THE OBSERVATORY

Vol. 137 2017 APRIL No. 1257

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2016 October 14 at $16^{h}\ 00^{m}$
in the Geological Society Lecture Theatre, Burlington House

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

The President. Before we start the programme of talks, it's my pleasure to present the award for the Gerald Whitrow Lecture, or rather the citation, to Neil Turok. The citation reads as follows, "Neil Turok is an outstanding theoretical physicist and currently Director of the Perimeter Institute, Canada. Much of his research concerns fundamental theories of the early Universe. During the 1980s, Turok investigated the role of topological defects in cosmology. With Stephen Hawking, he discovered instanton solutions describing the birth of an inflationary universe. More recently, Turok has been a prominent critic of inflationary cosmology, and he has proposed an alternative cyclic model of the Universe. Turok is an original thinker and is invited by the Royal Astronomical Society to give the 2016 Gerald Whitrow Lecture on the birth of the Universe." So that was the citation. The lecture will follow shortly.

The programme begins today with the Fowler Award Lecture which will be given by Dr. Andrew Pontzen of UCL, and the title is 'Genetically modified galaxies'.

Dr. A. Pontzen. Thank you very much for the invitation to speak at this meeting. I'd like to use the opportunity to tell you about a brand-new idea that I've been working on with several colleagues since arriving at UCL a few years ago. I particularly want to mention Michael Tremmel (a graduate student at the University of Washington) and Nina Roth (until recently a postdoc at UCL) who have worked very hard on aspects of what I am going to talk about.

I'd like to introduce a new way to set up computer simulations of the formation of galaxies. Our current techniques have served us well, but I'm going to argue that we now need more focussed ways to use the increasing power of computers. The goal is to account for the rich range of structures we see in the Universe.

I'm aware that this room has a huge range of expertise in it, so let me try to explain quickly where our current understanding lies. Computers have been invaluable in formulating the link between the early Universe (of 14-billion years ago) and the cosmos that we know today.

Over the last thirty years, a remarkable picture of the young cosmos has emerged. We now understand that our Universe was once near-uniform, with tiny irregularities that later grew into today's galaxies. The tiny irregularities were seeded by quantum fluctuations in the early Universe and have been observed directly in the cosmic microwave background (a left-over remnant glow from those early times) by missions such as ESA's *Planck* satellite.

The growth of galaxies over time is largely driven by gravity; if one region of the Universe has a tiny bit more stuff in it than its neighbours, there is a nett tug of gravity into that region. Consequently, its density becomes higher and higher. That process becomes immensely complicated to calculate, especially once the back-reaction from stars and black holes (both of which can heat and expel material) is included. This is where computers come in: we can program them with our understanding of those processes, and make very convincing virtual galaxies in that way.

But here's the question: how do we know what type of galaxy we should form inside our computer models? Compare M 101 with M 87 — one quickly realizes that galaxies come in many different sizes, colours, and shapes. What is it about the early Universe, or the later growth, or both, that decides what type of galaxy ends up where?

We think we know part of the answer. Remember that the tiny irregularities are initially generated by quantum effects; they are, to a significant extent, random. If we look at the blobs in pictures of the cosmic microwave background, each one is a slightly different size and shape. That means that the growth in each region is slightly different and it's logical to suppose that the differences lead to different galaxies.

But knowing that isn't enough on its own. We want to be sure that we've understood the evolution of the cosmos correctly. This is essential, for example, if we are to use results from future missions as a kind of laboratory to explore the more mysterious components of the Universe — things like dark matter and dark energy. We need to be sure that we're getting the basics right first. The trouble with a vague idea that different galaxies emerge from different early-Universe configurations is that it's not concrete enough to test.

Ideally we'd just re-create the entire Universe in a computer, and see if the right galaxies emerge in the right places. The trouble is that the cosmic microwave background only shows us a limited snapshot of the early cosmos — overwhelmingly insufficient to attempt this perfect re-creation.

What we can aim more realistically to reproduce is the overall mix in the observed population of galaxies as a whole. One way to do that is to get a computer to model the evolution of a giant chunk of the cosmos, set up with a range of different density enhancements and diminutions consistent with what we know from the microwave background. Doing that, and getting a sensible mix of galaxies in the computer output, is no mean feat; but it's exactly what people have achieved in recent years. Look at things like the ILLUSTRIS or EAGLE simulations and you'll get the idea.

But a major problem remains. By spreading the power of even the best supercomputers so thinly over such a vast region, one ends up with very little detail on each galaxy. That just doesn't mesh well with observational abilities that are coming from new-generation instruments — integral-field spectroscopy, deep surveys like *LSST*, the coming era of 30-m-class telescopes. All those give us enormous insight into the detailed structure of a galaxy. It's as though we're trying to compare high-definition movies with a few meagre computerized pixels.

That's still a valuable exercise, but really to get to grips with the observations there's another approach. Instead of trying to map out an entire virtual universe, the idea is to focus computational effort in a much smaller region. This isn't anything new — since the early 90s such simulations have been called "zooms". We keep a low-fidelity version of the cosmos at large, but focus the vast majority of the computer's effort on keeping track of a handful of galaxies in exquisite detail.

The drawback of this approach is that one can't tell, from just a handful of galaxies, whether we're really able to account for the vast diversity of the full population at large. So our new twist is to combine the best of both worlds. Having generated one (or a few) virtual galaxies using the 'zoom' technique, we systematically generate variants of those galaxies. We go back to a single patch of the early computerized universe and make controlled changes to the fluctuations that the galaxies formed from. Then, we run the computer code again to see what effect those changes have on the final galaxies.

By choosing the particular changes with care, we can investigate different questions. For instance, we've been looking at how a galaxy is altered by having either a gradual accumulation of matter or, conversely, a more catastrophic collision between two giant progenitors. Such collisions do occur in the real Universe (take a look at the Antennae galaxies) and so understanding their effects — while keeping the rest of the history of a galaxy fixed — is of particular interest. But it's just one example.

It can be helpful to think of this as 'genetic modification'. The slight fluctuations in the early Universe serve as a genome encoding the nature of the galaxies that will eventually grow. By slightly modifying one region, we're changing its genotype. Then we use the computer to show us how those changes impact on the final phenotype that emerges. So this approach offers a new path to understanding systematically the way that galaxies develop and grow.

Another avenue we've been focussing on is how similar controlled changes can be used to understand the large-scale structure of the Universe: the galaxies themselves are organized into enormous filaments. A better grasp on this organization could help interpret data from big forthcoming surveys which are designed to probe the nature of dark energy. One fun (and rather extreme) change is to replace every slight excess of matter in a computerized early universe with a slight under-density, and *vice versa*. That operation has a very precise symmetry to it; it results in regions that once became galaxies instead forming into an empty void — and *vice versa*. We've been able to show that such an abstract exercise actually gives a pathway to more rapid, accurate calculations of structure formation than can otherwise be achieved.

It's very early days and so far we have only a few publications using these new techniques. But I am really excited at hitting what seems to be a rich seam for interesting, novel results — stay tuned over the coming years as we explore what is enabled by this approach.

The President. Thank you. We have a very brief time for questions.

Professor C. Lintott. Thanks, Andrew, for a great talk. I suspect looking at a few feeble local galaxies that it's the time of the first big mergers rather than the relative strength of the mergers that matters. Can you fiddle with the genetics and alter that as well?

Dr. A. Pontzen. Yes, in fact you should join the team. That's exactly what we're doing right now.

Dr. R. Barber. I just wondered, because I have an interest in dwarf galaxies, did they ever come out of your simulations in any shape or form?

Dr. A. Pontzen. I spent a long time playing with dwarf galaxies, they're my favourite type of galaxy. Yes, we can certainly form dwarf galaxies. In fact, we are the world-leading group in forming dwarf galaxies. [Laughter.] I hope nobody watches this on the internet, I'm going to get all sorts of hate mail now. [Laughter.] Dwarf galaxies pose profound puzzles as I'm sure you're aware, and one of the questions is, is the distribution of dark matter through dwarf galaxies consistent with the dark-matter paradigm? A lot of the results we were getting a few years ago point towards a positive answer. Actually, when you model the astrophysics with sufficient detail you can form dwarf galaxies that look like the ones we see in the real world. But there is some way to go still.

The President. I'm afraid I'm going to cut matters short there, so can we again thank Andrew very kindly? [Applause.]

Our next speaker is Dr. Guillem Anglada-Escudé from Queen Mary, University of London, and the title is 'Proxima b and the search for terrestrial planets around the nearest red dwarfs'.

Dr. G. Anglada-Escudé. The race to search for planets around main-sequence stars started 21 years ago with the unexpected report by Mayor & Queloz in *Nature* in 1995 of a gas-giant planet in a tight orbit around the Sun-like star 51 Peg. Since then, about 3000 planet candidates have been reported. Most of the initial findings were massive gas giants but several techniques started to develop, enabling the detection of a wider variety of systems.

Most of the current understanding of planetary systems comes from two of those techniques: the photometric-transit and the radial-velocity methods. The photometric-transit method uses the fact that, when observing many stars (> 10 000 at the same time) random orientation of the orbits enables the detection of the small dip in the light of some of the stars caused by a planet passing in front of them once every orbit. This method is most sensitive to short-period planets because, given a random orientation, the chance of a transit is proportional to the inverse of the semi-major axis. The transit-detection machine *par excellence* has been NASA's *Kepler* mission. Initially designed to uncover Earth-sized objects transiting Sun-like stars, it has mostly detected shorter-period planets around stars smaller than the Sun, a result that was not anticipated, leading to over 2000 likely transiting candidates. Although some of them might still be false positives, as an ensemble they draw a picture of most planetary systems being crowded and packed with several planets within the orbit of our Mercury and sizes between one and four Earth radii ($R_{\rm E}$) (so called super-Earths). Notably, most detections of small planets ($1\,R_{\rm E}$ and below) were obtained on red-dwarf stars, on which the signal gets strongly boosted due to the favourable planet–star size ratio. Those planetary systems appear to be common, a result that already anticipates a large population of Earth-sized objects in compact but temperate orbits around such cool stars.

Kepler was designed as a population-study machine. Because of the requirement of observing 10^5 stars to find a handful of transiting Earth-sized objects, it could not possibly explore the immediate solar neighbourhood (of radius 25 pc, which contains only about 3000 stars). In the immediate solar neighbourhood, about 2000 of these stars are red dwarfs.

Three factors produce a nett gain in sensitivity: (*i*) lower-mass stars have larger signal due to favourable planet–star mass ratios; (*ii*) red dwarfs are fainter, so warm orbits are closer-in. In particular, the Doppler signal of a warm Earth-mass planet orbiting Proxima (~ 1·3 m/s) compared to the Earth–Sun signal (8 cm/s) is about 15 times larger. Finally, (*iii*) close-in orbits imply shorter orbital periods, meaning that the signal repeats much more often, that is about 30 cycles per year as opposed to one for a putative Earth analogue around a Sun-like star. Factors (*i*) and (*ii*) allow higher sensitivity to smaller warm planets, and (*iii*) enables observation of repeating patterns on a much shorter time span (within the visibility season each year). If our criteria to ensure strict periodicity were observing five cycles, two months would be enough for an M5 V star, while five years would be needed for an Earth analogue around a Sun-like star.

The time-sampling problem becomes much more complicated by factors that, although they have been acknowledged for a while, are very difficult to quantify. For example, the rotation period of stars is in the tens-of-days régime. In a continuous-monitoring season on an M dwarf, the effect of rotation on RVs can be observed to vary smoothly without generating interference (aliases) in the domain where the planets can be placed. When observing over several years, the rotation cycles act as correlated noise that — when combined with non-trivial sampling — generates all sorts of apparent periods at integer multiples of the sampling frequencies. Given that only now optimal sampling strategies are being implemented on late-type stars, and given the inertia of the community in following age-old strategies, it is very unlikely that the Doppler technique can uncover true Earth-analogues around Sun-like stars any time soon, even with much better instruments.

Proxima (GJ 551) is the nearest star to the Sun and is a red dwarf. It has therefore been an obvious target of searches for temperate low-mass planets around it. The first serious programme dedicated to the task was the *UVES* M-dwarf survey led by Martin Kürster and Michael Endl using the *UVES* spectrometer at the ESO 8-m *VLT* telescope. To produce the extreme wavelength-calibration requirements and given that *UVES* is not a stabilized instrument, the iodine-gas-cell technique was used. The *UVES* survey obtained 270 spectra of Proxima consolidated in 70 radial-velocity epochs (typically three spectra would be taken every night). When the results were reported by Endl & Kürster in 2008, no convincing signal was reported. Let us note that at that time the general architecture of planetary systems was completely unknown, so that first programme was useful to put upper limits to the typical planets around M-dwarf stars (about 50 other stars were also observed). An upper limit to 2–3 M_E minimum-mass objects in the temperate orbits around the star was placed and no evidence of longer-period gas-giant planets was reported either. From 2002, Proxima started to be observed with the brand-new *HARPS* spectrometer built by the Swiss team led by Michel Mayor. The star was occasionally observed in the years to follow, but only 25 epochs were recorded. One of the arguments for not following Proxima in more detail was that only moderate precision could be reached (~ 3-m/s level), and it was informally argued that RVs at the 1-m/s level were not possible on red dwarfs owing to intrinsic stellar variability. The star was still followed up by continuation programmes outside the *HARPS–GTO* effort by the team led by X. Bonfils. Still, the sampling was not optimized to any frequency and no evidence of any signal was reported in the summary paper of the survey published in 2013.

In 2012, Anglada-Escudé & Butler produced a new algorithm to derive precise velocities on stabilized spectrometers like *HARPS*. In the corresponding paper, it was shown that most of the previous noise floor was not from the variability of red dwarfs, but due to sub-optimal performance of the algorithms used to obtain the Doppler measurements (cross-correlation function with a binary mask). By applying a similar technique as used in the iodine-cell method (maximum-likelihood fitting of each spectrum to a template generated from co-adding all the observations), it was shown that precision at the sub-m/s level could be achieved (*e.g.*, record-holder stable M-dwarfs like Barnard's star and GJ 588 show 0·8–0·9 m/s r.m.s. over time-scales of several years). In that re-analysis effort, several planet candidates were reported, including one of the first super-Earth planets in the habitable zone of a nearby M-dwarf star (GJ 667Cc), which was simultaneously reported by the team that acquired the observations using 25% more observations.

Another development happened at the same time. Mikko Tuomi, a PhD student in applied mathematics at the University of Turku moved to the University of Hertfordshire as a postdoc, where he developed fast Bayesian Monte Carlo methods that enabled the consistent combination of data from different instruments. Tuomi and Anglada-Escudé started a collaboration consisting of combining all existing data from nearby M-dwarf stars (*UVES* and *HARPS* survey) to search for small Doppler signals in them. The team analysed data from about 500 stars (200 of them M dwarfs) and several signals were spotted among them. Some were published in the intervening years, others were followed up with additional observations, others remained ambiguous, mostly due to poor sampling of the periods of interest combined with the non-strictly-periodic magnetic activity of the stars. One of the stars was Proxima Centauri, which showed evidence for up to four signals, two of them corresponding to putative planets in the habitable zone of the star. Although a paper was submitted in 2013, the referee considered the evidence unconvincing and it was rejected for publication. After our own observing campaigns (two ten-day runs in 2013), we became convinced that Proxima was smoothly varying with a period between 10 and 20 days, but the solution was non-unique. It also became clear that continuous monitoring combined with additional information (*e.g.*, simultaneous photometric follow-up) was necessary to confirm unambiguously the strict periodicity of the signal of interest. Around the same time the planet candidate Alpha Cen Bb was reported by the Geneva team as a highlight of their *HARPS–GTO* high-precision programme. That detection was never very convincing, and soon after some papers argued against the existence of such a planet. The community shifted to not believing Alpha Cen Bb when two more papers re-analysing the same data disputed the detection. While the star was very different (Alpha Cen B is a K dwarf star and the planet would have been an Earth-mass object in a very hot, 3·14-day orbit), it became clear that extraordinary evidence would be needed to make any similar claim in the future.

The 'Pale Red Dot' campaign was conceived to address this. However, it proposed an observing mode which is still not supported for *HARPS*. That is, to obtain regular sampling and verify strict periodicity of the signal, we proposed to observe it for 60 nights in a row, for 20 minutes each night (monitoring mode). Instruments at La Silla must be operated in visitor mode (astronomer on-site), which was clearly not a reasonable option for the campaign. Among other things, including some strong hostility from the panel (likely related to the Alpha Cen B failure and the initial reluctance of the community to believe the detections reported by Tuomi and Anglada-Escudé), the first attempts at submitting the proposal were unsuccessful. To address this, the issue was discussed directly with ESO's high-level management, strongly emphasizing the potential high impact of the discovery even if the chances of success were slim.

It was agreed that the observations would be executed if the proposal ranked in the top 10%. The proposal finally met a sympathetic evaluation committee and the notification of acceptance for execution was received in 2015 July.

Given the potential high impact and uniqueness of the situation (only *HARPS* in monitoring mode was fit to do the job), the campaign was publicly announced and supported by an intensive outreach effort. It consisted of a web-site with articles on exoplanets by world-wide experts, follow-up articles on the progress of the observations, and live social-media connections to some enthusiastic observers in La Silla. That outreach effort was mainly organized by a sub-group of the science team (about ten members), Queen Mary University of London, Instituto de Astrofisica de Andalucia, and a generous partnership collaboration established with ESO's outreach office (Lars Christiansen Lindberg, Oana Sandu, Richard Hook). The outreach campaign was successful in warming up the attention of the public. The web-site counted hundreds of thousands of article reads, and about 2–3 thousand followers in both Twitter and Facebook pages prepared for the occasion.

Given that the most expensive resource was secured (*HARPS* has an over-subscription rate of ten), we wanted to perform simultaneous photometric follow-up with at least two observatories during the same time interval. A proposal was submitted and accepted to carry them out at the *Las Cumbres Observatory Global Telescope* network (led by Yiannis Tsapras) and on the *Astrograph for the Southern Hemisphere 2* at the semi-professional facility SpaceObs at Chile/Atacama (led by the IAA/Granada team). Both supporting telescopes produced high-quality photometric observations on 75% of the nights. Those observations showed the same modulation of the previously reported 83-day rotation period. No signal in the 10–20-day régime or close to it was found. The observations with *HARPS* ran extremely smoothly, achieving a success rate of 90% (the original plan expected 75%). After only 15 days into the campaign (about 20-night baseline owing to scheduled technical interruptions), it was clear that among the possible solutions, the anticipated signal at 11·2 days was clearly present in the *HARPS* data.

Simultaneously, we contacted the *UVES* M-dwarf team (Kuerster and Endl) and they unearthed their old *UVES* data. One of our colleagues (Mathias Zechmeister from the University of Göttingen) had identified a number of systematic errors in the extraction and reduction of the old *UVES* data. Paul Butler (exoplanet pioneer and progenitor of the iodine-cell technique) re-analysed the *UVES* data, achieving a significant reduction of its r.m.s. noise. The analysis of those newly-derived measurements showed directly the same period for Proxima b independently. At the end of the campaign, and with all the data in hand, it turned out that Proxima b was not only detected in the combined data, but independently confirmed with two instruments spanning 16 years of observations. Moreover, the signal was so strong that even sub-optimal analysis methods (*e.g.*, Lomb–Scargle periodogram techniques and pre-whitening) would provide extremely high significance without the need for any pre-processing or assumptions about the noise. This situation was diametrically opposed to the claim for the detection of Alpha Cen Bb, which required extensive modelling of stellar activity. This, combined with the absence of stellar activity on the time-scales of the signal, was deemed sufficient to submit the paper for publication in a high-impact journal such as *Nature*. In a rare outburst of enthusiasm at ESO and the European community, the official announcement was made at a live press conference at ESO's HQ on 2016 August 24, with the support of the Breakthrough Starshot Foundation's director Peter Worden, whose aim is to explore technologies to reach the nearest stars with small probes within the next few decades.

Beyond the large public interest in the discovery, the detection of Proxima b has triggered a very substantial reaction within the scientific community. This includes theoretical studies on the formation scenario of such planets and proposals to investigate the presence of its atmosphere and bio-marking molecules with the upcoming next-generation instruments. As of November 1, 30 publications have already cited the report and plans to optimize instruments on *E-ELT*-class telescopes are being drawn-up to obtain images of our nearest planetary neighbour within the next decade. The discovery of Proxima b, together with the recent detection of transiting Earth-sized objects around very cool dwarfs (*e.g.*, the TRAPPIST–1 system) mark the beginning of the race to search for evidence of life beyond the Solar System.

The President. Thank you very much indeed. We have only a very brief time for questions, so do we have any?

Mr. H. Regnart. Arising from what you've been saying, of course there has lately been the wonderful idea of trying to send a microprobe, virtually a chip, to Proxima Centauri. The worry that crosses my mind is that the velocity that would have to be attained would be so great that even in the interstellar medium, it would encounter a considerable amount of resistance from the small number of isolated atoms floating about and might even be destroyed in the attempt to get there just because of the friction. Can you comment?

Dr. Anglada-Escudé. Certainly, but when Galileo looked at the Moon 300 years ago he didn't know what was in between, and now we have probes orbiting Jupiter. It's not going to happen tomorrow but at least it is a target and it doesn't matter if we really reach there — if we aim for the stars, then at least the Solar System will be ours [laughter]. It's a wonderful thing, a motivational thing for future generations.

The President. I'm afraid we have pressure of time, so I hope the speaker will stay for the reception afterwards and you can talk with him then. So thank you very much indeed. [Applause.]

It's now my pleasure to introduce the 2016 Gerald Whitrow Lecturer. We've already heard the citation for the speaker who is Dr. Neil Turok from the Perimeter Institute, Canada. The title is beautifully simple, it is 'Universe'. You will have seen the abstract in the programme; I will just read one part of it which is very appealing to a mere planetary scientist. It says, "The universe is astonishingly simple on the largest and smallest observable scales with great complexity in between." [Laughter.] So, it's my great pleasure to introduce Neil Turok and I would just say I've already apologized to him because I have to leave. I will pass the Chair over to the Senior Secretary, Ian Crawford, who will conclude the meeting. [Applause.]

Dr. N. Turok. [It is expected that a summary of this talk will appear in a future issue of *Astronomy & Geophysics*.]

Dr. I. Crawford. Thank you, Neil. We are almost out of time but we do have time for a couple of quick questions. The gentleman there is obviously ready to ask one.

Reverend G. Barber. First of all, thank you very much — very interesting. What happens to your rulers and clocks in the pre-Higgs era?

Dr. N. Turok. It's a great question and I was alluding to that when I mentioned one of the most surprising discoveries of the *Large Hadron Collider*. The *LHC* discovery is pointing towards scale invariance at high energies. Scale invariance means that the theory of the Standard Model becomes like Maxwell's theorems. Maxwell's theorems are scale invariant, that's why a radio wave is like a light wave is like an X-ray. They're all the same because the theory doesn't have a scale and they all behave in exactly the same way. But there are hints now that the Standard Model may also have that property, and that at high energies there is no scale in the theory. That means there are no rulers, there's no preference of one scale over another. That is why we study quantum cosmology. We study quantum cosmology in a fluid which has scale invariance. That's the one which resolves the Big Bang singularity. If you want to understand what happens when the size of the Universe was zero, the best chance you've got is to look at a theory which doesn't know about the size, and that's what seems to work. So, this is very fundamental and I would say the suggestion is that the laws of physics have no scale at high energies.

Dr. I. Crawford. Perhaps one more question.

Professor I. Roxburgh. I deduce from what you said that the Universe would therefore have an infinite negative time.

Dr. N. Turok. That's also a good comment. My current belief is the following, and I hinted at it here. We're trying to explain this amazingly economical Universe. It has almost no numbers describing it, so we need a theory that is equally economical. The theory of the multiverse is the least-economical theory but equally a theory which is cyclic, which I have been keen on, and also has a lot of arbitrariness. You know that there's the chicken-and-egg problem of what came before and why was it like that? It's not an extremely simple theory. So, can we make a simple theory? I think that we can — I think that the way that quantum gravity works cries out for the following. Which is that I say I want to study the amplitude to get a universe here, a three geometry out here. Basically, the Feynman path integral gives you the vacuum amplitude so what I'm saying is, the Universe is in its vacuum state, this is the minimal state that we're in. But what about before the Big Bang? What the path integral cries out for is that this state is exactly the same as that state, so it gives you an amplitude for that state and you can calculate it at this end or that end. It just gives you a number and that's all you want. My current hope is that when we go through the Big Bang, indeed there was a bounce but what came before the bounce is exactly what came after it. It's not a mirror image, because there are no rigid mirrors in gravity and the only thing that's mirrored is the final state, not the intermediate state. So I think there is a prospect that that will work — it certainly will be an extremely economical prescription for what the state of the Universe is, and, in fact, I go further and I think this picture should explain the emergence of time. Why is there an arrow of time? That comes down to something extremely fundamental in gravity which is this: that the metric is the square of A, so when I represent a three geometry, I can use A or –A and one copy is A, one copy is –A, and if you have four geometry going between them, it has to pass through zero somewhere. That's why there was a Big Bang and that's why there's an arrow of time. Those are the long-term goals of the programme.

Dr. I. Crawford. We are well out of time, I'm afraid. So we'll just adjourn to the drinks reception in the library, and our next meeting will be on Friday 11th November. We thank Neil and the other two speakers for three very excellent talks. [Applause.]

MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2016 November 11 at 16^{h} 00^{m}
in the Geological Society Lecture Theatre, Burlington House

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

The President. A date which I'm sure you've all got in your paper RAS diaries is that of NAM 2017. In case you haven't, can I just remind you then that NAM will be held at the University of Hull from Sunday 2nd of July to Thursday 6th of July 2017.

So, without further ado, let us proceed to the programme, and it's a pleasure to introduce our first speaker, Professor Gerry Gilmore from the Institute of Astronomy, Cambridge, and his title is '*Gaia*: the 6-D Milky Way map is coming to you'.

Professor G. Gilmore. The *Gaia* project is now underway and our tagline is 'one billion pixels for one billion stars'. The satellite has been designed to provide three fundamental sorts of data, astrometry and photometry, from direct images, spectrophotometry between 3500 and 10 000 Å, and spectroscopy with a resolving power of 12 000 at the calcium triplet to give radial velocities. The first release of data came out in mid-September and included data on 1·1 billion stars. The next big release of data is planned for early 2018.

Since current high-precision cosmology depends on *Hipparcos* parallaxes for a few hundred stars, only five of which are Cepheids, we urgently need to solve the problem of stellar distance. *Gaia* is not only the highest-precision optical bench ever launched into space, it is also the most stable. It consists basically of a ring of silicon carbide which encloses two 1·5-metre mirrors which are tilted with respect to each other by 106°·5, and which feed a single optical bench. The key reason for the ultra-high stability is the need to measure very small angles, small enough to distinguish the splitting of a human hair at a distance of 1000 km. Solving these problems means dealing with formidable hardware and software requirements.

A typical star moves in a cycloidal pattern across the sky — the result of the combination of its proper motion and its parallactic motion. If the star is a binary, or accompanied by planets, the motion is more complex still. In order to get the absolute parallax, which is not possible from the ground, we need to observe each star with each mirror over a period of time.

Handling the data is also a very complex task. Additional problems have had to be overcome. We have had to deal with scattered light, ice on the mirrors — which can be obviated by the use of heaters — and 'microclanks', which are small releases of mechanical stress in the spacecraft, but in the last few months we have noticed that these are well-behaved and can be predicted and corrected. We are actually able to detect changes in angle between the mirrors which correspond to ⅒ of the diameter of a helium atom, thanks to a very-high-precision interferometer system which is installed as a backup.

In terms of data handling, we will need to invert a matrix of order 10^{13}, which requires very sophisticated algorithm development, but we have an extremely able and large group of hardware and software engineers.

As the spacecraft rotates the stars drift across the large focal-plane camera which measures about 1 × 0·5 metres — the stars first traverse the main CCD array which does the imaging and the last few columns of CCDs tackle the spectrophotometry and spectroscopy. The dynamic range is $V = 5$ to 21 and every star brighter than $V = 16$ has photometry to a precision of better than 1 milli-magnitude, and has already been observed more than 100 times. Today I am able to present an H–R diagram of two million stars (compare with *Hipparcos* which has 100 000). It shows complex structure which was not expected. In a year's time I will be able to show you the results from one billion stars.

We have been able to measure the distance to a number of clusters and in every case the results have agreed with those derived by *Hipparcos* with one exception — the Pleaides. That particular anomaly needs to be looked at. We can now resolve the distance to individual members of nearby clusters, so the depth of each cluster can be measured. Another problem which the new data on clusters has raised is the unusual width of the main sequence just before turn-off. That does not appear to be consistent with current ideas about stellar evolution.

For more-distant objects we have been able to measure the rotation of the Large Magellanic Cloud for the first time. Using 14 months of data we have determined that the LMC rotates with a period of 10^8 years. In a couple of years we will see the rotation in M 31 and M 33.

In the field of extra-solar planets we anticipate that 70 000 nearby stars will be accompanied by a planet of Neptune mass. We have tracked and observed the orbits of 35 million asteroids of which 250 000 are new, and because *Gaia* is at the Lagrangian point and looking sunwards towards Earth we can see the near-Earth objects which might threaten our planet, and which we cannot normally see from Earth because they are between the Earth and the Sun.

Another important aspect of our work is doing real-time astronomy and its impact on outreach. Every day we have a new list of transients which we make available — you can get them by an app for your phone. Some of them are being followed up by schools and amateur astronomers and I will mention one particular example. We have found the first microlensing event which is away from the Galactic Bulge. More than 10 000 observations have been made because it is relatively bright, 13th magnitude. It is a binary microlens and the next caustic crossing is due next Wednesday. At that time it is expected to vary between 14th and 11th magnitude in less than an hour. We are keen to pass on as much information as possible on events such as that, but we have no specific funding for this purpose. In the time I have been talking to you *Gaia* has measured another 100 million positions.

The President. Just one word: wow! [Laughter.] I would just like to take the opportunity to acknowledge Gerry's personal commitment to the project over many years for leading the UK effort on *Gaia*. Right, questions, comments; let me start. Several times you acknowledged the part played by industry, by engineers. I think you said some of them are here, so perhaps you could acknowledge them?

Professor Gilmore. Where is [Dr.] Ralph [Cordey] from Airbus? Airbus Defence and Space were the prime contractors, and also Airbus Toulouse, but particularly Airbus Stevenage who did the clever electronics on board. The CCDs were fabricated in Chelmsford by e2v and they are the heart of *Gaia*. The high-precision control system and the on-board software control system were built in the UK and then, of course, there's Dr. Fabio Favata and his colleagues who funded the whole thing at ESA, to whom we are totally indebted.

The President. And what about the bureaucrats at the UK Space Agency?

Professor Gilmore. You mean the ones who won't give me any outreach money? [Laughter.]

Dr. K. Khamchani. What is the status of the distribution of dark matter with *Gaia* at the moment?

Professor Gilmore. We don't know. The initial data release from *Gaia* only had bright stars and, although giants are a long way away, statistically the sample is useful for dynamical analyses only out to 100 pc. Inside 100 pc, one of the things we have discovered with *Gaia* in this time is that there's a huge amount of kinematic substructure in the local part of the Milky Way, driven by spiral arms, the bar, *etc*. So the system is so far from being fittable by a simple distribution function that we can't say anything useful just yet. We need a longer baseline, and this will come in the next data release when we get out to a kiloparsec and fit through some of the high-frequency structure. At face value, the numbers look remarkably like those that were first published in 1989 by me. [Laughter.]

Mr. I. Ridpath. What are the brightest objects that you measure?

Professor Gilmore. Well, there's no limit! Actually there is. You can't see the Sun and you should see what it looks like when Venus goes through the focal plane, but we can see all the stars. There's a special observing mode; the normal standard scanning mode works out to a magnitude of about 5 but the brilliant engineers at ESA worked out a way of doing special little scanning modes, fundamentally looking down the diffraction spikes half a period away from the star, so even Sirius is having its parallax measured. We haven't quite worked out how to process those data yet but they are being taken under the assumption that we'll crack it eventually.

Mr. Ridpath. Good, yes. Those are the ones I'm interested in.

Professor Gilmore. We go from Sirius ($V = -1{\cdot}5$) and the completeness limit at present is about $20^{m}{\cdot}7$. It's a lot fainter than expected. So the goal was a billion stars but we're actually going to have a complete sample of two billion — partly because we got fainter and partly because it turns out there are a lot more stars in the sky than we thought.

Dr. M. Dworetsky. Can you actually resolve any spectroscopic binaries with periods of a few days or more?

Professor Gilmore. A few days? I'd have to check the numbers. In terms of spatial resolution, we can very easily resolve Pluto and Charon. We can detect those very well. Fundamentally, the spatial resolution is about the same as *HST*; the mirror is about the same size so it's about $0''{\cdot}08$, but we can do a bit better than that because we have lots of scans on different scan angles and we can deconvolve it so we can get down to about $0''{\cdot}05$ spatial resolution. What that means for a binary of a given period depends on the mass of the binaries and the distance to the binaries, and in particular the nearby binary Cepheids. Several of the primary calibrators turned out to be binaries and we had to throw them out, so we're discovering a lot more binaries than one might have thought. *Gaia* is actually quite good at that but this is something that we have a special processing unit for and they haven't even started working yet because we've been busy with other challenges. We may start work next year.

The President. Last question.

Mr. D. B. Moody. First, from the United States, we're very grateful for Dr. Russell and his contributions. [Laughter.] Second, implicit in everything you were talking about are the interactions, and you talked about measuring clusters — is there going to be any effort to look at the interactions with the objects within this cluster at a more precise level?

Professor Gilmore. We can already because, particularly for nearby clusters, *Gaia* gives three-dimensional distances and three-dimensional velocities. We can already map out in three dimensions the changes in velocity and isotropy as a function of position down the line of sight: because clusters turn out not to be round you need to do it down the line of sight as well as across the line of sight. So we can see already that we've got mass segregation. In fact, I don't think I'm giving away any great secrets by telling you that next year we will be able to tell you whether the concept of a cluster forming in dynamical equilibrium and then mass-segregating is a gross exaggeration. We can already see that just in the velocities and the kinematics. It's hard to visualize really but just taking a cluster like the Hyades, an easy one, already we have three-dimensional velocities to an accuracy of half a kilometre per second for every star. The velocity dispersion is 1·5 km sec^{-1} so we've resolved the peculiar velocity of every star in the Hyades and its distance, and that's just today. We're going to do this across half the galaxy. We're in a whole new realm of data processing and challenging assumptions here.

The President. And the lifetime of the mission?

Professor Gilmore. Well, you'll have to ask Fabio Favata. The minimum lifetime is five years from when we started which was mid-2014 to mid-2019. There is a proposal going through the STFC process at present to extend that. The engineering lifetime is ten years, and everything is looking fine. In fact, we've been very lucky with the Sun not destroying our CCDs, so the physical state of the spacecraft is, as they like to say, phenomenal. It's just beautiful. So we hope for ten years and all we need is the money for the ground stations, and I think we'll lock Fabio in a room until he says "yes". [Laughter.]

The President. I'm afraid we must move on. Gerry, thank you very much. [Applause.]

Our next speaker is Dr. Simon Mitton from St Edmund's College, University of Cambridge, and his subject is 'Georges Lemaître: life, science, and legacy'.

Dr. S. A. Mitton. My talk this afternoon celebrates the remarkable life, science, and legacy of Abbé Georges Lemaître, the Belgian cleric and professor of physics; he was the architect of the fireworks model for the origin of the Universe. He died half a century ago, three days after learning that Arno Penzias and Robert Wilson had discovered the cosmic microwave background. Despite being gravely ill from leukaemia, Lemaître lucidly praised that news, which confirmed the explosive genesis of our Universe.

Georges, the first of four sons of Joseph and Marguerite Lemaître, was born on 1894 August 17. He grew up in Belgium's *pays noir*, a dark landscape blighted by the industrial production of glass, coal, and steel. His father Joseph founded a glassworks, where we can imagine that from an early age Georges became familiar with fiery furnaces and their smouldering ashes. Georges (aged ten) entered grammar school in Charleroi, where Jesuit teachers thoroughly grounded him in Greek and Latin. By his second year he began to demonstrate outstanding ability in mathematics. After an explosive conflagration reduced the glassworks to sparks and ashes, the family moved to an imposing mid-19th-Century townhouse in Brussels. To complete his high-school education, Georges joined 800 boys at Collège St-Michel, an easy 15-minute stroll from home.

After one year studying advanced mathematics and science, he began his university career at the Université Catholique de Louvain in 1911 July, taking the foundation course in engineering, plus a diploma in philosophy. He plunged into analysis and mechanics, and displayed a growing interest in the history of mathematics. He earned distinctions in mathematics and physics, but performed less well in engineering.

On 1914 August 4 the German army invaded neutral Belgium, following the Belgian government's refusal to allow safe passage to France. Lemaître, deeply loyal to 'king and country', signed up on August 9. Six weeks later, the exhausted Belgian army was bottled up along the Yser. Georges fought in the front line, where the infantry held their position from 16–31 October, taking casualties of 3500 killed and 15 000 wounded. The Germans scarpered when Belgian forces flooded the polders. During four years of service on the western front, Lemaître kept up his interest in science. He delighted his comrades in arms with accounts of scientific discovery. And he kept up with such developments at an advanced level, mastering Poincaré's *Électricité et Optique*. His bravery won him the Croix de Guerre with Bronze Palms.

On returning to Louvain, he dropped civil engineering to concentrate on mathematics and physics. He gained a doctorate in 1920, at which point he entered a diocesan seminary that fast-tracked men whose vocation had been delayed by military service. During 1921–1922 he prepared a personal memoir on Einstein's physics, which resulted in a major travel award to cover overseas travel during 1923–1925. Then he won a Fellowship to support study in the United States. In 1923 October, after ordination, he went to Cambridge to work with Eddington, lodging at St. Edmund's House (now College), a residential community of young priests.

When Eddington and Lemaître first met, relativistic cosmology offered two unsatisfactory models, both dating from 1917. Einstein's universe was of finite density, closed, and static; de Sitter's was open, empty, and expanding. Lemaître's period of collaboration resulted in an important paper in which he generalized the definition of simultaneity. Eddington later wrote: "I found M. Lemaître a brilliant student … of great mathematical ability." In 1924 August, Lemaître and Eddington participated in the British Association for the Advancement of Science meeting in Toronto, where Eddington gave an acclaimed public lecture on relativity and the bending of starlight.

The next month, 1924 September, Lemaître arrived at Harvard College Observatory, where he worked on Cepheids under Harlow Shapley. In Washington, at a meeting of the American Philosophical Society in 1925 April, he presented a paper on the deficiencies of de Sitter's universe. Then, during a meeting at the National Academy, he attended Hubble's famous presentation on the distance of M 31, which showed that Cepheids provided the key to unlock the extragalactic distance scale. Lemaître arranged to meet Hubble and learn more about extragalactic distances. Next he went to the Lowell Observatory, where Slipher had measured 36 redshifts.

On returning to teaching duties, Lemaître mounted a major attack on cosmological models, seeking a solution intermediate between the Einstein and de Sitter universes: a universe containing galaxies (Einstein) and with redshifts (de Sitter). In a stroke of genius, he abandoned static solutions. His paper, on a homogeneous expanding universe of constant mass, appeared in the annals of the scientific society of Brussels, a widely available but seldom-read journal. He had rediscovered the solutions that Alexander Friedman* had published in 1922. And like Friedman, Lemaître was given the silent treatment. That is, until 1930, when Eddington leapt into action by publishing a translation in *Monthly Notices*. In 1931 Lemaître published *The Beginning of the World* from the point

*It has always been the case that professional historians use Friedman's own spelling of his own name, which ends with one and only one letter n. This accords with the spelling on his papers: Фри́дман It is quite common, however, in scientific works to see it written as Friedmann.

of view of quantum theory, setting out his concept of a primeval atom that shuddered into expansion through radioactive decay. He had his moment of fame in 1931 during the 100th anniversary meeting of the British Association for the Advancement of Science, where he spoke eloquently.

To summarize Lemaître's legacy I'll jump to 1948 when Bondi, Gold & Hoyle published their steady-state model, which sparked the Big Bang *versus* Steady State debates. In 1948 Ralph Alpher & Robert Herman published a value of 5 K for the temperature of the cosmic microwave background (a result for which George Gamow took as much credit as possible). In 1965 the discovery of the CMB was announced; that marked the beginning of the end for the steady-state model, and the gradual acceptance of explosive (fireworks!) models. The discovery of dark energy rekindled interest in the cosmological constant that Lemaître had identified with vacuum energy back in 1933. In the five decades since his passing, Lemaître's reputation has risen from near obscurity to universal recognition of his achievements as the 'Father of the Big Bang'.

The President. I should just mention that we try to have every year in the Ordinary Meeting one lecture which relates to one of the anniversaries in the diary. In the 2016 diary there is the anniversary of Georges Lemaître.

Professor D. Lynden-Bell. I'd just like to add a comment by Vesto Slipher. In getting those redshifts, Slipher said "Many of these take three nights of exposure for one galaxy. I don't see there's a great future in this, it takes too long." [Laughter.]

Mr. H. Regnart. A very small historical point: the first time I came across the primeval atom concept in childhood, the substance of it was referred to in broadcast as ylem.

Dr. Mitton. That comes from George Gamow.

Dr. Francesca Vidotto. You mention the Big Bang atom but Lemaître also had a beautiful idea of the phased universe, that before the Big Bang there could be some other phase.

Dr. Mitton. Yes, he did try more than one model. That's true.

Dr. Vidotto. I mention it because there is a lot of work in cosmology today as well to try to describe those cosmologies, so we hope in a few years maybe to prove another mark by Lemaître.

The President. Last question over here.

Mr. C. Taylor. The hundred-page memoir he wrote before he went to Cambridge to work with Eddington — that's never seen the light of day?

Dr. Mitton. It's never been published but we have it in the archives and you can find it on-line if you dig around.

Mr. Taylor. Yes, it would be nice to have a modern edition; maybe CUP would like to do it?

Dr. Mitton. I don't think so. [Laughter.]

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

Our final presentation today is the 2016 Harold Jeffreys Lecture and this is given by Dr. Jenny Collier of Imperial College London and the title is 'Making Britain: evidence for catastrophic flooding in the English Channel'.

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

The President. Thank you very much indeed. We have a few minutes for questions or comments. Perhaps I could kick things off. When you were giving an historical perspective of the development of these ideas, there was the 1985 paper that you said was the first one to suggest catastrophic flooding. Was there any evidence or any thought process that produced that or was it out of the blue?

Dr. Collier. Whilst Smith had some 2-D sub-surface data, basically he put very few data together and had a very imaginative idea. Unfortunately the data weren't convincing to the general audience. If you've got a game-changing hypothesis and not really the data to back it up then people often choose to ignore it. It wasn't until we got our sonar out in 2003 that we could really image the landscapes and actually demonstrate not only the first-order features but also the small-scale features that were there. In truth we didn't set out to prove the catastrophic theory — I don't think we would ever have been funded for that. [Laughter.] We had funding for a more modest target — it was just serendipity that we found the flood landscape at all.

Reverend Barber. On the question of the trigger for that event, was there not a massive landslide off the coast of Norway that shaped the east coast of Britain? Would that be roughly at the same time or would I be completely out?

Dr. Collier. That event, known as the Storegga Slide, is not related. It is much younger than the catastrophic flood and also we're talking about a time when we have ice right across the North Sea. This helps constrain the timing of flood as the ice only formed a barrier during a few glacial periods. However, it has been suggested that the flood was triggered by a major collapse at the front of the ice wall which pushed the lake over the top of the Dover rock ridge. Maybe once it started going with the chalk you then got gullies developing and it kept going. We can only speculate.

Professor E. R. Priest. When did Ireland separate from Britain? [Laughter.]

Dr. Collier. Well, actually there are some interesting glacial features between Britain and Ireland as well, but we've always been separated during sea-level high stands. It's really just between southern England and France where it's clear the populations of the marine fossils, for example, are different in the English Channel and southern North Sea; and also the sediments are different. Britain and Ireland don't have the same history in terms of a land bridge that was later removed.

Professor S. Schwarz. So Scotland will never separate? [Laughter.]

Dr. Collier. Well, of course, parts of Scotland actually joined England through the process of plate tectonics back in deep time; they actually have more of an affinity with Canada.

Dr. J. Chamberlain. You've got an estimate of the rate of discharge, I think, and you must have some idea how big the lake was. Do you have an idea of how long that took?

Dr. Collier. Yes, of course, but the people who work on the lake also disagree with its height so we have an uncertainty of about 40% in terms of the water volumes in the lake, but we have done the calculation and estimate, say, three weeks.

Dr. Chamberlain. I wanted to know if it was days, weeks, months; so three weeks.

Dr. Collier. That's to drain all of the water out of the lake, but of course it wouldn't all drain. There are a huge number of uncertainties. Another thing we have difficulty in estimating is flexure; anyone who was at Tony Watt's Harold Jeffreys Lecture last year will have heard him talk about that. When you've got a big ice sheet the Earth flexes under the load and that affects the height of the lake as well. Unfortunately we don't know how thick the ice was and there are other unknowns in our estimate of the 'height of the bath tub'.

Professor P. G. Murdin. I was familiar with the teardrop islands being identified on Mars but I can't remember whether the plunge pools have been identified on Mars.

Dr. Collier. I'm not sure, maybe someone else in the audience knows better than I. I don't know where that theory fits.

Professor Murdin. Is that a deficit in the theory that those islands were formed by floods?

Mr. K. McNulty. The plunge pools would have been filled up with dust. The Hale Crater was covered over twice and exposed twice so they're probably there.

Dr. Collier. You need seismic like we had to image the infilled plunge pools. [Laughter.]

Professor M. A. H. MacCallum. Is there any hope of identifying where the scoured material got to?

Dr. Collier. No. In the Channelled Scablands you get lots of depositional features: there are big bars and gravel deposits but of course ours are now gone. When you've got soft, eroded material it will be moved around with the tides so we only have the solid bedrock eroded parts. In essence we only have half the story because we're underwater and that's something we have to live with.

Professor B. Davis. I'd just like to make a comment and it's slightly humorous. I live on the Isle of Wight and I sail up and down and across the English Channel relying on nautical charts, so I'm just wondering if we'll be needing a new set of nautical charts to incorporate your data. To ensure our safety. [Laughter.]

Dr. Collier. No, but that's a pertinent question because about 60% of our data come from the Maritime Coastguard Agency since they do the routine mapping. What they're interested in is the positions of the shallow, mobile sandbanks. Without those navigational hazards we wouldn't have the seabed surveys that we have. With our collaborator in the UK Hydrographic Office, we put data together over a thirty-year period that worked well when it's bedrock, but we do have problems when we've got mobile sediments. When you add data here over a thirty-year period you get a complete smudgy mess as you might imagine. As an academic group it would have taken us about 200 years to collect all the data I showed tonight. Many of those data were collected for maritime safety, so it's a very relevant question.

The President. Did I see English Heritage was one of your funding sources?

Dr. Collier. It was.

The President. How did you persuade them? [Laughter.]

Dr. Collier. I think we only persuaded them as I teamed up with my colleague Sanjeev Gupta who is a sedimentologist and you can always have much more confidence in someone else's science! We went to see them and Sanjeev was saying "We will image this" and I was thinking "Will we?" — and I was saying "Yes, and we think the sedimentology will be this." So it was quite speculative. However, scientific breakthroughs often happen when you step out of your 'comfort zone'. I'm being very honest; we had industry partners so it was a project looking for Palaeolithic landscapes linked to aggregates. Actually a lot (about 50%) of aggregates used in England come from offshore. We were winging it a little bit and this is one of the advantages of collaborating with people quite far from your discipline. Not only do you challenge each other but also when you propose something it is more creative. [Laughter.] Anyway, we were fortunate, and got this unexpected result.

The President. On that note of winging it, I think we should finish. The clock is approaching six o'clock so can we all thank Jenny very much. [Applause.] That concludes the November meeting. Now may I remind you of our usual drinks reception in the RAS library immediately following this meeting, and I give notice that the next monthly A&G Open Meeting of the Society will be on Friday 9th of December 2016.

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 253: HD 142178, HD 143777, HD 145373, AND HD 145933

By R. F. Griffin
Cambridge Observatories

The four stars treated here are all in Area 1 of the 'Clube Selected Areas' — in fact, in just the preceding part of that Area in terms of right ascension. The stars on the 'Clube' programme are all nominally close to the ninth magnitude and are classified as type K0 in the *Henry Draper Catalogue*. Only one of the stars discussed here, HD 145933, featured in the paper[1] that (thirty years ago) presented radial velocities for northern Clube stars; two of the others were added to the programme in an as-yet-unpublished extension to the survey in the northern hemisphere, and one (HD 145373) is not itself eligible for the Clube programme, not being of *HD* type K0 — it came to attention through being close to a genuine Clube star in the sky.

HD 142178, a $9^{m}\cdot 3$ G-type star in Corona Borealis, is found to have an orbital period of just over 1000 days, determined to better than a day. The considerable mass function of 0·14 $M_{\odot}$ requires the secondary star to have a mass not less than about 0·75 $M_{\odot}$, but that component has not been certainly detected. A companion star about 2½′ following HD 142178, *Tycho* 2040–779–1, has proved to be unrelated and to have a constant radial velocity.

HD 143777, also in Corona, is marginally brighter than 9^{m}, and proves to have an orbital period of about 331 days. It cannot be observed throughout the year, but it has been under observation long enough for the phases when it is inaccessible to have migrated all round the orbit. It has a quite small mass function and the companion star is not seen.

HD 145373, though not itself a Clube star, *looks* just like an adjacent one that *is*, HD 145403. The former has a period of some 63 days, determined to within less than an hour; the radial-velocity amplitude is quite modest (2·65 km s^{-1}), and the mass function of little more than 10^{-4} $M_{\odot}$ indicates that there is little likelihood that the secondary should be observable.

Finally, HD 145933, one of the brightest stars on the Clube programme, in Hercules, has an orbit with a period of 436 days and the rather high eccentricity of 0·618. The radial-velocity amplitude is smaller even than that of HD 145373.

Introduction

The 'Clube Selected Areas' programme of radial-velocity observations arose rather casually, when the present writer agreed to assist a project proposed by Dr. S. V. M. Clube, by measuring the velocities of samples of stars in 16 limited areas of sky, methodically distributed at Galactic latitudes ±35° and at 45° intervals in Galactic longitude. Clube's intention was to contribute some information on Galactic structure and dynamics, at least in the region within about a kiloparsec of the Sun, by observing a set of stars of a defined character systematically selected to be as distant as could be identified and conveniently observed in the different directions.* No catalogue could be found that offered two-dimensional spectral types for many stars of the desired brightness level in all the directions of interest, and it seemed necessary to fall back on the *Henry Draper Catalogue*. The stars selected were all classified there as type K0 and were attributed photo-visual magnitudes within half a magnitude of $9^{m}\cdot 0$. Although no luminosity classification was available for the *HD* stars, the hope was that most of them would be giants, with distance moduli of nine or ten magnitudes, and so would sample a volume with a radius of the order of a kiloparsec. Optimistic opinion was that most of the main-sequence interlopers that would inevitably adulterate the sample could be recognized from their large proper motions and omitted from the discussion of Galactic dynamics.

A major tranche of results from the programme was presented[1] thirty years ago, but a serious shortcoming was evident in that publication: because the observations were all made with the 36-inch reflector at Cambridge, six of the 16 'selected areas' were actually too far south to be accessible to the telescope and so did not feature in the results at all. Certain other areas were seen only at unhelpfully low altitudes in the Cambridge sky. Those problems were overcome when ESO kindly granted the writer five observing runs on the 61-inch Danish telescope at La Silla. With the larger telescope and better observing conditions than in Cambridge, the work there proceeded very quickly, with integrations normally needing only one minute per star; not only were the six previously un-observed far-southern areas well observed[2], but there was even time and opportunity also to re-observe some of the other areas at low declinations. By the conclusion of the efforts at La Silla, the disparity between the hemispheres had been reversed: owing to the much greater richness of the *HD* in the southern hemisphere than in the northern, far more stars had been observed in the southern areas than in the northern ones. Areas of equal size had initially been adopted for the 16 observed fields, and all eligible stars (those that fulfilled the criteria noted in the paragraph above) were observed. The only way of redressing the imbalance in the distribution of stars (short of disregarding half the stars already observed in the south) was to deem the northern areas to be increased in size (the same centres being retained), and that was done. The writer still owes the literature a third paper on the Selected Areas, in which the radial velocities of the additional stars that were belatedly included within the expanded northern areas would feature. Actually, three of the four stars to which the present paper is devoted (the exception is HD 145933) are 'additional' ones, in the arbitrary extension of Area 1, and do not feature in the original paper[1] giving results for that area.

Partly owing to the 'benefit' of the 20-year delay before the velocities of

*No such discussion has ever actually been published on the basis of the results of that investigation.

the southern stars were published, there was more information available then to allow the minority of main-sequence stars in the sample to be recognized and omitted from the foreseen discussion of the results. In the paper[2] on the southern areas, objects were identified and flagged as known or probable main-sequence stars if they had (*a*) proper motions in excess of 0″·1 per annum, (*b*) *Hipparcos* parallaxes greater than 0″·006 (implying distance moduli less than about 6 magnitudes, *i.e.*, M_V fainter than about +3 for 9^m stars), and/or (*c*) known spectral types* that included luminosities classes of IV–V or V.

HD 142178

Although Clube Area 1 is centred well within the huge constellation Hercules†, HD 142178, at the preceding edge of the Area, is to be found in Corona Borealis. It is only about 1° south-following the famous variable star R CrB, from which it is about 2/5 of the way to one of the bright 'crown' stars, ε CrB. Like all stars on the Clube programme, HD 142178 has an *HD* type of K0 and an apparent magnitude near 9. *Tycho 2* has given[4] actual measurements of its *V* and *B* magnitudes as 9·34 and 10·05, respectively, as well as a proper motion exceeding 0″·1 in both RA and declination, so it is surely of main-sequence luminosity, and its $(B-V)$ colour index of $0^m \cdot 71$ would accord with that of a single star with a spectral type of about G5 V. Alone among the stars treated in this paper, HD 142178 has an entry in the 1953 *General Catalogue of Stellar Radial Velocities*[5]: it reports a single velocity from Lick, which is noted as having quality '*d*', *i.e.*, a 'probable error' of 10 km s^{-1}, and so is unlikely to be helpful here for the determination of the orbit.

That brief summary more or less exhausts what is already known about HD 142178, but we can add something to that knowledge by presenting the 66 radial velocities, all obtained with the Cambridge *Coravel*, in Table I. They demonstrate, first, that the object is a spectroscopic binary, and then go on to show that it has an orbital period of 1019 days that is determined with a standard error less than a single day. The orbit is plotted in Fig. 1 and its elements are listed, with those of the other stars treated in this paper, in Table VII below. The mass function of 0·144 $M_\odot$ is large enough to be significant: if the mass of the observed star is taken to be almost a solar mass, then the secondary must have a mass of at least 0·75 $M_\odot$ — more, if the orbital plane is significantly inclined to the line of sight. Such a secondary should be no later in type than early K, and no more than $1^m \cdot 7$ fainter than the primary in the *V* photometric band — possibly 2^m in *B* where the radial-velocity instrument operates. It is accordingly a little embarrassing that the secondary, although it has on occasion seemed to be visible in radial-velocity traces, has not routinely been apparent in them, either as a separate entity near the nodes of the orbit or as a significant inflection of the velocity curve where it crosses the γ-velocity. There is, however, a possibility that the secondary object could be itself a binary system, in which case it could easily escape detection in radial-velocity traces, and some modification would then be needed to the discussion in this paragraph.

Nearly 2½ minutes of arc following HD 142178, and slightly (20″) to the south, is the star BD +28° 2485 (the *HD* star itself is +28° 2484). The companion

*By the time that the paper on the southern areas was published, it was possible to include two-dimensional spectral types for all the stars, from the re-classification[3] of the *HD* stars that started at the South Pole and worked north but unfortunately stalled at +5°.

†Only Cetus, Hydra, Ursa Major, and Virgo are larger — and only by a few per cent.

TABLE I

Radial-velocity observations of HD 142178

All the observations were made with the Cambridge Coravel

Date (UT)	MJD	Velocity km s^{-1}	Phase	(O–C) km s^{-1}
2003 Aug. 16·91	52867·91	−48·1	0·087	−0·2
2004 Sept. 15·84	53263·84	−48·7	0·475	+0·2
2005 Aug. 8·92	53590·92	−35·5	0·796	0·0
21·85	603·85	−34·1	·809	+0·7
Sept. 12·84	625·84	−34·1	·831	−0·6
25·79	638·79	−32·7	·843	+0·1
Oct. 27·74	670·74	−31·9	·875	−0·8
Nov. 13·72	687·72	−28·9	·891	+1·5
2006 Mar. 2·19	53796·19	−34·8	0·998	−0·1
Apr. 4·12	829·12	−40·4	1·030	−0·5
12·12	837·12	−41·5	·038	−0·3
26·06	851·06	−42·8	·052	+0·6
May 6·10	861·10	−44·1	·062	+0·8
16·04	871·04	−45·7	·071	+0·5
30·02	885·02	−48·4	·085	−0·6
June 21·99	907·99	−50·1	·108	−0·2
July 11·96	927·96	−51·3	·127	−0·1
23·98	939·98	−52·1	·139	−0·2
Aug. 28·86	975·86	−53·0	·174	0·0
Sept. 20·80	998·80	−53·4	·197	0·0
Oct. 24·75	54032·75	−53·4	·230	+0·2
2007 Jan. 14·29	54114·29	−53·2	1·310	−0·4
Feb. 15·25	146·25	−51·0	·342	+1·2
Mar. 27·12	186·12	−50·5	·381	+0·9
Apr. 30·08	220·08	−50·6	·414	0·0
May 1·09	221·09	−50·3	·415	+0·3
31·03	251·03	−50·8	·444	−1·0
July 24·97	305·97	−49·5	·498	−1·3
Aug. 26·85	338·85	−47·5	·531	−0·3
Sept. 24·81	367·81	−46·6	·559	−0·4
Oct. 17·76	390·76	−45·3	·582	+0·1
2008 Feb. 2·23	54498·23	−42·1	1·687	−1·0
Mar. 5·21	530·21	−39·5	·719	+0·1
31·15	556·15	−38·1	·744	+0·2
May 3·06	589·06	−36·6	·776	0·0
July 20·96	667·96	−32·3	·854	−0·1
Aug. 10·87	688·87	−31·0	·874	+0·2
30·84	708·84	−30·2	·894	+0·1
Sept. 12·85	721·85	−30·0	·907	−0·1
Oct. 2·78	741·78	−30·2	·926	−0·6
21·75	760·75	−29·8	·945	+0·1
Nov. 7·73	777·73	−30·6	·962	+0·2
2009 Apr. 2·14	54923·14	−49·6	2·104	0·0
Sept. 8·85	55082·85	−53·4	·261	0·0
10·82	084·82	−53·2	·263	+0·2
Oct. 8·76	112·76	−53·4	·290	−0·3
Nov. 17·71	152·71	−53·1	·330	−0·6

TABLE I (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O–C)* *km s⁻¹*
2010 Apr. 8·14	55294·14	−48·7	2·469	+0·4
May 24·09	340·09	−47·9	·514	−0·2
Sept. 1·85	440·85	−43·4	·613	+0·8
Oct. 6·77	475·77	−43·2	·647	−0·3
27·75	496·75	−41·5	·667	+0·5
2011 Sept. 12·83	55816·83	−33·3	2·982	−0·7
Oct. 18·78	852·78	−38·5	3·017	−0·8
26·74	860·74	−38·5	·025	+0·5
2013 Sept. 6·84	56541·84	−41·4	3·694	−0·6
2014 Mar. 23·21	56739·21	−31·0	3·887	−0·4
June 13·06	821·06	−31·2	·968	0·0
24·98	832·98	−32·2	·979	+0·2
July 21·92	859·92	−35·6	4·006	+0·3
30·90	868·90	−36·7	·015	+0·6
Sept. 9·86	909·86	−44·6	·055	−0·7
Oct. 7·77	937·77	−47·3	·082	+0·2
2015 July 5·96	57208·96	−52·6	4·348	−0·5
22·92	225·92	−51·2	·365	+0·5
Sept. 30·83	295·83	−49·6	·434	+0·5
2016 Apr. 17·14	57495·14	−42·6	4·629	+1·0

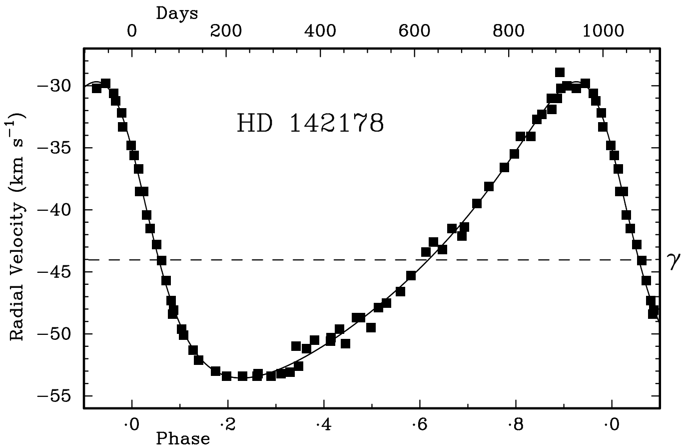

FIG. 1

The observed radial velocities of HD 142178 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations were obtained with the Cambridge *Coravel* and are plotted as filled squares.

star was measured by *Tycho 2*, whose designation for it is 2040–779–1, at $V = 10^{m}{\cdot}65$, $B = 11^{m}{\cdot}38$, making it practically the same colour as HD 142178 but about $1^{m}{\cdot}3$ fainter. The observer's curiosity, aroused upon seeing the object quite close to the star of actual interest, prompted him to measure its radial velocity on five occasions; the results are set out in Table II, where it will be seen that the velocity remained constant within observational uncertainty, with a mean of $-50{\cdot}8 \pm 0{\cdot}4$ km s^{-1} (the uncertain observation being attributed weight ¼) that demonstrates that the companion is only an optical one.

TABLE II

Cambridge radial-velocity observations of BD +28° 2485 (Tycho 2040–779–1)

Date (UT)	*Velocity km s^{-1}*
2003 Aug. 16·91	−51·2
2005 Aug. 8·92	−51·1
2008 Mar. 5·21	−49·0:
July 20·96	−50·2
2016 July 5·96	−51·3

HD 143777

HD 143777 is another 9^{m} star in Corona Borealis; it is exactly on the perimeter line of the apparent 'crown', slightly nearer to ι CrB (for northern observers the left-hand-most of the seven stars that constitute the circlet) than to ε (the next star that the naked eye sees, about 3° below it). *Tycho* 2 photometry[4] puts the magnitude of HD 143777 at $8^{m}{\cdot}93$, and its $(B-V)$ colour index at $0^{m}{\cdot}71$ — almost exactly the same as that of HD 142178. The literature on HD 143777 will not detain us: *Simbad* knows of *no* papers that include it, apart from catalogues that are of limited interest in the present connection.

The star was not observed for radial velocity until after the Cambridge *Coravel* was operational, in 2003. A second observation, a year later, produced a discordance of as much as 15 km s^{-1}, which after immediate confirmation led to the inscription of HD 143777 in the spectroscopic-binary programme and a sequence of tolerably systematic follow-up observations. The period of about 11 months became apparent within a year of the second measurement. Although there is an interval around the turn of the calendar year when the star cannot be observed from Cambridge, the nights are so long at that season that the gap between observing seasons is not very long; and anyway, since systematic observations began in 2004, the phase of inaccessibility has migrated completely around the orbit, so the 71 observations that are set out in Table III are rather evenly distributed in phase. The orbit has a moderately large eccentricity, approaching 0·5, and its 331-day period is determined to little more than an hour. The complete elements appear in Table VII and the orbit is depicted in Fig. 2.

The mass function of just under 0·03 $M_\odot$ is so small that there can be no surprise at the lack of any detectable signature of the secondary star in radial-velocity traces. If the mass of the primary star is close to one solar mass, the mass function does not require the secondary to have a mass as great as 0·4 $M_\odot$, about the mass of an M2 main-sequence star with an absolute magnitude of about 10. We cannot be certain whether the primary is a main-sequence object: the proper motion of about 0″·087/year is not quite enough to exclude

TABLE III

Radial-velocity observations of HD 143777

All the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O – C)* *km s⁻¹*
2003 Aug. 19·89	52870·89	−55·7	0·968	−0·2
2004 Sept. 15·86	53263·86	−40·7	2·156	−0·1
18·80	266·80	−40·0	·165	+0·1
Oct. 7·78	285·78	−38·3	·222	−0·5
Nov. 13·72	322·72	−36·1	·334	−0·4
2005 Jan. 23·28	53393·28	−35·6	2·547	0·0
Apr. 19·12	479·12	−41·2	·807	+0·3
May 28·01	518·01	−50·2	·924	+0·6
June 6·99	527·99	−54·5	·954	−0·3
23·00	544·00	−56·2	3·003	+0·1
July 16·93	567·93	−47·9	·075	−0·1
28·88	579·88	−44·1	·111	−0·2
Aug. 2·88	584·88	−42·6	·126	0·0
6·88	588·88	−41·6	·138	+0·1
25·91	607·91	−38·1	·196	+0·6
Sept. 8·87	621·87	−37·2	·238	+0·1
17·86	630·86	−37·0	·265	−0·3
Oct. 2·78	645·78	−36·0	·310	−0·1
20·76	663·76	−35·7	·365	−0·3
29·73	672·73	−35·9	·392	−0·6
Nov. 9·73	683·73	−35·0	·425	+0·2
2006 Mar. 23·17	53817·17	−43·0	3·828	−0·3
Apr. 4·12	829·12	−44·9	·864	+0·2
12·13	837·13	−46·8	·889	+0·3
26·06	851·06	−51·5	·931	+0·1
May 3·08	858·08	−53·9	·952	+0·1
16·06	871·06	−56·0	·991	+0·5
30·02	885·02	−53·4	4·033	+0·1
June 2·99	888·99	−51·9	·045	−0·1
5·98	891·98	−50·4	·054	+0·2
8·96	894·96	−48·4	·063	+1·0
21·99	907·99	−45·0	·103	−0·3
Oct. 24·77	54032·77	−34·9	·480	+0·4
Nov. 2·73	041·73	−35·3	·507	+0·1
18·71	057·71	−35·4	·555	+0·3
2007 Mar. 27·13	54186·13	−53·1	4·943	−0·1
May 1·10	221·10	−52·3	5·049	−1·0
Oct. 23·76	396·76	−35·6	·580	+0·3
30·74	403·74	−36·6	·601	−0·5
Nov. 12·72	416·72	−37·1	·640	−0·4
2008 Mar. 5·22	54530·22	−56·0	5·983	+0·3
Oct. 21·76	760·76	−38·0	6·680	−0·6
31·74	770·74	−37·7	·710	+0·4
Nov. 7·73	777·73	−38·6	·731	+0·1
18·71	788·71	−40·5	·765	−0·8
2009 Feb. 12·26	54874·26	−54·6	7·023	+0·1
Mar. 6·23	896·23	−45·5	·090	+0·6
July 2·99	55014·99	−35·0	·449	+0·2
Aug. 29·89	072·89	−36·0	·624	+0·4
Sept. 10·83	084·83	−36·8	·660	+0·2

TABLE III (*concluded*)

Date (UT)		*MJD*	*Velocity* km s⁻¹	*Phase*	*(O – C)* km s⁻¹
2010	Apr. 8·16	55294·16	−36·1	8·292	+0·1
	May 16·06	332·06	−35·0	·407	+0·2
	Sept. 11·82	450·82	−39·4	·766	+0·4
	Oct. 27·75	496·75	−49·1	·905	−0·4
	Nov. 15·72	515·72	−55·3	·962	−0·4
2011	May 21·08	55702·08	−35·0	9·525	+0·5
	Sept. 12·84	816·84	−46·1	·872	−0·4
	Oct. 26·74	860·74	−56·7	10·005	−0·5
	Nov. 19·71	884·71	−47·7	·077	−0·1
2012	July 22·98	56130·98	−42·6	10·821	−0·3
	Aug. 1·90	140·90	−44·1	·851	0·0
	15·88	154·88	−47·6	·894	0·0
2013	Sept. 6·85	56541·85	−49·1	12·063	+0·3
	Oct. 16·75	581·75	−39·1	·184	+0·1
2014	May 15·07	56792·07	−42·2	12·819	0·0
	June 11·03	819·03	−48·1	·901	+0·2
	19·00	827·00	−50·8	·925	+0·1
	July 30·91	868·91	−51·1	13·052	−0·1
	Aug. 10·88	879·88	−46·8	·085	−0·1
2015	July 17·96	57220·96	−43·8	14·116	−0·3
	Oct. 2·78	297·78	−35·4	·348	+0·2

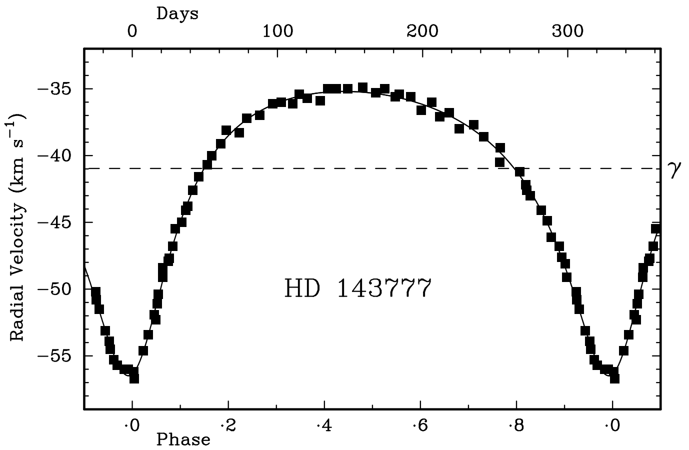

FIG. 2
Exactly analogous to Fig. 1, but for HD 143777.

the possibility that the star could be a giant, but even in that case the mass function would still imply that the companion star could well be invisibly faint in comparison with the primary, as is observed.

The nearest to HD 143777 of the adjacent *HD* stars, HD 143705 (G0 V), which is about 20′ north-preceding, was observed once, on 2007 October 23·76, and found to give a 'very poor dip' (a consequence of its relatively early spectral type); its radial velocity of –44·1 km s^{-1} differed appreciably from the γ-velocity determined for HD 143777.

HD 145373

This star, although it is another one that is within Clube Area 1 in Corona Borealis, is not actually a 'Clube' object at all, since the *Henry Draper Catalogue* attributes to it a spectral type of K5, not K0. It has been observed on the Clube programme only out of curiosity, because of its proximity to a star that genuinely *is* on the programme, HD 145403, which is to be found nearly 2° directly following ι CrB.

The field of view of HD 145403 is enlivened by the presence of the very similar-looking object HD 145373 only 2′·7 due west of the actual programme star. The *Tycho 2 V* and *B* magnitudes[4] of HD 145403 are $8^{m}·55$ and $9^{m}·75$, respectively, whereas those of HD 145373 are $8^{m}·32$ and $9^{m}·78$, giving a colour index that largely confirms the later type that is given for it in the *HD*. A quite similar type was also proposed by Stephenson, who listed HD 145373 as no. 1313 in a catalogue of *Dwarf K and M stars of small proper motion found in a large spectroscopic survey*[5], and on the basis of an objective-prism spectrogram classified it as K4. Subsequently Weis[6], who made a photometric study of Stephenson's stars, gave photometry for HD 145373 as $V = 8^{m}·36$, $(B-V) = 1^{m}·47$, $(U-B) = 1^{m}·67$. Main-sequence stars with $(B-V)$ colour indices similar to that of HD 145373 normally have $(U-B)$ indices that are no greater; it was no doubt the excess redness of the $(U-B)$ colour index that led Weis to note, "The photometric indices indicate that this is not a dwarf.".

HD 145373, like HD 142178 (discussed above), is noted by *Simbad*, in the main heading for the star, as a "High[-]proper-motion Star". But *Simbad* is quite uneven in its attributions, because whereas HD 142178 is rather clearly a main-sequence star, whose annual proper-motion components of more than 0″·1 in both coördinates would represent an improbably high transverse motion if the star were a giant (the implied distance modulus would be nine or ten magnitudes and the transverse velocity about 500 km s^{-1}), HD 145373, though a magnitude brighter, has a total motion of only 0″·050. On the other hand, HD 143777, despite its much larger annual motion of 0″·087, is described by *Simbad* only as "Star". But we cannot in any case use the relatively modest value of HD 145373's proper motion to make any definite inference concerning its luminosity: a large proper motion usually implies relative proximity, but a smallish one may be merely fortuitous.

It was not until the genuine Clube star (HD 145403) was observed for the fourth time, in 2006, that the observer's curiosity got the better of him and impelled him to observe the adjacent HD 145373 as well. Then he felt obliged to measure it again next time that he had occasion to observe HD 145403, in 2009, just to see whether its radial velocity was constant. There was a discrepancy of more than 2 km s^{-1} that was not to be accepted very willingly as observational error; it prompted a further measurement, about six weeks later, that demonstrated an unambiguous discordance with both of the previous ones and led to the admission of HD 145373 onto the spectroscopic-binary programme. The fact that there had been a considerable change in velocity in a matter of a few weeks implied a relatively short orbital period, so the star was then observed reasonably assiduously, and its period of about 63½ days (now

Table IV

Radial-velocity observations of HD 145373

All the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity* *km s*$^{-1}$	*Phase*	*(O – C)* *km s*$^{-1}$
2006 July 13·98	53929·98	−59·6	$\overline{18}$·403	+0·7
2009 Sept. 12·88	55086·88	−57·2	0·609	+0·2
Oct. 22·79	126·79	−61·5	1·237	−0·3
Nov. 3·76	138·76	−60·5	·425	−0·5
9·73	144·73	−59·5	·519	−0·8
17·72	152·72	−57·5	·645	−0·6
2010 Mar. 23·17	55278·17	−56·6	3·619	+0·6
Apr. 8·16	294·16	−55·9	·871	+0·4
13·11	299·11	−57·0	·949	+0·3
18·14	304·14	−58·9	4·028	−0·2
May 12·06	328·06	−60·0	·404	+0·3
17·05	333·05	−59·1	·483	+0·1
19·09	335·09	−58·8	·515	−0·1
June 4·04	351·04	−55·9	·766	0·0
12·01	359·01	−56·4	·892	+0·1
27·01	374·01	−60·0	5·128	+0·3
July 6·00	383·00	−61·2	·269	0·0
17·94	394·94	−60·0	·457	−0·4
29·91	406·91	−56·5	·645	+0·4
Aug. 10·90	418·90	−55·9	·834	+0·1
27·85	435·85	−60·3	6·101	−0·4
Sept. 11·83	450·83	−60·7	·336	+0·2
Oct. 6·77	475·77	−56·2	·729	−0·1
27·74	496·74	−59·4	7·059	−0·2
2011 May 11·09	55692·09	−60·2	10·133	+0·2
13·08	694·08	−60·4	·164	+0·4
Sept. 27·79	831·79	−60·9	12·332	0·0
Oct. 18·78	852·78	−56·8	·662	−0·1
19·75	853·75	−56·7	·677	−0·2
22·76	856·76	−56·2	·725	−0·1
26·75	860·75	−56·1	·787	−0·2
2012 June 23·01	56101·01	−57·7	16·568	+0·2
July 22·99	130·99	−59·1	17·040	−0·2
Aug. 20·89	159·89	−58·8	·495	+0·2
Sept. 6·86	176·86	−55·8	·762	+0·2
14·86	184·86	−56·3	·888	+0·1
15·85	185·85	−56·5	·903	+0·1
18·85	188·85	−57·5	·951	−0·2
2013 Apr. 6·15	56388·15	−59·6	21·087	+0·1
May 4·07	416·07	−58·6	·526	0·0
5·09	417·09	−58·2	·542	+0·1
6·04	418·04	−58·0	·557	+0·1
June 4·07	447·07	−58·7	22·014	−0·3
14·00	457·00	−60·6	·170	+0·2
Sept. 2·86	537·86	−60·2	23·443	−0·4
2014 Mar. 4·23	56720·23	−60·8	26·313	+0·3
May 15·07	792·07	−59·7	27·443	+0·1
31·05	808·05	−56·1	·695	+0·3
June 6·05	814·05	−56·0	·789	−0·1
11·03	819·03	−56·3	·868	−0·1
19·02	827·02	−58·0	·993	0·0

TABLE IV (*concluded*)

Date (UT)		*MJD*	*Velocity* *km s⁻¹*	*Phase*	*(O–C)* *km s⁻¹*
2014 July	1·04	57839·04	−60·8	28·183	+0·1
	3·95	841·95	−61·0	·228	+0·2
	6·98	844·98	−61·4	·276	−0·2
	13·99	851·99	−60·6	·386	−0·1
	23·93	861·93	−57·9	·543	+0·4
Aug.	2·96	871·96	−56·6	·701	−0·3
	11·87	880·87	−56·2	·841	−0·2
Sept.	9·88	909·88	−61·3	29·297	−0·2
Oct.	7·80	937·80	−56·4	·737	−0·3
2015 July	5·97	57208·97	−58·0	34·004	+0·2
Sept.	12·81	277·81	−59·7	35·087	0·0
	19·87	284·87	−61·5	·198	−0·5

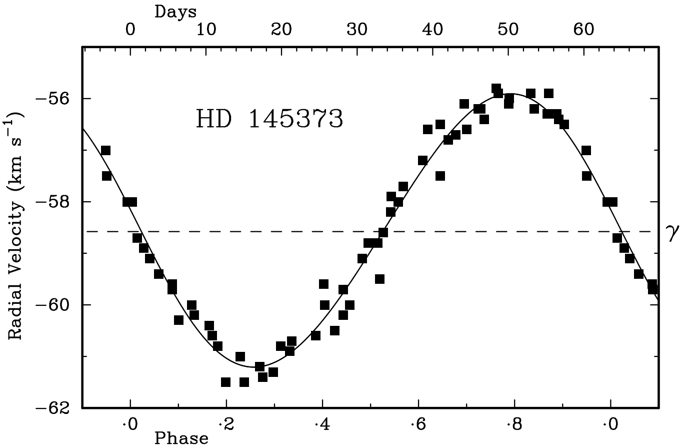

FIG. 3

Exactly analogous to Fig. 1, but for HD 145373.

determined to better than half an hour) was soon established.

The 63 radial velocities presently available for HD 145373 are listed in Table IV. They yield an orbit whose velocity curve looks to be close to a sine wave; but when the eccentricity is left as a free parameter in the solution, it takes the value 0·055 ± 0·020, so its significance is approaching 3σ. The sum of the squares of the 63 deviations of the observed velocities from those computed from the solution of the orbit is 5·08 (km s^{-1})^2. When zero eccentricity is forced upon the solution, the sum of squares rises to 5·68 (km s^{-1})^2. The significance of the difference can be assessed by means of the tests that the writer was taught long ago by Bassett[7], which lead to the conclusion that the difference is just significant at the 5% level. While that is hardly prescriptive, in conjunction with the naïvely determined significance of nearly 3σ in the eccentricity it encourages the tentative acceptance of the eccentric solution, and that is the one that is adopted in Table VII below and plotted in Fig. 3. The mass function is seen to be very small, little more than a ten-thousandth of a solar mass, so it is not at all surprising that the secondary object (whose 'dip', if appreciable, could in any case be expected to be blended with that of the primary) has not been recognized in the radial-velocity traces.

To complete this section of the paper, Table V offers the radial velocities that have been measured for the adjacent star HD 145403, both in its own right as a Clube star and also casually as a companion to HD 145373. There is certainly no hint of variability: the extreme range of the 12 measurements is only 0·4 km s^{-1}.

TABLE V

Cambridge radial-velocity observations of HD 145403

Date (UT)	*Velocity km s^{-1}*
2003 Aug. 19·91	−56·9
2004 Sept. 15·87	−57·2
2005 Aug. 17·95	−57·1
2006 July 13·98	−57·1
2009 Sept. 12·88	−57·2
Nov. 3·76	−57·1
2012 Aug. 15·93	−57·3
2014 Feb. 26·23	−57·1
Apr. 8·15	−57·1
June 6·05	−57·2
Sept. 9·88	−56·9
2015 June 1·00	−56·9

HD 145933

Among the stars mentioned in this paper, this is the only one that was already featured in the writer's 1986 publication[1] of the radial velocities of stars in the northern Clube Areas. The other stars to which reference has been made above are either not 'Clube' stars at all, or else became included in the programme only when the northern Areas were arbitrarily enlarged in order to make the numbers of stars that were eligible in them for the programme more comparable with the numbers in the southern-hemisphere fields, where the *Henry Draper Catalogue* is richer.

HD 145933 is in the constellation Hercules, very nearly 4° directly following the bright star β Her*; to the visual observer it is somewhat upstaged by the brighter ($6^{m}·7$) A-type star HD 146010 that is seen about 4′ north-following.

In the *Henry Draper Catalogue* HD 145933 is attributed a photo-visual magnitude of 8·5, putting it right at the bright end of the magnitude-selection criterion ($9^{m}·0 \pm 0^{m}·5$) for the Clube programme; the comparatively recent *Tycho 2* photometry shows it to be in fact one of the brightest stars on the whole programme, the actual V magnitude being 8·19 and the $(B-V)$ colour index $1^{m}·16$. The only paper retrieved for HD 145933 by *Simbad* is the writer's own[1], which lists, without comment, six radial velocities obtained between 1970 July and 1980 September with the original photoelectric radial-velocity instrument at Cambridge. Those velocities exhibit an extreme range of 5 km s^{-1}, but evidently the writer did not care at that time to base an assertion of real variation upon them, or even to continue to monitor the velocity. (The whole

* β Her is itself a spectroscopic binary whose orbit (but no data nor graph) was presented in a brutally short write-up by Plummer[8] well over 100 years ago.

TABLE VI

Radial-velocity observations of HD 145933

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

Date (UT)	MJD	Velocity km s^{-1}	Phase	(O−C) km s^{-1}
1970 July 31·89*	40798·89	−46·0	0·409	+1·3
1971 July 24·91*	41156·91	−48·3	1·230	−0·1
1977 June 2·00*	43296·00	−49·2	6·134	−0·4
1979 Sept. 21·85*	44137·85	−47·4	8·062	+1·9
1980 Aug. 20·88*	44471·88	−44·2	8·830	+1·2
Sept. 6·86*	488·86	−44·4	·868	+0·7
2003 Aug. 20·88	52871·88	−49·1	28·087	+0·1
29·89	880·89	−49·0	·108	0·0
Oct. 3·80	915·80	−48·5	·188	−0·1
Nov. 1·73	944·73	−48·3	·254	−0·3
2004 Mar. 1·21	53065·21	−46·8	28·531	−0·1
Apr. 7·13	102·13	−46·3	·615	+0·1
May 17·08	142·08	−45·8	·707	+0·2
June 13·02	169·02	−45·7	·769	0·0
July 6·97	192·97	−44·9	·824	+0·5
Aug. 7·95	224·95	−44·8	·897	+0·2
Sept. 1·87	249·87	−45·2	·954	−0·1
Oct. 7·77	285·77	−49·4	29·036	−0·2
Nov. 4·73	313·73	−49·0	·100	+0·1
2005 Jan. 23·29	53393·29	−47·8	29·283	+0·1
Mar. 23·19	452·19	−47·1	·418	+0·1
Apr. 19·13	479·13	−47·0	·480	0·0
May 28·04	518·04	−46·3	·569	+0·3
July 16·94	567·94	−45·8	·683	+0·3
Aug. 15·89	597·89	−45·7	·752	+0·1
Sept. 7·82	620·82	−45·4	·804	+0·1
25·79	638·79	−45·2	·846	+0·1
Oct. 4·78	647·78	−45·5	·866	−0·3
25·74	668·74	−44·6	·914	+0·3
2006 Mar. 2·21	53796·21	−48·0	30·207	+0·3
Apr. 26·07	851·07	−47·5	·332	+0·1
May 11·04	866·04	−47·3	·367	+0·1
June 12·01	898·01	−46·7	·440	+0·4
Aug. 7·92	954·92	−46·6	·570	0·0
Sept. 10·85	988·85	−46·7	·648	−0·4
20·81	998·81	−46·5	·671	−0·3
2007 Feb. 4·26	54135·26	−46·2	30·984	+0·1
15·24	146·24	−47·7	31·009	+0·3
Mar. 2·22	161·22	−49·3	·043	0·0
Apr. 16·12	206·12	−48·4	·146	+0·3
30·10	220·10	−48·3	·178	+0·2
May 23·08	243·08	−48·0	·231	+0·1
Aug. 9·96	321·96	−47·8	·412	−0·6
Sept. 22·82	365·82	−47·1	·512	−0·3

TABLE VI (*concluded*)

Date (UT)	*MJD*	*Velocity km s⁻¹*	*Phase*	*(O – C) km s⁻¹*
2008 Mar. 31·16	54556·16	−44·8	31·949	+0·3
Apr. 8·14	564·14	−45·6	·967	−0·1
24·11	580·11	−47·5	32·004	+0·2
May 3·07	589·07	−48·7	·024	+0·1
Sept. 12·84	721·84	−47·9	·329	−0·3
Oct. 11·77	750·77	−47·4	·395	−0·1
Nov. 14·72	784·72	−47·3	·473	−0·3
2009 June 18·06	55000·06	−45·8	32·967	−0·4
Aug. 7·89	050·89	−49·2	33·083	0·0
Sept. 3·88	077·88	−48·7	·145	0·0
2010 Mar. 23·17	55278·17	−46·3	33·604	+0·1
Apr. 18·15	304·15	−46·3	·664	−0·1
May 13·08	329·08	−45·9	·721	0·0
24·09	340·09	−45·9	·746	−0·1
July 29·91	406·91	−45·3	·899	−0·3
Aug. 15·91	423·91	−45·0	·938	0·0
23·92	431·92	−45·0	·957	+0·2
30·85	438·85	−45·9	·973	−0·2
Sept. 11·82	450·82	−47·4	34·000	0·0
12·83	451·83	−47·7	·002	−0·1
14·86	453·86	−47·8	·007	+0·1
20·82	459·82	−48·7	·021	0·0
Oct. 6·77	475·77	−49·6	·057	−0·3
2011 Sept. 27·79	55831·79	−45·2	34·873	−0·1
Nov. 17·71	882·71	−46·4	·990	+0·3
19·70	884·70	−47·3	·995	−0·3
2014 Apr. 8·16	56755·16	−46·6	36·990	+0·1
Oct. 27·75	957·75	−47·1	37·455	0·0
2015 July 6·01	57209·01	−49·2	38·031	−0·2
22·96	225·96	−49·4	·070	−0·1
2016 Apr. 17·16	57495·16	−46·3	38·687	−0·2
Aug. 9·91	609·91	−45·1	·950	0·0

*Observed with original Cambridge spectrometer

peak-to-peak amplitude of the velocity variations of HD 145933 is now seen to be less than 5 km s^{-1}.)

Fresh observations of stars in Area 1, made in 2003 after the new and more accurate *Coravel* spectrometer had been inaugurated at Cambridge, led to the recognition that HD 145933 is a spectroscopic binary, albeit of small amplitude, so after a lapse of about 23 years in its observations the star was finally added to the binary programme and observed reasonably systematically. A further 70 measurements were made with the new spectrometer between 2003 and the time of writing of this paper; all the observations are set out in Table VI. To bring the variances of the velocities obtained with the two instruments into approximate equality, it has been necessary to down-weight those obtained with the original spectrometer by a factor of 20. The r.m.s. residual for unit weight is 0·22 km s^{-1}, so the corresponding value for the six old observations is

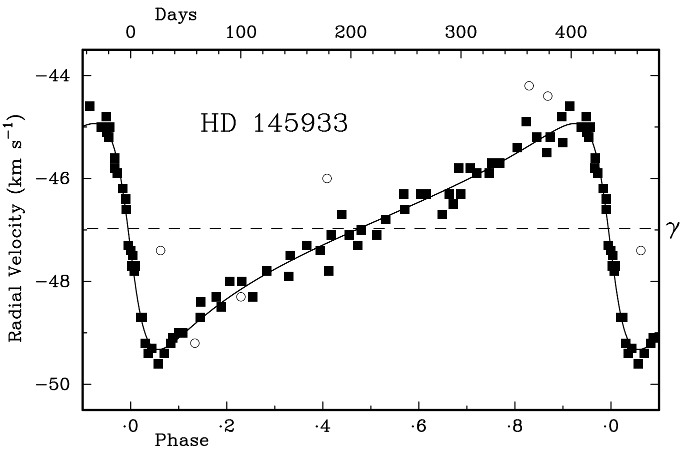

FIG. 4

Analogous to the preceding figures, but for HD 145933. In this case there are, in addition to the 70 observations made with the Cambridge *Coravel*, six measurements obtained with the original radial-velocity spectrometer at Cambridge; they are plotted as open circles. To bring the variances of the two data sources into approximate equality, the six old velocities were attributed a weight of only 1/20 in the solution of the orbit.

close to 1 km s^{-1}. That is actually not much worse than the normal performance of the original instrument, but what does give pause for thought is that the old velocities also have a mean residual of +0·76 ± 0·36 km s^{-1}. Statistically, only about 3·5% of a normal distribution should be so far (2·11σ) from zero. However, there is no indication among the newer velocities of any variation in the γ-velocity, so the discrepancy is accepted here as fortuitous. In any case, the solution of the orbit is scarcely influenced by the inclusion of the six old measurements, because they have such a small total weight that they make little change either to the derived orbital elements or even to their uncertainties. The orbital period proves to be 1·2 years, and the (semi-)amplitude is only a little over 2 km s^{-1}. The eccentricity is high (over 0·6); the orbit is orientated in such a way ($\omega \sim 90°$) that the high eccentricity is manifested as an abrupt decline that

TABLE VII

Orbital elements for HD 142178, HD 143777, HD 145373, and HD 145933

Element	*HD 142178*	*HD 143777*	*HD 145373*	*HD 145933*
P (days)	1018·6 ± 0·7	330·87 ± 0·05	63·545 ± 0·018	436·19 ± 0·22
T (MJD)	54816·9 ± 3·0	54535·7 ± 0·5	56064·9 ± 3·7	54578·5 ± 1·1
γ (km s^{-1})	−44·04 ± 0·07	−40·96 ± 0·05	−58·58 ± 0·04	−46·97 ± 0·03
K (km s^{-1})	11·97 ± 0·11	10·64 ± 0·07	2·65 ± 0·05	2·19 ± 0·04
e	0·373 ± 0·007	0·464 ± 0·005	0·055 ± 0·020	0·618 ± 0·012
ω (degrees)	56·8 ± 1·5	188·8 ± 0·8	81 ± 21	96·7 ± 2·3
$a_1 \sin i$ (Gm)	155·5 ± 1·5	42·91 ± 0·32	2·31 ± 0·05	10·35 ± 0·24
$f(m)$ ($M_\odot$)	0·145 ± 0·004	0·0288 ± 0·0006	0·000122 ± 0·000008	0·000233 ± 0·000016
R.m.s. residual (wt. 1) (km s^{-1})	0·53	0·35	0·28	0·22

occupies little more than one-eighth of the whole cycle. The orbit is plotted in Fig. 4 and the complete elements are included in Table VII. The mass function is again very small, though not quite as small as that of HD 145373, and especially in view of the smallness of the primary's radial-velocity amplitude the absence of any evidence of the secondary object in the observations is only to be expected.

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REVIEWS

The Life Story of an Infrared Telescope, by J. K. Davies (Springer, Heidelberg), 2016. Pp. 264, 24 × 16 cm. Price £59·99/$99 (hardbound; ISBN 978 3 319 23578 3).

The *United Kingdom Infrared Telescope* (*UKIRT*) was conceived way back in the 1960s as an innovative and relatively cheap 'light-bucket' to open the third window on the Universe (after the optical and radio) by Professor Jim Ring of Imperial College. This fascinating book by John Davies explores the story of that telescope from that moment of conception to its ultimate slow death on Mauna Kea, probably occurring as I write this review. It was a remarkable instrument whose optical properties were sufficiently good that, when located on a site with frequent spells of exceptional seeing, it could operate over an extended wavelength range and thus become a valuable workhorse for British astronomy.

Davies describes in detail not only the building of the telescope but the progressive construction and testing of ever-more-sophisticated instrumentation to exploit fully its capabilities, from simple photometry through to high-resolution spectrographic studies and, in its final form, wide-ranging and deep surveys to complement the work of other facilities, both ground- and space-based.

But it's not just a tale of machines but also of the men and women who built them, operated them in a harsh environment, and extracted some world-beating astronomy from them. I found their stories fascinating, especially when familiar names cropped up — "I didn't know they were involved" or "so that's what they did". This certainly makes it a personal account (Davies was himself a *UKIRT* man) which tells the story like it really was, warts and all: no blushes are spared and arguments and disasters go side by side with the successes and triumphs. It really is an account the like of which should follow every large project, especially those with international connections, not least to act as a warning for others planning such endeavours. — DAVID STICKLAND.

The Unforgotten Sisters: Female Astronomers and Scientists before Caroline Herschel, by G. Bernardi (Springer, Heidelberg), 2016. Pp. 179, 23·5 × 15·5 cm. Price £59·99/$99 (paperback; ISBN 978 3 319 26125 6).

In this book, Gabriella Bernardi presents the lives and careers of 25 women who worked across a span of over 4000 years up to the early 19th Century. Interested in the role of women in science as I am, I was surprised to encounter many figures of whom I had never previously heard, or about whom I knew little, and consequently, I learned much. These include women astronomers from classical, medieval, and modern Europe, from China, ancient Mesopotamia, and on to Arabic Spain. The book begins with Enheduanna, the Babylonian High Priestess and astronomical record-keeper, and covers six women from the ancient world, including the much-better-known Hypatia of Alexandria. The rest extend from the 10th-Century-AD Fatima of Madrid, down to Mary Somerville, whose long life overlapped that of Caroline Herschel, and who died in 1872.

This is a fascinating volume. Each figure is introduced *via* a historical timeline, which supplies the wider context. Then we have the presentation of their known 'works', 'curious facts' about their lives, and what contemporaries and later figures said about them. One of the many things I learned from this book was that Tycho Brahe had a very mathematical and astronomical younger sister, Sophie Brahe, later Thott, who even as a young teenager was assisting *Tycho* in calculating eclipses.

One point upon which I might take issue, however, is the author's assumption that the Christian Church somehow set out to suppress female education and aspiration, with the all-male medieval universities. Yet we must not forget that Europe's medieval universities came into being from the 12th Century very largely to train people to meet the growing need for effective lawyers and civil servants to help administer Europe's increasingly sophisticated society. And for good or bad, they just happened to be male professions as the world then stood — and would be so for several centuries to come. One cannot blame the past for not being like the present.

The Unforgotten Sisters is very well written, in a clear style, and is abundantly illustrated. I wish, however, that it had been equipped with an index, to make it easier to locate specific details.

I very much enjoyed *The Unforgotten Sisters* and learned a great deal from it, and I warmly recommend it to all those interested in the history of astronomy. My only regret is that its exorbitant price, £59·99, may put many people off purchasing it. — ALLAN CHAPMAN.

45 Years of Heck in Professional Astronomy, by Joe Hube (Venngeist, Duttlenheim, France), 2016. Pp. 637, 20·9 × 14·7 cm. Price €98·00 (about £89) (paperback; ISBN 978 2 9542677 3 9).

This book is devoted to the itinerary and professional activities of André Heck, a peripatetic astronomer and prolific scientific author of Belgian origin. The first eight chapters of the book (about 300 pages) focus on Heck's life (from studentship to retirement) as a scientist, and on the astronomical research that he carried out during his 45-year-long career. That first part reads like a comprehensive interview summary; the second part of the book is an exhaustive collection of documents, citations, and letters of reference, complemented with lists of meetings, lectures, publications, and summaries of papers.

The first chapter narrates Heck's coming to astronomy, and also sketches a most personal image of his early years: born in 1946 into a modest family, he always had to keep spending to a strict minimum during his youth and adolescence. That was also the case throughout his student years at the University of Liège, where he lived on a tight budget in coal-stove-heated student rooms with rudimentary furniture and facilities beyond imagination of today's typical student. At Liège University he had the privilege of being tutored by Paul Ledoux, an excellent and fair teacher. His professors were, among others, André Monfils, Léo Houziaux, and Pol Swings.

The next chapter describes life at the Liège Institute of Astrophysics (then located in the suburb of Cointe), where Heck joined Pol Swings' Group at the observatory. In particular he reports on several early trips abroad: to Hoher List Observatory in Germany, to Paris and Strasbourg Observatory, to Haute Provence Observatory, as well as on his first contact with the observatories in Chile (*viz.*, the Cerro Tololo Inter-American Observatory, and the Las Campanas and ESO La Silla observatories). The highlights of this chapter are the description of his discovery of Comet 1973a at Haute Provence Observatory, and an account of his first observing runs at ESO La Silla. The chapter concludes at the moment that is specified as "A Career in Full Momentum" and describes the devastating consequences of the Belgian government's decision to allot financial support to universities on the sole basis of their number of students. That policy — an indirect consequence of the social and political situation after the 'May 1968' student revolts in Belgium — heavily cut into budgets at research-intensive institutes like the place where Heck was on a tenure-track position.

The turning point of Heck's career is the topic of the third chapter: his appointment in 1978 as Resident Astronomer (and later on as Acting Observatory Controller) at the *International Ultraviolet Explorer* (*IUE*) ground observatory at Villafranca in Spain. This chapter describes in detail how the *IUE* Science Operations functioned, and refers to the numerous visiting astronomers that he met and supported during many observing shifts. In 1983 he decided to leave Spain and to take up a position at Strasbourg Observatory. His life and work in Strasbourg is described in the two following chapters: how he finally obtained tenure, and how he acquired two additional academic degrees — one at Strasbourg University, and one in Liège.

Then follows a bitter account under the title "Anni Horribiles", the disastrous years that followed after Heck was diagnosed in 1987 with an incurable life-threatening ailment. Thus in 1989 he resigned, for health reasons, from the Directorship of Strasbourg Observatory.

The next three chapters deal with his multifarious work in publishing as scientific author, as freelance writer, and editor of the well-known *Star*s Family* publications and the seven *Organizations and Strategies in Astronomy* books, for which he was awarded a prize by the Royal Belgian Academy.

The first part of the book closes with a last chapter on diverse activities and on the transition to definitive retirement after having worked 45 years in professional astronomy.

The intended readership of this book spans scientists, PhD students in the natural sciences, and young postdoctoral researchers. Readers studying the history of astronomy may also find the book of interest. It has a particular appeal to two specific generations of astronomers and scientists, *i.e.*, those (like myself) of retirement age who have witnessed those times and who have lived through some stories and anecdotes so well described in this biographical account, and those of the very young generation — evidently for an entirely different reason: this publication clearly demonstrates the crucial importance of a good scientific education at a home institute. But upright scientific education and mentoring is only a *necessary* condition, but certainly not a *sufficient* condition: Heck's itinerary clearly illustrates that losing a good home institute is like losing a home forever.

The prime historical value of this book is the well-documented description of facts and situations that span more than half a century from someone's primary school to university and beyond. The touching story told is one of the shaping of a personality — in this case a scientist coming from an underprivileged family background — through economic hardships, the rigours of the university system of the time, unprecedented calamitous political decisions, grave health adversities, and severe job insecurities.

This book is extremely well documented with hundreds of references to books, papers, and web sites, and comprises nearly 250 photos and illustrations. Several indices — one hundred pages altogether — render any search very practical and effortless. — CHRISTIAAN STERKEN.

Maxwell's Enduring Legacy: A Scientific History of the Cavendish Laboratory, by M. Longair (Cambridge University Press), 2016. Pp. 664, 25 × 19·5 cm. Price £39·99/$69·99 (hardbound; ISBN 978 1 107 08369 1).

In the earlier part of the 19th Century, mathematics was pre-eminent in Cambridge. Sciences, on the other hand, were the poor relation. The Chancellor of the University at the time was Prince Albert, who used a Royal Commission to investigate the state of Cambridge University and introduce reforms. His efforts were resisted: in the view of William Whewell (mathematician and master of Trinity College): "... such departments of science as Chemistry are not proper subjects of academic instruction." Eventually the Natural Sciences Tripos was started in 1851, with Physics recognized as a separate discipline in 1861, but as yet without a department. One problem was that the colleges were wealthy and the University was not; major expenditure would have needed a levy on the colleges.

Prince Albert died in 1861. A crucial step was then taken: the Chancellorship was offered to William Cavendish, seventh Duke of Devonshire. Besides being a serious academic (2nd Wrangler, 1st Smith's Prizeman) and industrial innovator (large iron-ore deposits on his northern estates), the Duke was wealthy. In 1870, he offered the University the funding required for the building, equipping, and staffing of the proposed Department of Physics. And the other important move by the University was to persuade James Clerk Maxwell to accept the Chair — the Cavendish Professorship.

Malcolm Longair has worked in the Cavendish Laboratory for much of his career, including eight years as Head of Department. This volume is an impressive record of the Department from its beginnings up to the current time. It traces the development of the teaching and research in many areas of physics pursued by Maxwell and his successors. Although I have worked in the Department for most of my scientific career, there are wide areas about which I knew very little, and any physicist (from within or outside the Laboratory) will surely find a wealth of information of interest. At about 1·6 kg, it is not exactly light reading, but it is very good. — GUY POOLEY.

My Tale of Four Cities: An Autobiography, by J. V. Narlikar (National Book Trust, India), 2016. Pp. 513, 23·3 × 15·8 cm. Price 595 Indian Rupees (about £7) (paperback; ISBN 978 81 237 7845 7).

Jayant Narlikar is the most distinguished Indian scientist of his generation, well known for his contributions to non-standard cosmology and theoretical astrophysics. In 1988, at Pune, he founded the Inter-University Centre for Astronomy and Astrophysics, which he directed for ten years. Thanks to Narlikar's vision and leadership, IUCAA has initiated nationwide outreach campaigns in schools and colleges. Narlikar also launched a major science popularization programme for the general public. *My Tale of Four Cities* is an autobiographical account of a career that involved extensive travels. It is divided into four parts, the first of which details his early life. The second part starts with his arrival in Cambridge in 1957, and takes us to 1972 when he returned to India. The third part covers his 17 years with the Tata Institute in Mumbai, and the saga concludes with an account of his 12 years at Pune with IUCAA. The book covers the period 1938–2003, during which there were tectonic changes in India on the political front. In terms of the growth of astronomy, this was the era in which India transitioned from being an outpost for British solar astronomers at Kodaikanal, to having a space agency and world-class institutions such as IUCAA. The text is in the style of a travelogue in which the events, the places, and the personalities that influenced the author appear as the narrative unfolds. Narlikar gives us a ringside account of the lively political state of astronomy at Cambridge 1964–72: that period opened with the discovery of the cosmic microwave background and ended with Fred Hoyle's dramatic resignation. Narlikar provides a vivid, objective, and modest account of a scientific life of great achievement. It is regrettable, therefore, that at the time of writing this review the book was only available by ordering on-line from India. It deserves to be in every library that features biographies of scientists. — SIMON MITTON.

Annual Review of Astronomy and Astrophysics, Volume 54, 2016, edited by S. M. Faber & E. van Dishoeck (Annual Reviews, Palo Alto), 2016. Pp. 815, 24 × 19·5 cm. Price $264 (print only for institutions; about £212), $102 (print and on-line for individuals; about £82) (hardbound; ISBN 978 0 8243 0954 1).

The autumnal arrival of dark evenings, compounded by the return to Greenwich Mean Time, heralds the annual apparition of the *Annual Review* together with conditions appropriate to settle into an armchair by the fireside to catch up with what is at the latest frontiers of astronomical research. As is now customary, the *apéritif* is some reflections by one of the major players in the field, and this year Jeremiah Ostriker gives a brief biography, some detailed insights to the topics of particular interest to him, and concludes with some speculations on future developments.

Then on to the 'coal face'. Starting here at home, Nittler & Ciesla in the laboratory examine the extraterrestrial material available to us from meteorites, the Moon, and various landers, probes, and sample-return missions, with particular reference to isotopes created in type-II supernovae and AGB stars. Another chemically orientated chapter is a fascinating study by Gerin *et al.* of hydrides in space revealed by *Herschel*; I'd never heard of argonium, but now I have! It's ArH^+. Such materials will surely seep out into the intergalactic medium, treated by McQuinn in the context of modelling over a range of redshifts. And those same materials will also be found accreting onto pre-main-sequence stars whose evolution is considered by Hartmann *et al.* and who remind us that the problem of angular-momentum loss is still not completely solved.

Can it really be almost 30 years ago that SN1987A burst on to the scene? In a wide-ranging review of what remains of that dramatic event, with particular emphasis on observations from *ALMA*, McCray & Fransson take a close look at the interior of the remnant, but without finding a compact object at its heart. If such an object were a neutron star, then its basic properties would be of interest to readers of the paper by Özel & Freire, who discuss the equation of state in such stars — whose masses now seem to extend above 2 $M_\odot$. Stars also take centre stage in articles by Girardi, who assesses the value of low-mass, core-helium-burning, 'Red Clump' stars in providing a recognizable feature in the HRD of galaxies, allowing estimates of extinction and distances; by Bally who examines proto-stellar outflows (mainly bipolar) across a range of masses; and by Kratter & Lodato in a review of disc instabilities relating to proto-stars and proto-planets.

Galaxies then take centre stage, first in an overview of the Milky Way by Bland-Hawthorn & Gerhard who examine it as a 'benchmark' system for the study of others. That said, whether input from the Magellanic Stream, shown by D'Onghia & Fox to prolong star formation, is typical of those 'other' galaxies is probably a question for the future. The spirals more generally are treated to an update of spiral density-wave theory by Shu, while Cappellari shows what integral-field spectroscopy can do for early-type galaxies. What galaxies looked like in the first 10^9 years after the Big Bang (*i.e.*, $6{\cdot}5 < z < 10$), when star formation was booming, is considered by Stark; and the γ-ray emission of AGN, particularly blazars, observed by *Fermi*, is analysed by Madejski & Sikora, who, along the way, show a nice whole-spectrum energy curve of 3C 273 (p. 738).

A very topical discussion of the 'B mode' in polarization of the CMB, predicted by inflationary models of the Universe, is presented by Kamionkowski & Kovetz, but since the very recent retraction of the claim by the *BICEP2* team, the matter is literally still up in the air.

Finally, for a little theoretical *digestif*, and, if celestial mechanics is your 'bag' (as we used to say in the '60s), try Naoz's paper on the eccentric Kozai–Lidov effect in 3-body systems. — DAVID STICKLAND.

Picture This! Grasping the Dimensions of Time and Space, by M. Carroll (Springer, Heidelberg), 2016. Pp. 192, 28·5 × 21·5 cm. Price £19·50/$34·99 (hardbound; ISBN 978 3 319 24905 6).

At first sight, this looks like a coffee-table book with a stunning picture on the cover of the asteroid Itokawa to scale next to the CN Tower in Toronto; but this turns out to be a slightly misleading impression. The premise of the book is to put the Universe to scale using more-easily-understood analogies. And where comparison pictures, like that on the cover, are used, this premise works well. However, it soon becomes clear that this is not a 'pretty-astronomical-pictures' coffee-table book but one packed with facts and figures, some illustrated.

The author, Michael Carroll, is a space artist who has picked up much astronomical information through his work and discussions with astronomers. He is at his strongest when writing about the Solar System, but less good on stars, galaxies, and the Universe as a whole. His comparative descriptions of planets' atmospheres, rings, and moons are clear, with original diagrams to reinforce the written descriptions. There are some scientific mistakes (gravity in m/s) and some badly expressed ideas (the descriptions of supernovae are unclear) but, on the other hand, his language in describing some phenomena is more poetic than one would expect from most astronomer-written books — the Pleiades are "drifting lethargically through the cold vacuum of space". As good as most of the illustrations are, there are long descriptive passages just crying out to be illustrated — a picture is worth a thousand words. There has been an effort to use well-known international landmarks and objects for scale comparisons so that the book is not completely USA-centric, and units are nearly all S.I. though Carroll could not completely resist a few lapses into Imperial!

In the second, much shorter, part of the book, he moves away from the strict facts into his own area of expertise — commenting on the quality and accuracy of space artists' work in representing other worlds and imaginative space travel. The writing feels more relaxed here as he showcases the illustrations of his fellow imaginers.

Overall, this is a book packed with information and many good illustrations. It may be a bit daunting for complete beginners but it does present much of current astronomical knowledge in an original way. One last point: proof-reading should have picked up a few obvious typos and repetitions. I particularly liked "Our travels have taken us from the smallest of a steroids to the largest of galactic structures" on the last page! — DEBRA HOLTON.

Breakthrough! 100 Astronomical Images That Changed the World, by R. Gendler & R. J. GaBany (Springer, Heidelberg), 2015. Pp. 171, 28·5 × 21·5 cm. Price £19·99/$34·99 (hardbound; ISBN 978 3 319 20972 2).

This book basically has at least the middle part of what it says in the title — it has 100 numbered pictures, although in some cases there are multiple panels (the record is 31 in the case of Fig. 5.2!) over one caption, and in a few instances the picture would be better characterized as a diagram. Collectively, the pictures offer a diverse and interesting view of the Universe, ranging from a view of a few square feet of the surface of Mars (taken by the *Phoenix* lander, of the ground underneath it) to views, probably 100 kiloparsecs or more on a side, of mighty galaxies. They are in general good pictures (even though it smacks of exaggeration to claim that they changed the world), and most *aficionados* of astronomy will find many of them to be of interest; but in several cases the captions do not actually tell the reader what the picture is *of*.

At a rough estimate, there is twice as much space given to text as to pictures. Unfortunately the text rather lets the pictures down. Although the book is published in Germany, the text has many of what the reviewer regards as negative characteristics of the American language. It also has many idiosyncrasies that the reviewer has not previously thought of as being particularly American. There are shoals of split infinitives that result in pseudo-verbs such as 'to visually' [observe] (p.148), 'to partially' [reduce] (p. 149), 'to soft' [land] (p. 151). 'This' is constantly used in place of 'that' to refer *back* to something already specified — the record is probably held by p. 93, where that error occurs 11 times. Similarly, 'these' is used where 'those' is meant. The omission of semantically essential hyphens seems endemic: the highest resolution images, high energy electron, bird's eye view, non-light polluted sky, and so on. 'Phenomenon' is constantly used as a plural, in place of 'phenomena'; for example on p. 73

we have 'some of the extreme phenomenon' and 'The … suggested wave phenomenon'. Conversely and perversely, the word 'data' is routinely treated as singular. Sentences sometimes begin with a comma after the first word, 'But,', 'So,', 'Thus,', 'Therefore,'. All too often the possessive apostrophe is missing, as in 'The stars explosive variability' (p. 73). Then there are what I take to be 'merely' out-and-out spelling mistakes, of which a few examples are 'line of site' (pp. 84, 96), 'brief instances of time' (p. 145), 'parachute opened to slow its decent' (p. 156), and 'accidently' (p. 159). There is a surely erroneous reference to the '225[th] annual meeting of the American Astronomical Society' (p. 117). There are also typographical errors and infelicities, such as 'the great Orion Nebula 42' (p. 71), and the splitting between lines on p. 126 of the minus and the 273 in the specification of the temperature of absolute zero. Another misfortune regarding temperatures is the alleged equivalence of 37,000° K, 66,000° C, and 119,000° F on p. 107.

In the review copy of *Breakthrough!*, almost every page is littered with my pencilled complaints; it would be impossible as well as inappropriate in a review such as this to catalogue any substantial proportion of them. The reader of this *Magazine*, however, will not have needed to be particularly perceptive to have gathered that, for his £15 or $35, he would get something like 100 pictures (mostly very nice), and about twice their acreage of text whose detail this reviewer, at least, finds inelegant. — R. F. GRIFFIN.

Welcome to the Universe: An Astrophysical Tour, by N. deGrasse Tyson, M. A. Strauss & J. R. Gott (Princeton University Press, Woodstock), 2016. Pp. 470, 26 × 19 cm. Price £29·95 (hardbound; ISBN 978 0 691 15724 5).

This is a beautifully presented book from the Princeton University Press, written jointly by alumnus and American celebrity astronomer Neil deGrasse Tyson and two current professors of astrophysics at the university, Michael A. Strauss and J. Richard Gott. It started from an extremely successful course taught by those three authors to undergraduate non-science students and is structured in three sections, each contributed by one of them.

Tyson kicks off with the 'Solar System and Search for Life'. His written style is 'accessible American colloquial' as befits a scientist well known through all types of modern media but, make no mistake, the science is there! He uses some original analogies as illustrations — squirrels, chipmunks, and mixed nuts to explain absorption spectra, stars brushing their teeth to reinforce ideas from the H–R diagram — and, for blackbody radiators, is not afraid to throw in $I_\lambda(T) = (2hc^2)/\ \lambda^5/(e^{hc/\lambda KT} - 1)$. What did non-science undergraduates make of that?

Michael Strauss then takes over with the second part, 'Galaxies and the History of the Universe'. His written style is more conventional but still very readable.

The last part, 'Relativity and Ideas in Theoretical Cosmology', is written by Richard Gott and it is at that stage that the gloves come off. He is clearly a wonderful teacher, with many analogies and original and clear diagrams, but this is tricky stuff. Wormholes, cosmic strings, time travel, the shape of the Universe, and much more — this man is a theorist who thinks very deeply. His enthusiasm is obvious but the conjectures are not for the faint-hearted. Interestingly, Gott finishes this section, and the book, with a well-argued but controversial chapter about humankind colonizing first Mars and then further afield. He is a big advocate for that course of action in the near future.

Welcome to the Universe is a book that falls between popular science and a textbook. It is a comprehensive account of up-to-the-minute ideas in astronomy and cosmology and will surely be treasured by the serious astronomer who enjoys theoretical astrophysics as well as observational. — DEBRA HOLTON.

The International Atlas of Mars Exploration: From Spirit to Curiosity, by P. J. Stooke (Cambridge University Press), 2016. Pp. 444, 28·5 × 22·5 cm. Price £94·99/$145 (hardbound; ISBN 978 1 107 03093 0).

Philip Stooke wrote Volume 1 of this work, *The International Atlas of Mars Exploration: The First Five Decades*, for the same publisher in 2012, and I regret that I somehow missed it. Volume 2 charts — in full day-to-day detail — the exploration of the Martian surface from *Spirit* to *Curiosity*, from 2004 till 2014. (Coverage of both missions ended in mid-2014, marking the close of the primary mission for *Curiosity*.) Part 1, by far the largest part of the book (pages 1–400), is devoted to a chronological sequence of their various activities, and contains useful tables and summaries. It begins with details of site selection. There are many illustrations (all monochrome) and maps charting every move of the rovers. Part 2, much shorter, deals with the imaging of the Martian moons. Part 3, also brief, is a short update to Volume 1. There is an extremely useful table of Mars Mission data to conclude, plus a Bibliography and Index.

It is marvellous to be able to pick a date and effectively to read *Spirit*'s diary for the day, though if you want to correlate it with your own diary you will have to count carefully the number of sols since the start of the mission. A short extract for *Opportunity* as the rover approached Cape Verde will give an idea of the content of Part 1 from a page opened at random: "Power dropped slightly as the cliff blocked part of the sky. A Pancam tau mosaic, Sun images taken at many places across the frame to map dust on the camera, was taken on sol 1570, which was the southern winter solstice … staying out of the shadow of the cliff was very important." A few sols later and "The RAT was tested under warm and cold conditions ... ." and on sols 1582 and 1584 there was a lot of wheel-slip, and "on the latter sol the left front wheel looked as if it was about to pick up a potato-shaped rock which might jam it." A complete chronicle of those missions in this sort of detail makes for an extremely important record, and to put it mildly the author's labours must have been considerable.

The production standards of this book are very high. I warmly commend the *Atlas* to purchasers, but I suspect its pricing will limit its sales to university and observatory libraries and to dedicated research groups or individuals. — RICHARD MCKIM.

SpaceX's Dragon: America's Next Generation Spacecraft, by E. Seedhouse (Springer, Heidelberg), 2016. Pp. 188, 23·5 × 15·5 cm. Price £16·99/$29·99 (paperback; ISBN 978 3 319 21514 3).

This is the story of how a billionaire technophile, who made his fortune by producing software and creating PayPal, became one of the leading lights in developing and promoting his own ambitious, commercial space enterprise. Elon Musk is perhaps the best known of the new group of space entrepreneurs who are investing large sums of their own money in the fast-moving field of space innovation. Starting with the creation of SpaceX in 2002, Musk risked failure and financial insolvency by setting out to develop his own family of low-cost launch vehicles. The project to develop the *Falcon 1* expendable rocket survived a number of early failures, and in 2008 NASA provided a much-needed boost by awarding a $1·6 billion contract to develop the *Dragon* craft to carry cargo to the *International Space Station*. Following the retirement of the Shuttle in 2011, NASA turned to the commercial sector to transport its astronauts to the *ISS*, and in 2014 SpaceX was awarded a $2·6 billion contract to modify the *Dragon* for crew transportation.

The first half of the book is devoted to the rise of SpaceX and the development of the *Dragon* cargo ship, including summaries of its first six missions. (The seventh mission was destroyed during a launcher malfunction. At the time of writing, eight *Dragons* have successfully carried cargo to the *ISS*.) The remaining chapters cover the free-flying *DragonLab* variant and provide an overview of possible human missions to Mars. This is quite topical, since Musk has recently grabbed the headlines with a glossy presentation on how he envisages launching powerful, reusable boosters to fuel a massive human 'spaceship' for a relatively fast trip to Mars. This spacecraft would be able to deliver 450 tons to Mars, including at least 100 settlers and the cargo they require, for $100 000 a head.

The author describes Musk as a "genius on a mission" and "a legend in his own lifetime". There is certainly no doubting the achievements of SpaceX to date, but the road to success has often been rocky — witness a recent *Falcon 9* rocket explosion which destroyed the Florida launch pad and grounded the *Dragon* craft for many months. The more powerful *Falcon Heavy* launcher is already four years behind schedule and the crewed *Dragon* will not fly before 2018. Will the dreamer's vision of colonizing Mars become a reality, with SpaceX as the facilitator? Watch this space. — PETER BOND.

The Hunt for Alien Life: A Wider Perspective, by P. Linde (Springer, Heidelberg), 2016. Pp. 385, 23·5 × 15·5 cm. Price £29·99/$39·99 (paperback; ISBN 978 3 319 24116 6).

A lot of the content of this book is about well-known subjects. Some examples: OZMA (1960); CTA-102 (1965); LGM-1 and Jocelyn Bell (1967); *Pioneer 10*'s Galactic Message (1972); *Pioneer 11*'s Earth Science Symbol Plaque (1973); Arecibo's Interstellar Message (1974); *Voyager 1* and *2* Interstellar Records (1977), and WOW! (1977). Included is a listing of A. Zaitsev's *Cosmic Calls* to nearby stars (1999–2009). The author, Peter Linde, comments on the risk of sending those calls, suggesting that SETI scientists wait until they have a better basis for decision.

In regard to exoplanetary systems, Linde believes that some of them may look like the Solar System, but is silent as to whether there might be exo-moons revolving around exo-habitable zones.

As to intelligent terrestrial life he points out that we need to know what initiated it. On the basis of limitless possibilities, he speculates that terrestrial past and future species might link to a paradoxical intellectual experiment — as postulated by R. Gott and N. Bostrom. Gott, known for the Doomsday Argument, and Bostrom, an existentialist, appear to be two players in Linde's thinking. That terrestrial life might link to an 'intellectual experiment' implies the existence of exotic extraterrestrial societies — perhaps similar to Kardashev's suggested Technological Type-3 civilizations able to communicate with one another. If in existence, how will we be able to recognize that form of life differing radically from our own? (The present-day search for extraterrestrial life is on the basis of life as we know it; the discovery of ETI signals rests upon current and future technology.)

Near the end of this book the author focusses on artificial intelligence and eternal life. He points out that with cultural technological advances, biological evolution is now out of the game, and that the destiny of humankind is no longer in its own hands. Probably, post-biological technological evolution is open to risks and dangers. This perspective parallels what Andrei Sakharov pointed out[1] about the risks of using ETI information: "to a clever and good person any additional knowledge is of use, whereas to a silly and evil one, doomed to self-destruction, nothing can help or do harm".

In short, Linde's book is a mix of already well-known and new topics, meant for popular-science readers. — P. CHAPMAN-RIETSCHI.

References

(1) L. M. Gindilis, *Andrei Sakharov and the Search for Extraterrestrial Intelligence*, in *Proceedings of the Third Decennial US – USSR Conference on SETI*, edited by G. S. Shostak, *Astronomical Society of the Pacific Conference Series*, **47**, 1993, p. 27.

Astronomical Surveys and Big Data (ASP Conference Series, Vol. 505), edited by A. Mickaelian, A. Lawrence & T. Magakian (Astronomical Society of the Pacific, San Francisco), 2016. Pp. 278, 23·5 × 15·5 cm. Price $88 (about £67) (hardbound; ISBN 978 1 58381 894 7).

This volume of the ASP Series contains the Proceedings of a 2015 conference held at Byurakan Observatory (Armenia) to mark the 50th anniversary of the launch of the First Byurakan Survey. With an initial goal of searching for galaxies with UV excess, that photographic objective-prism survey led to the discovery of 1500 such objects, and to the creation of a database (now in digitized format) which has inspired and supported much research. Its successor, the Second Survey, used hypersensitized plates to reach fainter objects, and searched particularly for quasars, emission-line galaxies, and more UV-excess galaxies. Most of the conference participants were from the host observatory or ones in eastern Europe, and the papers largely, though not exclusively, reflect research involving the products of the two surveys or parallel studies and follow-ups. A few papers focus on galaxy research without mentioning any survey at all, and serve to enrich what must have been quite a comprehensive acclamation of the work which the two surveys stimulated. One paper is devoted to the actual digitization of the survey plates but is a bit coy on details about reconstructing direct intensities, and referenced papers are also not helpful. That is a shortcoming for the slit spectra, since photometric conversions are central to the usefulness of the products as quantitative scientific data.

Several of the contributions refer to other surveys; some list their characteristics, and one even compiles errors. For good measure, one paper describes a successful attempt to cross-identify stars in Ptolemy's *Almagest*, and another the digitization of historical astronomy manuscripts in Georgia. Together they present a well-rounded coverage of conventional surveys, *i.e.*, prior to the advent of 'big data' (neatly defined as data which are too voluminous to move and require a very different approach). Although 'Big Data' is in the conference title, the contributions which mention it adumbrate the challenges rather than address them outright. One paper does tackle the issue head-on from the viewpoint of a data manager, but unfortunately only its abstract is published.

The book follows the customary format of the ASP Series and includes photos — some posed, others casual — but does not include a report of any discussions. That is a pity, because many of the papers have probably been published elsewhere anyway, and at a conference it is the *discussions* that tend to contain the new ideas or seed new projects. English was adopted for both talks and papers, and although that must have been a chore for some of the authors, by and large the quality of the writing is pretty good. Some grammatical errors recur repeatedly, and sometimes important words are missing, suggesting that better editorial attention would have been an advantage (one of the editors was British), if only to prevent the invention of words like "catalogization". However, I do recall the warning about those of us who live in glass houses.

This book certainly deserves a place on library shelves, not only for its comprehensive study of what has been, and still could be, achieved with the two Byurakan Surveys, but also as a marker. On the one hand it bridges quite seamlessly the change in detector from photographic to electronic by highlighting the value of their complementarity, while on the other it is unlikely that there will be another conference so closely confined to those earlier, manageable surveys. This volume is a happy mixture of the technical and the scientific. The next generation of surveys will have to tackle big-data issues in real time, so future conferences will probably become dominated for many years by the concomitant problems rather than by the science. — ELIZABETH GRIFFIN.

Astrophysics and Cosmology, Proceedings of the 28th Solvay Conference on Physics, edited by Roger Blandford, David Gross & Alexander Sevrin (World Scientific Publishing, Singapore), 2016. Pp. 357, 24·5 × 15 cm. Price £81 (hardbound; ISBN 978 981 4759 17 5), £45 (paperback; ISBN 978 981 3142 80 0).

Solvay is a chemical company, the largest in Belgium and, by sales, the 23rd largest in the world at $12 258 000 000, up from 24th largest in 2014. Solvay conferences have tended to be held about every three years in peace-time, ranging over many different subjects. The last one in our field was in 1973 on astrophysics and gravitation, organized by Eduardo Amaldi. The 28th, in Brussels in 2014 October, was a worthy successor, according to one of its participants, the only conference he had attended in many years worthy of hard-bound proceedings (my copy is a paperback, but the principle surely holds). Chances are you have a Solvay conference photo hanging somewhere in your department. The 1904 physics one is the indoor photo, with Marie Curie next to Poincaré, and Einstein the youngest participant. Solvay's head is too big because it was pasted in after the fact. The 1927 conference is the one with the outdoor photo, with Marie Curie between Planck and Lorentz. It was on electrons and photons, and 17 of the 29 participants were Nobelists, past or future.

The 28th conference had 62 participants listed, 62 in the conference photo, including five women, and 60 of them stuck it out to the last day to provide a 15-second item on what they had found most interesting, outside their own topics (unless some of those were pasted in; the fully-reproduced discussions were edited).

The programme consisted of five topics: neutron stars, black holes, cosmic dawn, dark matter, and the microwave background. Each session had a chairman, two rapporteurs or rapporteures, a few prepared statements of up to several pages, and very many short questions, answers, disagreements (not as many of those as Saleen Zaroubi wanted), and digressions.

What were the highlights? According to the participants' 'souvenirs', the top rank goes to re-ionization and cosmic dawn. Dark matter ("MOND is dead") and dark energy (not everyone likes that name, including me) were next; then neutrinos (including perhaps detecting the cosmic ones) and other non-WIMP dark-matter candidates; the improving models of galaxy evolution, though they haven't been using the best models of single-star and binary-star evolution. Also mentioned were magnetic fields (because not addressed at all at the meeting); the need for CMB from space, but also *LOFAR*; a description of neutron-star binaries as a noise source (if you are trying to look for gamma rays from the Galactic Centre; not if you are looking for *LIGO* events!), and black-hole binaries of enormous mass (for detection by pulsar timing) and large stellar masses (for *LIGO*). The most mysterious contribution in this rapid-fire discussion came from Marc Kamionkowski, who plans to take out a life-insurance policy on George Efstathiou's goldfish.

Not quite everything was sweetness and microwaves. A prepared comment from Jim Peebles pointed out that, of the 13 most luminous galaxies within 8 Mpc of us, five or six (including the Milky Way) are pure disc galaxies, supported by motions largely in the galactic planes. These are really very difficult to form in conventional ΛCDM, and he wonders about something in the stress–energy tensor to which CDM is a good approximation, but not on all scales at all times. Someone mentioned that Λ can be thought of as an integration constant (which Einstein said once upon a time) but seems to have gone out of fashion. Only moderate concern was expressed about discordant numbers for H_0 coming from different techniques (Cepheids and supernovae *versus* the CMB). Furlanetto's report on cosmic dawn (and a subset of the others) gives the month of publication for each of his references. Thus the careful reader, encountering 'Gunn–Peterson troughs' for the first time, can discover that the less detailed paper by Scheuer was actually published first. Vicki Kaspi responded to a question by Martin Rees on why pulsars pulse with the classic remark that the pulsing is understood, but the radio radiation is more difficult. She also said that the X- and gamma-ray radiation (which is nearly all the spin-down energy) is much better understood. Phil Podsiadlowski, in a 'prepared comment', confessed that we still do not understand very well how the energy from core collapse gets put into an envelope to make a type-II supernova, but that the neutron stars with very small kick velocities probably came from electron-capture-induced collapses.

Scott Tremaine closed one of the sessions with a classic quote from Eugene Wigner: "The miracle of the appropriateness of the language of mathematics for the formulation of the laws of physics is a wonderful gift which we neither understand nor deserve. We should be grateful for it and hope that it will remain valid in future research." So far, so good, as it were. I was not at the conference, but would have been the oldest woman, though not the oldest participant, and have in common with all 62 of them that none of us has (yet) received a Nobel Prize. — VIRGINIA TRIMBLE.

Black Hole Blues and Other Songs from Outer Space, by Janna Levin (Alfred A. Knopf, New York) 2016. Pp. 242, 20·5 × 13 cm. Price $26·95 (about £21) (hardbound; ISBN 978 0 307 95819 8).

Despite the title, Janna Levin's book deals almost entirely with *LIGO* and the search for gravitational waves. *LIGO* stands for *Laser Interferometer Gravitational-Wave Observatory*, pronounced as a two-syllable word, *LIGO* with the 'I' of 'irate' and the 'O' of 'no'. And if you are taking the trouble to read this, you undoubtedly already know that the thousand-and-four authors of a paper uploaded on 2016 February 11 announced the first direct observation of gravitational waves in a burst that reached Earth on 2015 September 15, just in time for the centenary of Einstein's first key publication on General Relativity and gravitational waves and in time to feature in the Appendix of the book.

There are two chapters called 'Joe Weber' and 'Weber and Trimble', to which I shall return, but the *LIGO* cast, in order of appearance, consists of Rai Weiss (designer and builder), Kip Thorne (theorist and champion), Ronald Drever (designer, builder, and experimenter), Rochus (Robby) Vogt (first manager), and Barry Barish (second manager). Each of the five leads is introduced with a brief (very interesting) outline of his life before *LIGO*, and the story ends with them all retired from the project.

Despite the triumphal appendix, the volume as a whole left me with a feeling of great sadness, coming from the story of how Drever and Vogt left, the former expelled by the latter, and the latter in turn expelled by the funding agency. Since *Black Hole Blues* went to press, the project has won (in order of decision-making) the Gruber Cosmology Prize, a Breakthrough Prize (the first announced, to the distress of the Gruber folks), a Shaw, and a Kavli. All singled out Weiss, Thorne, and Drever, though of the \$3 000 000 Breakthrough Prize, \$1 000 000 divided among the three, and \$2 000 000 among the remaining thousand (including Vogt, and a couple of others who were not on the author list). Many colleagues (I don't know about the *LIGO* folks) expected this list to culminate with a Nobel Prize for 2016, but the deadline for nominations was 2016 January 30, shortly before the official announcement of success, so someone would have had to have had the courage to nominate in advance.

I am a good deal bothered by issues of accuracy. Here is an impersonal example. The author seems to indicate that the phrase "black hole" dates from 1967, but it appeared in print with the current meaning in *Science News Letters* early in 1964. Marcia Bartusiak chases it down in her recent volume, entitled simply *Black Hole*. (She also made use of a musical analogy in her earlier *Einstein's Unfinished Symphony*, a much more cheerful book than *Blues*, as perhaps both authors intended.)

Now we come to issues less impersonal, and the problem of accuracy for cases where I really do know, and that leave me wondering a bit about the rest. Take page 111, which has Weber and Trimble singing Kaddish (roughly, a prayer for funerals) rather than Kiddush (a blessing over bread and wine), puts Richard Feynman in a drawing class (no, I modelled for him 'one on one'), and says "she was also a fine astronomer". Gee, thanks! The same page mentions Joe Weber's sisters, but page 104 made him the youngest of four boys. He had four sons, but was one of a sibship of two and two. Page 57 gives his father's original surname as Geber rather than Gerber; and Joe's final navy rank as commander, rather than lieutenant commander. And so forth.

A distinguished historian colleague has e-written that he thinks the book also makes me sound volatile. I didn't notice that particularly, though I suppose I am volatile, in the sense of being given to sudden, great enthusiasms for people, ideas, and projects and so would not have been bothered by it. But page 190, with "an insane, doomed, impossible bar detector designed by the old mad guy, crude laboratory-scale slabs of metal that inspired and encouraged his anguished claims of discovery", is a bit distressing to me, wearing my bridal veil as Joe Weber's wife for the last 28·5 years of his life.

A conflict to the conflict of interest: my copy of the book was a gift from Barnard Professor Levin, and has a nice inscription, but a clock striking 13 is still a clock striking 13, and a turn-over to page 112, has me falling and breaking a hip. Mercifully not, merely a joint replacement that dissected, which is much easier to repair. — VIRGINIA TRIMBLE.

Deconstructing Cosmology, by R. H. Sanders (Cambridge University Press), 2016. Pp. 152, 25 × 18 cm. Price £24·99/$39·99 (hardbound; ISBN 978 1 107 15226 8).

This book grew out of lectures on observational cosmology which Sanders had been invited to give at a summer school in 2003; he was surprised at the invitation because he is neither an observer nor a cosmologist. Seeing an opportunity to bone up on the 'Standard Model', but also interested in finding inconsistencies in it, to his surprise he found that the standard model of cosmology — at least nowadays — stands on a very firm footing. Most of the book is a summary of the standard model and its successes, with most of its problems put into proper perspective (*i.e.*, they are probably not as serious as some hype suggests). Of course, the title suggests something a bit more sceptical, and those familiar with Sanders (who is Professor Emeritus at the Kapteyn Astronomical Institute of the University of Groningen, having previously worked at Princeton, Columbia, and NRAO) are of course aware that he is something of an outsider in his support for MOND (MOdified Newtonian Dynamics, an alternative to dark matter on the scale of galaxies). Sanders makes it quite clear that he has no wish to be associated with the many "absurd criticisms of the methods and results of science" and the associated "anti-rationalist or even anti-realist sentiment". Neither is the title meant to be negative, but is meant in the sense of 'investigating' or 'critically examining'. As I write this, several papers have appeared just in the last few weeks debating whether MOND or the standard model can better explain observations of galaxies, with both sides rather heavy on rhetoric. Although I don't always agree with Sanders' views, by contrast he is cool and more objective. (Of course, both MOND and the corresponding observations of galaxies have been around for a long time, as has the debate, but new and better observations and numerical simulations in the context of the standard model have revived discussion on those issues.)

The standard model (or, rather, simulations based on it) does not readily explain all observed properties of galaxies. However, only two of the ten chapters discuss MOND, not only its successes but also its problems. As such, the treatment is balanced, though those more familiar with the standard model — many people do not consider MOND at all — will be confronted with more uncertainty than is usually the case. My personal impression is not only that most proponents of MOND know more about conventional astrophysics than most conventional astrophysicists know about MOND, but also that most proponents of MOND know more about conventional astrophysics than many conventional astrophysicists know about conventional astrophysics. While in the minority, MOND proponents are not crackpots nor even on the fringe (such as, say, Burbidge, Arp, and Hoyle were, at least in some respects); with people such as James Binney, who literally wrote the book on galactic dynamics[1], now seriously considering MOND[2], it is perhaps time for the community at large to take stock of the debate.

The book is relatively short, but is not intended to be comprehensive; it is rather a long essay. References are provided in the Notes, which are a mixture of simple references, 'footnotes' (I would prefer them as proper footnotes), and combinations of the two, so those wishing to learn more have a place to start. Thirty black-and-white figures and an index round out the book. After the Introduction, the first and last of the main chapters are more philosophical in nature. Of the remaining eight, four describe the successes of the standard model (and don't exaggerate its problems); two on dark energy and dark matter are more critical of, but still essentially fair to, the standard model; and two discuss MOND, both on its home turf of galactic dynamics, and also in relation to cosmology and possible connections between MOND phenomenology, dark matter, and dark energy.

Although a more balanced discussion than most, of course Sanders makes a case for MOND, but a fair one (though sometimes there might be subtle insinuations*). However, there are some points on which I have to agree to disagree with Sanders (and many other supporters of MOND). First, I see no problem in the fact that we don't know what dark energy and dark matter 'really are' (on this point I also disagree with some supporters of the standard model); that is no more a deficiency of General Relativity than the fact that gorillas were not predicted is a deficiency of Linnaeus's binomial nomenclature. Referring to them as "ethers" is an exaggeration. (At the same time, it would be valuable to have non-astronomical evidence for both dark energy and dark matter.) This also contrasts with Sanders' own remark that we should actually be surprised if, at this early stage of modern cosmology, we actually did have all the important information. Second, while classifying standard cosmology, even metaphorically, as a religion might have had some truth to it a quarter of a century ago, the fact that observations led to the acceptance of dark energy indicates a healthier attitude in more recent times. Third, it is unfair to criticize the standard model because CDM-only simulations disagree with observations. (However, one cannot just claim that more-complex simulations will explain all anomalies, any more than MOND supporters can just claim that all of its problems will be cleared up by a proper relativistic theory.) Invalid criticism of MOND by some proponents of the standard model, though, is often even more unfair. In particular, claims that MOND phenomenology follows naturally from the standard model are often overblown, and detailed rebuttals by the MOND camp are often simply ignored.

Potential-conflict-of-interest statement: I know the author from my time in Groningen at the end of the last millennium, and commented on a draft of the book, as mentioned in the Acknowledgements. This seems at least to have led to fewer typos† and so on than in his previous book (somewhat more technical than the present one), also reviewed in this *Magazine*[3]; finding other influences is left as an exercise for the reader. With that in mind, I recommend the book. It is a good introduction to an important topic in modern astrophysics and cosmology, accessible to the 'interested layman' but also valuable for those with more-advanced knowledge of astrophysics but with less knowledge of MOND. As a challenge, an opponent of MOND and supporter of the standard model

*For example, I am always annoyed when Lemaître is described as a priest, at least if it is not also mentioned that his scientific career took him from Louvain *via* Cambridge, Toronto, the DAO, and Harvard to MIT and then back to Louvain, obtaining two doctorates along the way (in mathematics in Louvain with de la Vallée Poisson and in physics at MIT with Shapley). I don't know if it is intentional here, but in other cases I sometimes have the feeling that it is meant to suggest that his religion influenced his science, though actually Lemaître kept the two more separate than do many others.

†An important one which, however, no-one caught: at the top of p. 102, it should be $g_N = g\nu(g/a_0)$ rather than $g = g_N\nu(g_N/a_0)$.

should write a similar book which is just as informed and balanced about both sides of the debate. It is not clear how this conflict will be resolved; it might be that both turn out to be correct in some sense, *i.e.*, as approximations valid in the appropriate régimes (much as one expects General Relativity and quantum mechanics both to be valid limiting cases of a future theory of quantum gravity). In any case, any correct theory must explain 'MOND phenomenology', *i.e.*, observations which are readily explained by MOND but not by more-standard approaches, so whether or not one takes the effective theory of MOND seriously, one should be familiar with the observations (about which there is no debate). — PHILLIP HELBIG.

References

(1) J. Binney & S. Tremaine, *Galactic Dynamics* (2nd Edn.) (Princeton University Press), 2008.
(2) http://www-thphys.physics.ox.ac.uk/people/JamesBinney/
(3) P. Helbig, *The Observatory*, **134**, 146, 2014.

Mapping the Heavens: the Radical Scientific Ideas that Reveal the Cosmos, by Priyamvada Natarajan (Yale University Press, New Haven), 2016. Pp. 267, 24 × 15 cm. Price £16·99/$26 (hardbound; ISBN 978 0 300 20441 4).

Let's start nearly at the ending, a very odd place to start, where the author (generally called Priya Natarajan) opines "why are we still witnessing the most vehement denial of science? In my opinion, what fuels rampant denialism is not lack of knowledge of scientific *facts* but rather ignorance about how science and scientific reasoning work. Pulling back the curtain on the scientific process for the public to watch and understand will quell the disbelief." And this is an important part of the purpose of her present volume. I wish it were true, but am not optimistic: too many of the disputed issues (climate change, nuclear power, genetic engineering, evolution, …) have significant non-scientific issues, for which confidence in our results is not just irrelevant, but often negative. But forward into what else she has to say.

The author begins with early maps and pictures of the cosmos and ends with exoplanets and multiverses. But this is not in any sense a standard introductory astronomy textbook. Instead, the focus is on about seven key ideas (not radical to me, but then I am very old). These are the expanding universe, black holes, dark matter, cosmic acceleration (dark energy or cosmological constant), the cosmic microwave background, and multiverses (as part of fine tuning) and exoplanets. She has worked on most of those (as well as active galaxies, accretion discs, and even X-ray binaries), but also brings a culturally different slant, deriving from her Indian heritage. We meet the Hindu zodiac as well as Babylonian and Greek ideas at the beginning, for instance, and the careful reader of 'forematter' will learn that her first language was an Indo-European one, in which mother and father are Amma and Appa.

My copy of *Mapping* was a complimentary review one, but if I had purchased it, it would have been worth every one of the $26 for a single reference (p. 237, note 13), to a translation of Karl Schwarzschild's (German) first black-hole paper into English by Salvatore Antoci and Angelo Loinger (arXiv.org/abs/physics/9905030). Why? Because Loinger is surely the last physicist who does not believe that gravitational waves exist and can carry energy. He has also recently written that the Schwarzschild solution does not describe a black hole, nor can you have a pair of them orbiting within a general relativistic universe (abstracts by Angelo Loinger and Tiziana Harsico, dated 2016 February 13 and April 20). Also culturally noteworthy is a much better treatment, in the black-hole chapter, of the Black Hole of Calcutta than is usually found. Remarkably, the first citation is to the 8th, 2009, edition of a history of India written by Stanley Wolpert. Why remarkable? The first edition was the text for a UCLA course on the history of India that I audited in 1963, taught by the author, who was not absolutely a spring chicken then.

At other points, of course, the reviewer screamed, or anyhow pencilled at the page NO, NO, NO! Harrison of the Harrison–Zeldovich spectrum (of perturbations that grew into galaxies) was Edward (Ted) not Robert (in both index and text). And I would hate to hear a violinist trying to perform under the following instructions: "Imagine a violin string tuned by stretching it under tension. Varying the tension produces different musical notes, which can be thought of as the excitation modes of the string." Changing the tension changes the fundamental, and the harmonics with it. The analogue of excitation modes are those harmonics, unavoidable because a real string always vibrates in a mixture of full length, half length, and so forth.

If you are old enough to have been a secret fan of the cosmological constant before it became respectable in the late 1990s, you will be pleased to learn that Eddington was a supporter (along, of course, with Lemaître) in 1932, and perhaps sad, given the supernova connection, to be reminded that, while Baade and Zwicky had proclaimed the class and energy source together in 1933–34, by 1938–39 they were publishing separately on the narrow dispersion of absolute magnitudes (Baade) and possible use for cosmology (Zwicky, but also Olin C. Wilson, who, as usual, gets no credit).

Another "a ha!" is the description of just what it was that got Giordano Bruno into trouble. It was not primarily support for plurality of worlds, but rather the denial of the divinity of Christ and the virginity of Mary. There is also an unusually accurate citation of Fred Hoyle's invention of the phrase "Big Bang". But pencilled "NO"s also adorn the statement that black holes are the most massive astronomical objects and that the first glimpse of the X-ray sky came in 1962. Solar X-ray detection goes back to 1949, and indeed that launch vehicle was a captured V-2 (instrumented by Herbert Friedman and colleagues), but the US had built some of its own rockets 13 years later.

How much should we worry about proper apportionment of credit? Back in 1918 Sir William Osler said that in science it goes to the man who convinces the world, not to the man to whom the idea first occurs. Still unresigned, I would have liked to see mention of the 1974 paper by Einasto, Kaasik & Saar summarizing the evidence for dark matter very shortly before that by Ostriker, Peebles & Yahil (which is cited, and has twice as many citations over the years by many others), and the *Kepler* mission has indeed added enormously to our inventory of exoplanets, so how can anyone leave out its moving spirit, Bill Borucki? As for the epilogic hope to persuade our voters and taxpayers, Osler also said, "This is the childhood of the world, and a simple credulity is still the most charming characteristic of man."

In summary, if you read, think about, or teach recent history of astronomy you will surely find your own copy of Priya's Maps worth the price, and I will happily provide a pencil for your own notations of "neat", "oops", "a ha!", and "no!" in the margins. — VIRGINIA TRIMBLE.

THESIS ABSTRACTS

Cosmic-Shear Analysis from Theory to Data

By Marika Asgari

One of the most important challenges in cosmology today is understanding the dark matter and dark energy which together compose 95% of the cosmic energy density of the Universe. Weak gravitational lensing by large-scale structures is one of the most promising probes for understanding those components and therefore the Universe. The imaging surveys of the future will cover wider fields of view, more-accurate-redshift estimations, and deeper galaxy images. That will lead to smaller statistical errors and tighter parameter constraints. The increased statistical precision will not be satisfactory, however, unless there are trustworthy and accurate methods to analyse the data in order to extract all the information they can offer.

In this thesis I will explore two cosmic-shear-analysis methods, COSEBIs (Complete Orthogonal Sets of E-/B-Integrals) and PCls (Pseudo Cls). Both of those methods are able to separate gravitational-lensing effects (E-modes) from the contaminants (B-modes).

A prominent challenge for cosmological surveys is the estimation of accurate data covariances. N-body cosmological simulations are the most common method used for estimating the covariance, but a large number of simulations with high enough resolution have to be run to estimate accurate data covariances. This number grows with the number of data points used in the analysis. Running cosmological simulations is time-consuming and expensive. Thus data compression is highly desirable for many disciplines. In Chapter 3 I introduce a method that optimally compresses the number of observables according to their sensitivity to the parameters to be estimated. I then apply this method to COSEBIs, an analysis method for weak gravitational lensing, and show that the compressed observables are not sensitive to the choice of the input covariance matrix used to define them.

In Chapter 4 I set up a blind analysis of CFHTLenS*, the state-of-the-art weak-gravitational-lensing survey, using COSEBIs and their compressed version. I present a likelihood analysis to estimate cosmological parameters from the data. This is the first time this form of optimized compression has been applied to data. I will also use tomographic redshift bins with COSEBIs and compressed COSEBIs for the first time. The tightest constraints I find for the best cosmological parameter combination is $\sigma_8(\Omega_m/0{\cdot}27)^{0{\cdot}62} = 0{\cdot}825^{+0{\cdot}033}_{-0{\cdot}044}$, which is consistent with previous analysis of CFHTLenS data.

In Chapter 5 I employ Gaussian and log-normal simulated shear fields to explore a flat-sky Pseudo Cl analysis pipeline which I have developed. Although shear two-point correlation functions are insensitive to the mask which is always present on galaxy images, their Fourier counterparts, shear power spectra, are biassed by them. Therefore, the effects of masking should be considered in Fourier-space analysis of weak-gravitational-lensing data. I use different masks and propagate errors to cosmological parameters using Fisher analysis to explore the limitations and strengths of Pseudo Cl method.

In the final Chapter I will conclude that the studies presented in this thesis

*http://www.cfhtlens.org/

strongly advocate and prefer the use of the methods presented in Chapters 3 and 4 for any future analysis of weak-gravitational-lensing data. In addition, the compression method in Chapter 3 can also be applied to other cosmological analysis. And finally, to avoid biassed results, Pseudo Cl analyses for future surveys have to be performed with the considerations detailed in Chapter 5. — *University of Edinburgh; accepted 2015 December.*

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White-Dwarf Luminosity Functions from the *Pan-STARRS1* 3π Survey

By Marco Cheuk-Yin Lam

White dwarfs are among the most common objects in the stellar halo; however, due to their low luminosity and low number density compared to the stars in the disc of the Milky Way, they are scarce in the observable volume. Hence they are still poorly understood one hundred years after their discovery as relatively few have been observed. They are crucial to the understanding of several fundamental properties of the Galaxy — the geometry, kinematics, and star-formation history, as well as to the study of the end stage of stellar evolution for low- and intermediate-mass stars.

White dwarfs were traditionally identified by their ultraviolet (UV) excess; however, if they have cooled for a long time, they become so faint in that part of the spectrum that they cannot be seen by the most sensitive modern detectors. Proper motion was then used as a means to identify white-dwarf candidates, due to their relatively large space motions compared with other objects with the same colour. The use of proper motion as a selection criterion has proven effective and has yielded large samples of candidates with the *SuperCOSMOS* Sky Survey and Sloan Digital Sky Survey. In this work I will further increase the sample size with the *Panchromatic Synoptic Telescope And Rapid Response System 1* (*Pan-STARRS1*).

To construct luminosity functions for the study of the local white dwarfs, I require a density estimator that is generalized for a proper-motion-limited sample. My simulations show that past works have underestimated the density when the tangential velocity was assumed to be a constant intrinsic parameter of an object. The intrinsically faint objects which are close to the upper proper-motion limits of the surveys are most severely affected because of the poor approximation of a fixed tangential velocity. The survey volume is maximized by considering the small/intermediate-scale variations in the observation properties at different epochs. That type of volume maximization has not been conducted before because previous surveys did not have multi-epoch data over a footprint area of that size. The tessellation of the 3π Steradian Survey footprint is so complex that the variations are strong functions of position. I continue to demonstrate how a combination of a galactic model and the photometric limits as a function of position can give a good estimate of the completeness limits at different colour and different line-of-sight directions. Finally, I compare the derived white-dwarf luminosity function with previous observational and theoretical work. The effect of interstellar reddening on the luminosity functions is also investigated. — *University of Edinburgh; accepted 2016 August.*

A full copy of this thesis can be requested from: mlam@roe.ac.uk

Red Supergiant Stars in the Local Group and Beyond

By Lee R. Patrick

Red supergiant (RSG) stars are the most luminous stars in the infrared sky. Their intrinsic luminosities combined with the low dust extinction observed in that régime make those objects very attractive to study in the near-infrared (IR). In addition, RSGs are necessarily young objects, as they are tracers of recent star formation in extragalactic systems. As the next generation of telescopes will be optimized for study in the near-IR, it is clear that, in the coming years, RSGs will play a prominent role in the way that astronomers probe the local Universe and out to larger distances with space-based observations. Therefore it is vital to better our understanding of these objects now and develop the tools that will allow us to take full advantage of the suite of instrumentation that will become available in the near future. This thesis aims to further the understanding of RSGs by focussing on quantitative studies of near-IR spectroscopic observations.

To that end, I develop an analysis technique that uses spectroscopic and photometric observations to estimate stellar parameters of RSGs. The observations are compared with synthetic spectra extracted from stellar model atmospheres, where departures from local thermodynamic equilibrium have been calculated for the diagnostic spectral lines. That technique is tested thoroughly on synthetic and real observations and is shown to estimate reliably stellar parameters in both régimes when compared with input parameters and previous studies, respectively.

Using the analysis routines developed in this thesis, I measure the chemistry and kinematics of NGC 2100, a young massive cluster (YMC) of stars in the Large Magellanic Cloud, using near-IR spectroscopic observations of 14 RSGs taken with the new *K*-band multi-object spectrograph (*KMOS*). I estimate the average metallicity to be $-0{\cdot}43 \pm 0{\cdot}10$ dex, which is in good agreement with previous studies. I compare the observed location of the target RSGs on the Hertzsprung–Russell diagram with that of a solar-like-metallicity YMC, and show that there appears to be no significant difference in the appearance of the RSGs in these two clusters. By combining the individual RSG spectra, I create an integrated-light cluster spectrum and show that the stellar parameters estimated, using the same technique as for individual RSGs, are in good agreement with the average properties of the cluster. In addition, I measure — for the first time — an upper limit of the dynamical mass of NGC 2100 to be $15{\cdot}2 \times 10^4\ M_\odot$, which is consistent with the literature measurement of the photometric mass of the cluster.

I then move on to present observations of RSGs in NGC 6822, a dwarf irregular with a turbulent history, observed with *KMOS*. The data-reduction process with *KMOS* is described in detail, in particular where the reduction has been optimized for the data. Stellar parameters are estimated using the technique presented and an average metallicity in NGC 6822 of $-0{\cdot}55 \pm 0{\cdot}13$ dex is found, consistent with previous measurements of young stars in that galaxy. The spatial distribution of metallicity is estimated and weak evidence is found for a radial metallicity gradient, which will require follow-up observations. In addition, I show that the metallicities of the young and old populations of NGC 6822 are well explained by a simple closed-box chemical-evolution model, an interesting result as NGC 6822 is expected to have undergone significant recent interactions.

In my final scientific chapter, I present multi-epoch *KMOS* observations of 22 RSGs in the Sculptor Group galaxy NGC 55. Radial velocities are measured for the sample and are shown to be in good agreement with previous studies. Using the multi-epoch data, I find no evidence for radial-velocity variables within the sample. Stellar parameters are estimated for ten stars and are shown to be in good agreement with previous estimates.

I conclude this thesis by summarizing the main results and present a first-look calibration of the relationship between galaxy mass and metallicity using RSGs. By comparing the RSG metallicity estimates to metallicities estimated from ~ 50 000 Sloan Digital Sky Survey galaxies, I show that the absolute metallicities of the two samples disagree. A more quantitative analysis requires additional RSG observations.

In addition, using ~ 80 RSGs, with stellar parameters estimated in a consistent way, I show that there appears to be no dependence of the temperature of RSGs upon metallicity. This is in disagreement with current evolutionary models, which display a temperature change of ~ 450 K over the studied range in metallicity.

Finally, I outline potential areas for future work, focussing on follow-up studies that have been identified as a result of the work done in this thesis. — *University of Edinburgh; accepted 2016 August.*

A full copy of this thesis can be requested from: lpatrick@iac.es

AOLI — Adaptive Optics and Lucky-Imaging Integral-Field Spectroscopy

By David L. King

The gold standard of traditional high-resolution astronomical imaging in the visible has been set by the *Hubble Space Telescope* (*HST*); in a one-off experiment several years ago the Cambridge Lucky Imaging Group obtained images in the visible at higher resolution than *HST* images using the 5-metre *Hale Telescope* at the Palomar Observatory, California, by combining the techniques of adaptive optics and lucky imaging.

The *Adaptive Optics Lucky Imager* (*AOLI*) is an instrument which has been designed and built in Cambridge to combine those two techniques for the first time in one dedicated instrument. Using *AOLI*, obtaining near-diffraction-limited observations in the visible will be routine, first on the 4·2-metre *William Herschel Telescope* (*WHT*) at the Isaac Newton Group (ING) of Telescopes on the island of La Palma, Canary Islands, and later on the 10·4-metre *Gran Telescopio de Canarias* (*GTC*).

This dissertation describes the concept, design, and build of *AOLI*, with particular emphasis on the wave-front sensor used in the adaptive-optics system. This wave-front sensor is a novel curvature-based system. Previous curvature wave-front sensors sampled two imaged planes equidistant about either a focal plane or conjugate pupil plane. The non-linear curvature wave-front sensor developed here samples four imaged planes, two either side of the conjugate pupil plane. That arrangement leads to increased sensitivity to both low- and high-order wave-front distortions, enabling a significant improvement in sky coverage using natural guide stars compared with more-traditional wave-front sensors.

The first part of this dissertation introduces the background to ground-based high-resolution imaging, describing techniques for adaptive optics and lucky imaging. The middle sections cover the design, build, and initial commissioning of *AOLI*, culminating in the proof-of-concept observing run at the *WHT*, followed by the improvements which have been, and are being, implemented in the laboratory in Cambridge.

The final part of this dissertation investigates coupling *AOLI* to an integral-field spectrograph to obtain high-spatial-resolution spectra of small areas of the sky over a range of wavelengths and resolutions. The background to integral-field spectroscopy is introduced, and detailed descriptions of two instruments to which I have made major contributions are described. The last chapter looks at the possibility of making a new instrument by combining *AOLI* with *OASIS*, a pre-existing integral-field spectrograph.

AOLI has the long-term ambition of obtaining direct images and integral-field spectroscopy in the visible from the ground on the *GTC*, using the complementary techniques of adaptive optics and lucky imaging, at resolutions close to the diffraction limit. — *University of Cambridge; accepted 2016 January*.

Titan's Interaction with the Saturnian Magnetosphere

By Leonardo H. Regoli

In this thesis, a combination of data analysis and test-particle simulations is used in order to study several aspects of the complex interaction of Titan with the Saturnian magnetosphere. First, the energetic-charged-particles' environment at the orbital distance of Titan is studied using data from the *Magnetospheric Imaging Instrument/Low Energy Magnetosphereic Measurement System* (*MIMI/LEMMS*) instrument. Average fluxes and spectral slopes for energetic ions and electrons are analysed. A large variability is found, and it is interpreted as originating from the high mobility of the energetic ions and electrons, making a simple classification of this environment practically impossible, with only a weak correlation between the ion average fluxes with the plasma environment detectable and an asymmetry between the noon-to-dusk and midnight-to-dawn sectors. Second, the effect of local electromagnetic-field disturbances in the access of energetic H^+ and O^+ ions is studied. By studying the trajectories of individual particles to predict where they will deposit their energy, differences in ionization rates at different locations around the moon of almost 80% are found for H^+ ions and of more than 15% for the case of O^+ ions. Finally, the contribution of freshly produced pickup ions to the overall mass loss of the atmosphere is investigated by looking at particular signatures left by those ions in the thermal-plasma data from the *Cassini Plasma Spectrometer/Ion Mass Spectrometer* (*CAPS/IMS*) instrument. A statistical survey of all the fly-bys with available data leads to a constraint of the region around the moon where those ions are detected. Mass losses on the anti-Saturn side of the moon of between 570 kg/day and 1 tonne/day are derived depending on the species, accounting for a small fraction of the total losses estimated from distant tail observations. — *University College, London; accepted 2016 July*.

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EDITORIAL

Where's *Here and There?* Unfortunately, the cupboard is bare! The Editors of *The Observatory* rely heavily on inputs to that popular feature from the readership. Either that readership is getting inured to the poor standards to be found in the literature, or the editors of other publications are making strenuous efforts to improve their products. We hope the latter is not the case for surely *Here and There* will then disappear altogether! So this is a call to our readership to watch out for appropriate errors in published material (*i.e.*, not the Web) and send us full details, especially the reference, by post or email. No reward is available save seeing your vigilant efforts reported on the last page of the *Magazine*.