, rather than one of the major science publishers. Therefore, it might not gain the broad readership it deserves: it was not on my radar until I received the invitation to review it. However, it should be of particular interest to scholars of the history of astronomy, giving a different perspective to the more usual European/USA focus, as well as those who are working, or might want to work, with astronomers and space scientists in the Middle East. I will certainly be much better informed for my next journey there, and I will arrive with a much better appreciation of the contributions of those countries and the often challenging path leading to them. — MARTIN BARSTOW.

Bode's Law and the Discovery of Juno; Historical Studies in Asteroid Research, by Clifford J. Cunningham (Springer), 2017. Pp. 304, 24 × 16 cm. Price £88/$139 (hardbound; ISBN 978 3 319 32873 7).

With this volume Dr Cunningham continues his deep plunge into the complexities and details of early asteroidal history. Juno, the third asteroid to be found, and now the eleventh largest, was picked up by accident by the German astronomer Karl Harding on 1804 September 1, just over two years after the gap between the orbits of Mars and Jupiter was found to be populated by the big two, Ceres and Pallas.

The Titius–Bode's law in the book's title was greatly supported by the 1781 discovery of the planet Uranus on an orbit of the predicted size. Much more praise was gleaned when the first two asteroids were also found to have orbits that fitted. Cunningham's first chapter considers how most scientists and philosophers of the day appreciated this indication of planetary harmony. Next we are treated to a description of the discovery and naming of Juno and the tentative first investigations of its physical properties and possible origin. Chapter 5 reviews the early-19th-Century poems that contain reference to the first four asteroids. This is an unusual treat. Poets, poetesses, school masters and school mistresses, plus an assortment of clerics, all vie for our attention. Many poems are quoted, and, where necessary, are translated into English. It would be rude to suggest that the infamous Scottish doggerelist William McGonagall has been trounced but many of the quoted poems run him a close second.

What I like about this book is its comprehensive nature and its thoroughness. Very, very little is left out. Anyone who deemed to mention the asteroid Juno in the early decades of the 19th Century is in, referenced, illustrated, described, translated into English, and quoted in full. We get the science, the research papers, and the appropriate letters, and the philosophic musings, and the poems, and the potted biographies of the observers and thinkers, and descriptions of their observatories and instruments. The book is a fount of information and a joy. — DAVID W. HUGHES.

Discovering Pluto: Exploration at the Edge of the Solar System, by Dale P. Cruikshank & William Sheehan (University of Arizona Press), 2018. Pp. 475, 23·5 × 16 cm. Price $45 (about £32) (hardbound; ISBN 978 0 8165 3431 9).

I have to admit that I am a Plutophile. I revel in the story of Percival Lowell's obsession with the Solar System and his theoretical and financial approach to the search for the elusive Planet X, the big one supposed to orbit beyond Neptune. I greatly admire the skill and tenacity of Clyde Tombaugh, an exemplar of an astronomer if ever there was one, who even after finding Pluto in 1930 quickly realized that it was too faint to be the alleged mystical perturber of the orbits of Uranus and Neptune and then kept on searching for nearly a decade. I love the stories of the naming of the third planet to be discovered in the modern history of the human race, and the reliance on Venetia Burney, an 11-year old Oxford school girl. I can understand Walt Disney, in 1930, changing the name of Mickey Mouse's dog Rover to Pluto in order to capitalize on the sensation of the newly named planet. I can sympathize with our American planetary colleagues who saw the estimated mass of 'their planet' Pluto diminish over the decades until it ended up at a mere fifth that of our Moon. I was heartened by James Christy's serendipitous discovery of Pluto's satellite Charon in 1978 and then the realization that the Earth and Sun would pass through Charon's orbital plane between 1985 and 1988 producing a series of eclipses, clearly not seen during the American Civil War when they had occurred before, and eclipses that will not be seen again until 2107/8. To me, as a young astronomer, one of the most intriguing diagrams was that produced by the Cambridge astronomer Ray Lyttleton showing how Pluto, after allegedly spending much of its life in a prograde orbit around Neptune, escaped from that planet and forced its satellite Triton into a retrograde orbit. I was fascinated by the possibility that Pluto and Charon, their mass ratio of seven indicating a binary planetary system if of ever there was one, were possibly formed by the condensing rotating fluid bifurcation process suggested by Sir James Jeans.

And then we were confronted with the demotion and relegation. I can sympathize with the story that a museum curator, tasked with putting on an exhibition of the planets in only two rooms (with thus only eight walls) realized that one of the known nine planets had to go, and small Pluto was the one. But then, looking on the bright side of Plutophilia there is the joy associated with the splendid success of the NASA *New Horizons* fly-by mission to Pluto and Charon and the confirmation of their incredibly diverse surfaces covered with nitrogen and methane ices, and the unmasking of regions of youthful geology fashioned by dynamical processes that are still taking place.

New Horizons flew past Pluto and Charon in 2015 July; so now is the ideal time to review the spacecraft results and compare them with expectations. This is exactly what the book under review does. It describes the tortuous road to the discovery of Pluto, the ever-present belief that there is a Planet X out there waiting to be found, the struggles and fortitude of Clyde Tombaugh, the efforts of Gerard Kuiper to investigate the surface characteristics using the then-rather-primitive tools of infrared spectroscopy, the attempts of the American planetary scientists to convince the funders that the 'main course' of outer-planet exploration (the Voyager missions) should be followed by the 'dessert' of a fly-by trip to Pluto, the role of methane, nitrogen, carbon monoxide, and water ice in the fashioning of certain planetary and satellite surfaces, the effects of ultraviolet radiation on those compounds to produce colourful organic tholins, the expectations and seasonal complexities of Pluto's atmosphere, and the choice of the space experimentation for the fly-by mission.

Dale Cruikshank, a renowned planetary spectroscopist, and a co-investigator on the *New Horizons* mission, and William Sheehan, an historian of planetary astronomy and a prolific author, are Pluto experts. Not only that, they have great skill in introducing the complexities of this planetary body to a general readership in a highly readable and engaging fashion. This authoritative, well-illustrated, and thoroughly-referenced book will be the 'go to' tome for anyone interested in that intriguing object for many years to come.

I am rather saddened that the somewhat derogatory term 'dwarf' is now being applied to Pluto's planetary status. When it comes to planets, Pluto might be somewhat metrically challenged, but when it comes to interesting characteristics, I certainly rate it above three of the 'Big Eight'; (Venus, Uranus, and Neptune, if you must know). What I liked specially about Cruikshank and Sheehan's approach was their optimism, and their emphasis on the mysterious. Many aspects of the superb images of the surfaces of Pluto and Charon pose more questions than they answer. The data from *New Horizons* will be studied for many decades to come. I am still not convinced we know where Pluto came from, or why it is the only double planet we have, or if it really is an example of what an Edgeworth–Kuiper-Belt object looks like. There is still a huge amount of work to be done, and this book will encourage many to set out on a fascinating investigation. — DAVID W. HUGHES.

Planetary Ring Systems: Properties, Structure, and Evolution, edited by Matthew S. Tiscareno & Carl D. Murray (Cambridge University Press), 2018. Pp. 582, 28·5 × 22·5 cm. Price £145/$190 (hardbound; ISBN 978 1 107 11382 4).

In olden days only Saturn was known to have one. But in the last 40 years we have learnt that all the outer planets have ring systems (and even the centaur asteroid 10199 Chariklo and the dwarf planet Haumea). These rings are equatorial, inside the Roche limits and also inside the magnetospheres. They abound with gaps, embedded moons, radial lanes, arcs, clumps, waves, and wakes. They suffer from plasma drag, electrostatic elevation, and a host of gravitational controlling factors.

For a review we previously had to rely on the 1984 University of Arizona classic *Planetary Rings*, edited by Richard Greenberg and André Brahic. But much has changed recently. Monumentally successful space missions such as the *Galileo* orbiter of Jupiter and the *Cassini* orbiter of Saturn mean that new data have flooded in and a new book is needed. And the book under review is a worthy and fitting update. It is a collection of 21 review articles, written by the experts in the field. All are superbly illustrated and referenced. We are introduced to the relevant facts, the history of the subject, and we are instructed as to the dynamic processes. Every ring in the Solar System is described in detail (if you want 25 large pages just on the F ring of Saturn, this is the book for you).

The book has detailed discussions on ring dust, radiation environments, ring origins, and computer simulations. The relationship between planetary rings and other astronomical ring systems such as pre-planetary nebulae and galactic discs is investigated. Reasons are given for the gaps and sharp edges.

This book is a *tour de force* which emphasizes the fact that not only are planetary rings one of the most beautiful phenomena in our subject they are also one of the most physically and dynamically challenging. And still we are not sure whether they are just remnants of the initial planetary-formation process, or were produced at a later time when some unfortunate satellite was ripped apart after being perturbed inside the Roche limit. And even though we have a good idea of what is on the surfaces of the ring particles, their interiors are still mysteriously hidden. And best of all we still have the problem of estimating the ring mass and longevity. As with many planetary objects, we now know a lot but there is still a huge amount to find out. This book is a great encouragement to those starting out on the investigation. — DAVID W. HUGHES.

A TRIBUTE TO DONALD LYNDEN-BELL

GIVEN AT THE MEMORIAL SERVICE, CLARE COLLEGE CAMBRIDGE, 2018 JUNE 22

By Ofer Lahav
University College London

It is an honour to pay this tribute to Professor Donald Lynden-Bell FRS CBE. He co-supervised me in Cambridge for my PhD in 1985–1988, and later I had the privilege to be his colleague at the Institute of Astronomy for many years. We also kept in touch after I moved to UCL. Last year I saw Donald and Ruth* at conferences in both Pune (India) and in Jerusalem (Israel). The always-energetic Donald was in his prime at those meetings, giving excellent talks, asking as usual clever probing questions in his distinct voice, and having stimulating conversations with all participants, junior and senior.

Donald was born on 5 April 1935 in Dover Castle. By a cosmic coincidence I was also born on 5 April (in Israel), and over many years we congratulated each other on that day (with Donald reminding me it is the end of the tax year!).

Donald's father was a military officer. He was with Field Marshall Edmund Allenby in 1917, when the British Army was taking over Palestine from the Ottoman Empire. He returned to the then-Palestine in the early 1930s, for another commanding role. When travelling with Donald across Israel I was impressed by his knowledge of the country, from biblical stories to the present-day complicated politics of the region.

*Ruth Lynden-Bell FRS is Emeritus Professor of Chemistry at Queen's University Belfast.

Donald's 'academic father' was the late Leon Mestel, who told me once that Donald was very independent as a PhD student. Donald made seminal contributions to astrophysics over six decades, among them the following major two: his 1962 paper (with Olin Eggen and Allan Sandage) proposed that our Galaxy (the Milky Way) originated through the collapse of a single large gas cloud. This has led to numerous other theoretical studies and experiments, including the *Gaia* satellite, which just released its recent excellent data; and in 1969 Donald hypothesized that quasars are powered by massive black holes accreting material, suggesting that most massive galaxies have black holes at their cores. This is currently our best understanding of those energetic objects. That work was recognized by the inaugural Kavli Prize for Astrophysics (jointly with Maarten Schmidt) in 2008. Other well-known studies by Donald include the highly creative ideas of 'Negative Heat Capacity' and the gravitational process he called 'Violent Relaxation' (what a poetic combination of those two words!).

My very first meeting with Donald was in the early 1980s. He visited his long-term collaborator Joseph Katz at the Hebrew University and gave an inspiring talk about the 'Mass of the Local Group of galaxies' at a conference there*. In September 1985 I arrived in Cambridge. My original PhD project† got 'side-tracked' by a conversation with Donald in one of the Institute of Astronomy morning coffee breaks.

He mentioned to me that he was part of a team of seven astronomers that later became known as the '7 Samurai', who were studying the motions of 400 elliptical galaxies relative to the overall expansion of the Universe¶. The 7 Samurai found that those galaxies share a motion towards a hypothetical clump of mass. Donald asked me to help him to create a galaxy map by merging three catalogues. It revealed a major concentration of galaxies, about 200 million light years away. We were so excited to see this 'Great Attractor' in full glory. The plot made it to the Lynden-Bell *et al.* (1988) paper and even to the cover of the *New York Times*!

Donald and I continued to exploit these maps, to figure out what is causing the motion of our Galaxy with respect to the Cosmic Microwave Background. After 30 years, the 'Great Attractor' still features in galaxy maps, but it is understood to be part of a larger network of clusters, filaments, and voids, called the Cosmic Web. At the same time Donald supervised other students‡ on a wide range of other topics, from Galactic Dynamics to General Relativity.

*Recently I revisited with students this mass estimate of the Local Group in the presence of Dark Energy, and had stimulating discussions with Donald about it.

†I started my PhD project with George Efstathiou on galaxy formation, which seemed a natural extension of my Masters project with Jacob Bekenstein. George Efstathiou succeeded Donald as the Professor of Astrophysics.

¶The '7 Samurai' were: Dave Burstein, Roger Davies, Alan Dressler, Sandy Faber, Donald Lynden-Bell, Roberto Terlevich, and Gary Wegner.

‡Among Donald's students that time were Wyn Evans (galactic dynamics), Jose Lemos (General Relativity) and Somak Raychaudhury (galaxy motions). At present they are Professors in Cambridge, Lisbon, and Pune, respectively.

Donald's research style was unique. He loved mathematics, and his blackboard and notebooks were always full of equations. I recall numerous sessions with him by the blackboard in his previous office at the Observatory building, which served earlier as Sir Arthur Eddington's dining room. Donald said once to a student that "a day without a calculation is a wasted day!". At the same time he really wanted to understand Nature, so mathematics was his tool to achieve that.

In an article in *Annual Reviews of Astronomy and Astrophysics* (2010) he reflected on the big questions of the field and on how to address them: "The great challenges for future astronomers will be the exploration of the 96% of the Universe now believed to be neither atomic nor baryonic but perhaps partially leptonic. However, most advances do not come *via* frontal attack but from 'bread-and-butter' investigations in related areas where observation is possible today!"

Donald served as Director of the Institute of Astronomy and as President of the Royal Astronomical Society, inspiring in these roles the work of others and promoting careers of many young researchers. A conference was held in 1995 for Donald's 60th Birthday, with the dinner hosted here at Clare College, and a conference book published by Cambridge University Press*. But it was only a 'mid-term' summary of his work, as Donald continued his highly creative research for 22 more years, until last December†.

On a personal level, Donald was warm and generous, and cared a lot about his students and colleagues. One of his many admirers told me the other day: "Donald's curiosity may have led to his fearsome questioning, but he was always inspiring. You always knew when you had been in a discussion with Donald!"

Donald was delighted to see his granddaughter Helen starting her Natural Sciences degree this year in Cambridge.

In recent years Donald became a movie star! The film *Star Men*‡ features Donald and three colleagues, Roger Griffin, Wal Sargent and Nick Woolf, on their 50th-reunion hike. It gives an insight into Donald's perspective on life, science, and religion. He was proud of the film and seeing his work appreciated that way outside academia.

Donald passed away peacefully at home on 2018 February 6, and his funeral took place on February 20 at St Edward's Church and was followed by a reception at Clare College. Today's memorial service is a great opportunity to celebrate Donald's life and his remarkable scientific achievements in understanding our cosmos. He inspired generations of astronomers, and those of us who were lucky to work with him will do our best to pass on Donald's spirit to our students and to our children.

* *Gravitational Dynamics*, eds. O. Lahav, E. Terlevich & R.J. Terlevich (Cambridge University Press), 1995.

† His last paper, with Kumar Chitre, on the entropy of the Universe, was published in *The Observatory* (**138**, 1, 2018). Donald published regularly in this *Magazine* and served as its Editor in 1967–1969.

‡ The film's director is Alison Rose.

Here and There

NOT ON THIS PLANET

An inaccuracy of a second will, on the equator, mean an error of a mile in the calculated ship's position. — *Daily Telegraph*, 2018 January 13, Letters to the Editor.

ENGINEERING OR ASTRONOMY?

New parallaxes of Galactic Cepheids from spatially scanning the Hubble Space Telescope — https://arxiv.org/abs/1801.01120, accepted for *ApJ*.

HUBBLE CONSTANT TAKES A KNOCK

This galaxy is at redshift 0·193 (about 3 million light-years from Earth) and associated with a persistent radio source, also of unknown nature. — *A&G*, **59**, 2.21, 2018.