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MEETING OF THE ROYAL ASTRONOMICAL SOCIETY

Friday 2015 October 10 at $16^h\,00^m$
in the Geological Society Lecture Theatre, Burlington House

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

The President. Good afternoon everybody, and welcome back to this new academic year's session of RAS ordinary meetings. The first speaker this afternoon is Dr. Tiago Campante from the University of Birmingham, who is going to talk to us about 'An ancient extra-solar system with five sub-Earth-sized planets'.

Dr. T. Campante. Today I will be talking about a truly fascinating system of five sub-Earth-sized planets, whose origin dates back to the dawn of the Galaxy. The parent star in this system is called Kepler-444, an orange dwarf, 25% smaller and less massive than the Sun, being also the brightest and closest multiple-planet host detected so far by NASA's *Kepler* mission. We acquired a high-resolution spectrum of this star with the *HIRES* spectrograph on the *Keck* telescope, which shows that it has only 30% of the Sun's iron content, while being enhanced in α-process elements such as silicon and titanium, which are mainly synthesized in type-II supernovae and are found to be more abundant than iron in the early Universe.

Kepler-444 is a member of the thick disc, an old structural component of the Milky Way. Thick-disc stars are overabundant in α elements relative to thin-disc stars in the low-metallicity régime. Being a member of the Galactic thick disc, Kepler-444 also follows that chemical trend. Furthermore, it is known that in the solar neighbourhood, old, low-metallicity stars generally have higher velocities than younger, higher-metallicity stars. Kepler-444 is to the best of our knowledge the exoplanet host with the second-largest peculiar velocity after Kapteyn's star. That is a further indication of the likely old age of this system. But how old exactly? I will come back to that point later.

Kepler-444 is also a member of the Arcturus stellar stream, a moving group of stars from the thick disc. The origin of the Arcturus stream has long been a matter of debate. It was initially thought to be of extragalactic origin, as a result of a merger event. However, its members are chemically similar to thick-disc field stars, which in turn have abundance properties different from those of satellite galaxies in the Local Group. Consequently, the stream is now being interpreted as arising from dynamical perturbations within the Galaxy.

A fainter companion was detected visually on the *HIRES* guide camera at an angular separation of 1·8 arc seconds, thus being unresolved in *Kepler* observations. We therefore conducted high-resolution imaging to determine the amount of dilution of the *Kepler* light-curve due to the presence of that companion. Furthermore, the two components in the system are co-moving as implied by their systemic radial velocity. After cross-correlating the spectrum of the secondary with that of a template red dwarf, we found that it in fact comprises two red dwarfs. That means that Kepler-444 is the primary star in a hierarchical triple system.

But before we go any further, let me tell you about a field of astrophysics called asteroseismology. Asteroseismology is the study of the interiors of stars by the observation and analysis of oscillations at their surfaces. In the case of the Sun and other Sun-like stars, these oscillations are excited by turbulent convection in the outer layers of the stars. This produces sound waves that get trapped in the stellar interior, making it resonate just like a musical instrument. We may observe the effects of the trapped sound indirectly by performing precise Doppler-shift measurements or else by looking at the tiny variations in a star's brightness. The information contained in solar-like oscillations allows the internal stellar structure to be constrained to unprecedented levels, while also allowing fundamental stellar properties (*e.g.*, mass, radius, and age) to be determined precisely. Our group at the University of Birmingham has been playing a leading role in the asteroseismological study of the Sun and other stars, and I invite you to visit our website at: http://bison.ph.bham.ac.uk.

The *Kepler* satellite was designed to survey a small patch of the Milky Way in the northern constellation of Cygnus. Its primary goal is to discover Earth-like planets orbiting other stars and to estimate the rate of occurrence of such planets. To that end, *Kepler* monitored the brightness of nearly 150 000 stars. The high-precision photometry provided by *Kepler* is also well suited for conducting asteroseismological studies of stars that show solar-like oscillations, which have now been detected by *Kepler* in several thousand main-sequence, subgiant, and red-giant stars. This has led to a revolution in the field of asteroseismology.

We detected solar-like oscillations in the flux time-series of Kepler-444. We proceeded with the estimation of stellar properties by matching the observed frequencies of individual modes of oscillation to those of stellar-evolutionary models. We were able to measure the stellar radius with 2% precision, which is crucial to obtaining precise planetary radii from transit observations. The same analysis returned a stellar age of 11·2 billion years, its precision being 9%. Kepler-444 is thus the oldest-known system of terrestrial-sized planets. By the time Earth formed, that star and its terrestrial-sized companions were already older than our planet is today.

As I mentioned earlier, *Kepler*'s primary goal is the detection of extrasolar planets. *Kepler* measures the periodic dips in starlight due to the transits of planets across the faces of their stars. This is called the transit-detection method, and 65% of all planets known to date have been detected that way. Transit observations, being an indirect-detection method, are, however, only capable of providing planetary properties relative to the properties of the parent star. Specifically, all we get from a transit observation is the relative size of a planet. Here resides the importance of the synergy between asteroseismology and exoplanetary science. Asteroseismology gives us the radius of the star and we convert that into an absolute planetary radius. Being capable of producing photometric observations with a precision of a few parts-per-million, *Kepler* is able to detect the transit of an Earth-sized planet across the face of a Sun-like star. In this scenario the planet would cause a relative drop in the star's brightness of 1 part in 10 000.

Kepler has so far successfully detected over 4 000 planet candidates, of which approximately 40% are in multiple-planet systems. Three-quarters of all planet candidates have sizes ranging from that of Earth to that of Neptune, which is nearly four times as large as Earth. Interestingly, those planets dominate the Galactic census but are not represented in our Solar System. A pertinent question would be to ask: How common are Earth-sized planets? After correcting for false positives and for the incompleteness of the *Kepler* sample, it has been shown that at least one in six stars has an Earth-sized planet in an orbit closer than Mercury's. Since the Milky Way has about 100 billion stars, this means that there are at least 17 billion Earth-sized worlds out there!

We investigated the planetary and orbital properties of the Kepler-444 system by using four years of data that virtually span the entire duration of the nominal *Kepler* mission. We did that by fitting a five-planet transit model to the *Kepler* data using an affine-invariant MCMC (Markov chain Monte Carlo) algorithm. We next compared the sizes of the planets to those of the Solar System's inner planets. Kepler-444b, the innermost planet, has a size within 2σ of the size of Mercury. Its radius has been measured with a precision of 100 km. The intermediate planets are the size of Mars. Finally, the outermost planet has a size between those of Mars and Venus. Kepler-444 thus expands the population of planets being found in low-metallicity environments from the mini-Neptunes around Kapteyn's star, and Kepler-10's super-Earths, down to the régime of terrestrial-sized planets.

This system is also highly compact, both in terms of its architecture and in a dynamical sense. All planets orbit the parent star in less than 10 days, or within 0·08 AU, roughly one-fifth the size of Mercury's orbit. Those orbits are thus well interior to the inner edge of the system's habitable zone, which lies about 0·5 AU from the parent star. Furthermore, all adjacent planet pairs are very close to being in exact first-order mean-motion resonances.

The chemical composition of stars hosting small planets (with radii less than four Earth radii) appears to be more diverse than that of gas-giant hosts, which tend to be metal-rich. This implies that terrestrial-sized planets may have readily formed at earlier epochs in the Universe's history when metals were more scarce, perhaps when the Universe was less than 20% of its current age. This then suggests that Earth-sized planets have formed throughout most of the Universe's history, thus providing scope for the existence of ancient life in the Galaxy.

There is also growing evidence that the critical elements for planet formation in iron-poor environments are α-process elements. As we have seen, thick-disc stars are overabundant in α elements compared to thin-disc stars in the low-metallicity régime, which may explain the greater planet incidence among thick-disc stars for metallicities below half that of the Sun. Thus, thick-disc stars were likely hosts to the first Galactic planets. The discovery of an ancient system around the thick-disc star Kepler-444 thus not only confirms that the first planets formed very early in the history of the Galaxy but also helps to pinpoint the beginning of what we may call the era of planet formation.

The President. We have a few minutes for questions. I'm sure there will be plenty.

A Fellow. How eccentric are the orbits in the system that you spoke about? Are the planets like returned comets or are they a bit more circular like the Earth?

Dr. Campante. All the planets have circular orbits in this system. I think the error bars are large but they are all consistent with circular orbits.

Professor T. Marsh. Do you have any indication of their masses — can you measure TTVs?

Dr. Campante. There is an indication for a marginal TTV for one of the planet pairs. If we would rely on radial-velocity measurements of the mass, it would not be visible because even combining all the planets in the system we would get a semi-amplitude of $0{\cdot}3\ \mathrm{m\,s^{-1}}$. By the way, I forgot to say this during my talk but these results have been published earlier this year. You can look for them in the *Astrophysical Journal* [**799**, 170, 2015].

Dr. Jane Greaves. How relevant do you think the thick-disc dynamics of this star system might be for planet formation? I'm thinking of systems like τ Ceti, which is very close and almost as old and has three or five small planets as well.

Dr. Campante. I don't have an idea. There is on-going follow-up work on the dynamics of the system but I don't have a detailed picture of how they got to that place and how the migration proceeded.

Professor I. Roxburgh. It was a nice talk but I just wish to correct you on a misunderstanding that you may have made, in that we don't compare theoretical frequencies with observational frequencies. We have to make some sort of corrections for the unknown properties of the outer layers of these types of stars or use techniques to subtract off that effect. We can't just make a direct comparison for this type of star, as we might be able to do for more massive stars.

Dr. Campante. Thanks for that remark. Obviously, being an asteroseismologist I am perfectly aware of that. I wanted to simplify things and skip that detail.

The President. Thank you very much. [Applause.] The next speaker is actually our Fowler Award winner for Geophysics, so I'm going to introduce her by reading out the citation.

Dr. Catherine Rychert is the 2015 winner of the Fowler Award of the Royal Astronomical Society. Dr. Rychert's work focusses on imaging the tectonic plate and constraining the mechanism that defines it. She investigated what makes a 'plate' plate-like on a variety of scales and in a variety of tectonic environments. She imaged the lithosphere–asthenosphere boundary beneath eastern North America using scattered waves, showing that it is too sharp to be just a thermal gradient. Another mechanism is required, and this may be a change in composition or the appearance of melt. She built on this work, adapting it to the global scale and finding sharp boundaries in a variety of tectonic environments. She went on to expand her results to oceanic areas, developing a novel SS-waveform method to deal with situations where there are few seismic stations. Recently she has focussed on the lithosphere–asthenosphere boundary at the continent-to-seafloor spreading transition in the Ethiopian Rift and at subduction zones. Dr. Rychert's impressive body of significant contributions in this field makes her one of the world's leading young seismologists. For these reasons, Dr. Catherine Rychert is awarded the Royal Astronomical Society's Fowler Prize. [Applause.]

That means I can now introduce the talk formally after trying not to stumble through that string of long words and syllables which is clearly designed to trip up the RAS President. [Laughter.] Catherine is going to to talk about 'What defines a tectonic plate?'

Dr. Catherine Rychert. The tectonic plate, or lithosphere, is the rigid layer at the surface of the Earth that moves coherently over the weaker, convecting asthenosphere. The transition that defines the base of the plate, the lithosphere–asthenosphere boundary (LAB), is fundamental to plate-tectonic theory. However, neither the location of the LAB nor the mechanism that defines it is well-understood.

Seismically imaging the LAB has proved challenging. Global- and continent-scale stacks of long-period data reveal no evidence for discontinuities at predicted LAB depths. Therefore, the LAB must either occur gradually in depth and/or vary significantly in depth. Classically, a gradual gradient was assumed, given that it is consistent with a thermal transition from a cool lithosphere to a hotter asthenosphere, and the large effects of temperature on the mechanical behaviour of rocks.

However, many observations of sharp discontinuities have altered that view. Beneath the continents linear, long-range (>500 km), active-source reflection and refraction experiments have imaged upper-mantle depths finding sharp discontinuities in the 80–125-km depth range, sometimes interpreted as the lithosphere–asthenosphere boundary. Passive source imaging using receiver functions, in particular S-to-P phases, has increased lateral resolution, showing velocity decreases with depth at 60–120 km are common features in both ocean and continental regions. Beneath Phanerozoic regions, the phases are frequently coincident with the gradual drop in velocity from the rigid, seismically fast lithosphere to the asthenosphere in surface-wave tomography. These sharp, strong seismic discontinuities cannot be defined by temperature alone, and require a mechanism such as hydration and/or melt to define them. These mechanisms would necessarily delineate the LAB, since experimental results suggest their presence not only affects seismic-wave velocities but also the strength of the mantle at geological time-scales. However, beneath the ancient continental interiors discontinuities at 60–120 km must be frozen-in, since hydrations and/or melt would not be consistent with the strength, longevity, and thickness of the continental cratons. Instead, these shallow discontinuities within the continents may offer interesting insight to continental formation, perhaps related to frozen-in chemical boundaries or stacked slabs.

Beneath the oceans, studies of large ocean transects using phases including multiple S bounces constrain a discontinuity at constant depth, about 65 km, which is similarly inconsistent with a thermally defined LAB. The thermally defined oceanic LAB is predicted to increase gradually in depth with age as it cools with distance from the ridge. Increased lateral resolution is provided by recent SS precursor studies. Although sharp discontinuities are imaged beneath the oceans, results are intermittent, and interpreted both with increasing depth–age trends and also at constant depth. Better constraints on complications such as anisotropy are required to resolve apparent discrepancies. Anisotropy probably varies at the LAB, although a mechanism such as hydration or melt is also likely to be required to explain observed sharp, strong discontinuities and/or achieve a sharp change in anisotropy.

Overall, better lateral resolution of depth, sharpness, and anisotropic properties of the LAB and mid-lithospheric discontinuities from a variety of methods with comparisons among tectonic environments will improve our understanding. These constraints must then be integrated with experimental results for the effects of hydration and melt on seismic velocity and also mantle viscosity, considering implications for the coupling of the plate to the asthenosphere and the formation and stability of the continents.

The President. Time for some questions.

Mr. M. Hope. In your slide on anisotropy, there were a whole lot of individual graphs there. There appeared to be something happening at around a hundred million years and then it seemed to flatten out. Then on your last slide, the flattening out seemed to start much, much earlier at around 10 million years and then you have this sort of dampened something else. What's the significance of these age-related curves?

Dr. Rychert. It is well known that the ocean subsides as expected from 0 to about 70 Myr, although older lithosphere does not continue to subside as expected. So that is really interesting in itself. The cause of that is debated. One possibility is that most of the old lithosphere has been perturbed somehow by anomalies like hotspots and upwellings that have melted the lithosphere and altered it in some way. How the lithosphere–asthenosphere boundary, the base of the plate, relates to the observed subsidence is also poorly understood and debated. It is one of the questions I will attempt to answer with the upcoming *I-LAB* ocean-bottom seismic experiment that will image the Atlantic plate from the ridge out to 40-Myr-old seafloor. A wide range of seismic resolutions and magnetotelluric constraints will allow us to distinguish thermal *versus* compositional boundaries and locations of potential partial melt, and finally determine the depth and defining mechanism of the lithosphere–asthenosphere boundary at the base of the plate.

The President. Any other questions? It seems not, so let's thank our speaker again. [Applause.] Our final talk of the afternoon is the James Dungey Lecture given by Helen Mason from the University of Cambridge. I read out Helen's citation at NAM, so I don't need to do it again, but I'd like to welcome her to come and talk to us about 'A golden age of solar physics'.

Dr. H. Mason. [It is expected that a summary of this talk will appear in a forthcoming issue of *Astronomy & Geophysics*.]

The President. I do remember the RAS report on 'Human spaceflight', I think we wrote that when I first joined Council — worrying to think how long ago it was! We've got time for a few questions.

Dr. Lyndsay Fletcher. Thank you very much, Helen, for that lovely talk. Two questions. First one, of course, is where can I buy the dress? [Laughter.]

Dr. Mason. I'll tell you what, Lyndsay. I was up in Newcastle and there's an artist called Helen Schell and she's also working on the Sun and she has a Sun-goddess dress which I think, for you, would be much more appropriate [Laughter.]

Dr. Fletcher. My serious question is where do you think is the next important place that we go with spectroscopy for the Sun?

Dr. Mason. That's a difficult question. I think that when I am asked the question "where do we think we're going in the future?", I would say that it is going to be driven a little bit by political agenda and I think space weather is probably going to feature quite high in that. The need to understand the Earth and its environment is key, and the Sun of course plays a role in that — both with space weather but also in other work that's being done on irradiance and climate. With spectroscopy, we have *Solar Orbiter*, an ESA-funded project which is coming up in 2018. It's one of the major ESA projects and has a spectrometer aboard called *SPICE*, which is being led by the Rutherford Appleton Laboratory, but also I think that we're looking at rocket flights as well — the smaller missions. We're involved in something called *MaGIXS*, which is an X-ray mission that will target that higher temperature range. Sadly, although there have been a lot of astronomical X-ray missions and I believe there is one going to be launched in January as well, they have been rather neglected in the solar area, which is a huge pity because actually the X-ray wavelength range is really rich and it would be very nice to get some more X-ray observations.

The President. Any more questions?

Professor P. G. Murdin. I was struck, as I always am when I listen to talks about solar physics, by just how complicated it all is. You yourself referred to the difficulty that we're at now in matching the observations and the theory. On the other hand, I was also struck by the fantastic success that you've had with *CHIANTI* in understanding particular aspects of solar physics. You put a lot of intellectual effort into understanding what the observations were giving you and I was wondering if perhaps it's time to pause in launching space hardware and putting equivalent amounts of resources into human brains and thinking — to try to understand where we are, and try to map out and define the immediate path to the future; just to pause and think.

Dr. Mason. I think I would agree with you, but unfortunately funding agencies don't always agree with that. That's the sad thing. There has been a big effort in the UK on the theoretical side — there are some excellent theoretical groups. I've mentioned St. Andrews, but there are other groups around the UK. It's really important that theory is developed but it's also important that it's tied down to what we're observing. Now, I've mentioned quite a few space missions here but actually I would say the percentage of the data that are brought down and actually analyzed is very small — tiny. That's mainly because people then move on to something else. Also, I would love to go back now to the *Solar Maximum Mission* we had in the X-rays. I'd love to go back to other ones, but they are no longer available. We can't do it but we would now have been able to put many things into context. At that time we just had snapshots — we didn't even publish the papers because we couldn't understand what we were seeing. Now, in retrospect, we have a better understanding, we could probably go back and publish new results. So, I agree, I think that more funding for the exploitation of observations would be great.

The President. It's a common problem we all have isn't it? Exploiting archives, retaining archives, and I think certainly more investment in those is really long overdue. Sadly, we have to finish. I think we should thank Helen again for a wonderful talk. [Applause.] I'm sure you don't really need me to remind you that we have the drinks reception in the RAS library now, following this meeting. I'll give you notice that the next monthly A&G Open Meeting of the Society will be on Friday the 13th of November. I'm sure we'll all defy superstition and turn out in numbers. [Laughter.]

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

The President. I should mention, before we start our programme, that you probably noticed that we sent out a lot of template letters to encourage you to write to your MPs about the comprehensive spending review. If you haven't yet done so, I really encourage you to make use of that template and get those letters out. There's a lot to fight for still as far as astronomy and geophysics funding goes, but if we remain silent then we won't have the opportunity to say "we told you so" when they don't do what we want them to do. So please take advantage of all the hard work that Robert Massey has done by drafting the letters to make it easy, but do amend them to your personal circumstances.

Now on to the main programme, and it's my pleasure to introduce Michal Michałowski. It's so rare that the speaker actually provides you with absolutely precise instructions as to how to pronounce his or her name and Michal is going to talk about 'Massive stars formed in atomic-hydrogen reservoirs'.

Dr. M. Michałowski. I want to discuss the process of gas inflow on galaxies and subsequent fuelling of star-formation. Using recent *Australia Telescope Compact Array* (*ATCA*) H I observations I have shown that galaxies with anomalous metal-poor regions (long-gamma-ray-burst [GRB] host galaxies) have substantial atomic-gas reservoirs, and are deficient in molecular gas. This suggests that star formation in these galaxies may be fuelled by recent inflow of metal-poor atomic gas. This is controversial, but can happen in low-metallicity gas near the onset of star formation because cooling of gas (necessary for star formation) is faster than the H I-to-H_2 conversion.

Galaxy-formation models require significant gas inflow from the intergalactic medium to fuel star formation. Indeed, the current gas reservoirs in many galaxies are too low to sustain star formation, even for normal galaxies such as the Milky Way. Filamentary structures suggesting gas inflow have only been detected for three galaxies, so most of what we know about gas inflow is based on indirect evidence. In particular, metal-poor regions in inner parts of galaxies suggest recent accretion of metal-poor gas.

Gamma-ray bursters are explosions of very massive stars, so they pinpoint locations of recent star formation, which is usually believed to be fuelled by molecular gas (H_2). However, GRB hosts were found to be deficient in molecular gas. Moreover, those galaxies often exhibit metal-poor regions close to the GRB positions.

These properties, together with large atomic-gas (H I) masses reported in my first H I survey of GRB hosts (performed with *ATCA*) can be interpreted as a sign of recent metal-poor atomic-gas inflow fuelling star formation giving rise to the GRB progenitor. Indeed, H I centroids are offset towards the GRB locations, and in one case an optically dark H I object is present about 20 kpc away from the GRB host, which can originate from inflowing gas. Moreover, the concentration of H I close to one GRB position was confirmed by follow-up observations with the *Giant Metrewave Radio Telescope* (*GMRT*).

Star formation fuelled by atomic gas can happen in recently-acquired metal-poor gas (even if the metallicity in other parts of a galaxy is higher), because gas cooling (necessary for star formation) is faster than the H I-to-H_2 conversion. GRB sites would then be expected to be metal poor but relatively dusty (due to rapid dust production), consistent with observations.

The President. I should just remember to announce that Michal is the recipient of the 2014 RAS Winton Capital Award for Astronomy. Any questions?

Professor D. Lynden-Bell. You've said something that's very important for high-mass stars; do you think that it really holds for low-mass stars or do lower-mass stars only occur somewhat later? And the last thing you said was that this relates to high-mass stars but of low metallicity, and most stars do not have low metallicity.

Dr. Michałowski. Whether or not it applies to low- and high-mass stars, I think it applies to everything if there is a star-formation episode — the high-mass stars are born and some of them explode as GRBs and low-mass stars are also formed.

Professor Lynden-Bell. How do you know that for those stars?

Dr. Michałowski. I don't see it here, but from the theory of star formation I think that apart from extreme, low-metallicity, Population III stars, the range of masses of stars that are being formed is always very broad. It's not that you form just high-mass stars or just low-mass stars. That is how I understand it, but I cannot see it in these data. The second question is about metallicity. GRBs are very useful but it's likely that they are not a representative population of stars. Maybe they trace only the low-metallicity stars at a given epoch — that's perfectly plausible. There are theoretical models which predict that high-metallicity stars would not explode as GRBs because the loss of angular momentum is too high and it cannot drive a jet. It's less of a problem at high redshift because low metallicity is normal metallicity and every star will be similar to the GRB population. At low redshift, of course, they may not be, or are probably not, representative.

Professor R. Kennicutt. I find your explanation really appealing but you probably know that it mirrors a debate that's been going on for a long time trying to understand star formation in low-metallicity galaxies in our neighbourhood. You see molecular gas with very high rates of star formation. The other possible explanation is that, as you showed in an earlier slide, the molecular gas is there but you're not seeing it in CO, so what is the argument against that as the preferred explanation?

Dr. Michałowski. The metallicity of those galaxies is not that low. I think that it is, on average over entire galaxies, 0·5 solar. At that metallicity we should still see CO. It's not 10 per cent or less than that. So I think this is not a problem. Actually, in the plot I showed you, the metallicity of those two galaxies is solar. You can invoke some special physical properties but, as we know, they should show a lot more CO emission. They too are normal-metallicity galaxies.

Mr. J. C. Taylor. Would it not be the case that, even starting from a cloud of atomic hydrogen, by the end of the process you're going to get plasma in the fully formed stars; it's certainly not molecular hydrogen then. Would there be an intermediate stage where the collapsing cloud becomes sufficiently dense before it gets hot that it would go molecular? Or does gravitational heating stop that happening even at that stage?

Dr. Michałowski. I think that's the generally accepted picture: that the H I or atomic cloud is becoming molecular because of the shielding. I don't want to overturn that theory. It's just that I think at the very beginning of star formation it's possible that gas starts star-forming before it gets molecular, but usually we see that it is the molecular phase which fuels star formation.

Mr. Taylor. Is there likely to be any difference between stars, the final product, produced from atomic-hydrogen clouds and from molecular hydrogen clouds? Of course it goes through an intermediate molecular stage — maybe the slate's wiped clean.

Dr. Michałowski. I doubt it, because it is still the same gas. If the process of star formation is somewhat different, maybe — and I don't know much about chemistry — the cooling is different. In general, when you form a star, it is not a molecular-gas star or an atomic-gas star, it's just a hydrogen star. Perhaps if there were something physical — maybe H I gas would cool faster and make it fragment faster; maybe the initial mass function would be different. This is very tricky, so I don't think we are there yet with either observations or with the theory.

The President. Thank you. We need to move on now to our next speaker. Hannah Christensen from the University of Oxford is the 2014 Keith Runcorn thesis prize-winner, and firstly I'm to give her a certificate: congratulations. [Applause.] She's going to talk about 'Can randomness reduce uncertainty? The use of stochastic physics in weather and climate prediction.'

Dr. Hannah Christensen. I would like to start by asking the following question: can you trust a weather forecast? For example, consider the case of a deterministic, or 'best guess', forecast for the next few days. Such a forecast indicates what the weather forecaster considers to be the *most likely* weather for the coming week, with no indication of how certain they are in their prediction. If you pose the question, "can you trust a weather forecast", to a member of the public, the likely answer is "no, you can't trust a forecast". Or at the very least, that "you should take such a forecast with a pinch of salt — they are often wrong". So when provided with a best-guess forecast for the coming week, even if no indication of the uncertainty in the forecast is given, the public will infer some uncertainty in the forecast given their past experience. Unfortunately for the weather forecaster, the public tend to remember those occasions when the forecast went horribly wrong rather than those occasions when the forecast was spot on. The perfect example of this is the most infamous UK weather forecast of all time: Michael Fish's mis-forecast of the Great Storm of 1987. On the evening of the 15th October, Michael Fish gave the following forecast: "Earlier on today, apparently, a woman rang the BBC and said she heard there was a hurricane on the way; well, if you're watching, don't worry, there isn't ...". The following morning, people woke to scenes of devastation: gusts of 90–122 mph had swept across the south of the UK overnight, uprooting 15 million trees, and leading to the deaths of 18 people. We can repeat the forecast for that night using a modern weather-forecasting system. If we produce a 'best-guess' forecast, very much like the forecast which Michael Fish would have seen, it predicts a mild, low-pressure system over the south of the UK — certainly nothing concerning, or out-of-the-ordinary. Even given thirty years of advances in the computer simulators used to make weather predictions, the forecast model still predicts a calm night, instead of the observed 'Great Storm'.

However, in addition to the 'best-guess' forecast, a modern weather-forecasting system also predicts the uncertainty in the forecast. Fifty alternative, but equally likely, forecasts are produced which represent the uncertainties involved in making a forecast: this is called an ensemble forecast. If we produce this probabilistic ensemble forecast for the night of the Great Storm, we see that while most ensemble members indicate a calm night, a third of the ensemble members indicate the possibility of a very deep low-pressure system, with very tight isobars, indicating a strong-wind storm. Instead of leaving it up to the public to infer how certain they can be in the forecast, it is important to calculate this explicitly by using our forecasting model. In the case of the Great Storm, it was as if the atmosphere was teetering on a knife edge, and it was impossible to tell which way it would fall. Presenting this uncertainty information to the public gives a much more accurate and useful forecast. An important property of these probabilistic forecasts is that they are *reliable*. This refers to the statistical consistency of the ensemble forecast with the observations. For example, it asks the question, if I collect together all the occasions when the forecast predicted rain with a 20% probability, and looked at what actually happened on those occasions, did it rain 20% of the time? If the forecast probabilities are consistent with those observed, the forecast is said to be reliable.

In order to achieve reliability, we must represent all sources of uncertainty in the forecast. There are two sources of uncertainty in particular which it is important to represent in a weather forecast. The first is initial-condition uncertainty. We have access only to limited satellite and weather-balloon data with which to estimate the current state of the atmosphere for initializing our models. We can represent the uncertainty in the initial conditions by perturbing them slightly between the fifty members in our ensemble forecast. As the atmosphere is a chaotic system, these very small errors can grow rapidly and, in some cases, can lead to very different forecasts after just a few days. The second key source of uncertainty in a weather forecast is model uncertainty. This stems from the fact that our computer simulator is merely a model of the atmosphere, and includes many approximations and simplifications. In particular, small-scale processes are not resolved by the model, and must be approximated through parametrization schemes. Errors introduced into the forecast in this way can also grow rapidly in time. While accurate representation of initial-condition uncertainty is well understood in the atmospheric community, there is still much debate as to the optimal way to represent model uncertainty. The remainder of this talk will discuss this important question, and will focus in particular on two proposed techniques: stochastic parametrization schemes, and perturbed-parameter approaches.

We will begin by considering those two representations in an idealized model: the Lorenz '96 System. This can be thought of as a 'toy model' of the atmosphere. It consists of a set of coupled equations with two types of variables arranged in a ring: the large-scale, low-frequency variables represent large-scale atmospheric dynamics, and they are coupled to small-scale, high-frequency variables, which can represent individual convective clouds. We use this system to perform a set of idealized experiments. We run the full set of equations with both large- and small-scale variables — this is what our 'real atmosphere' is doing. We can also build a forecasting model of this system, where we assume that the small-scale variables are unresolved. However, we must represent their influence on the large-scale variables, so we develop a simplified representation, or parametrization scheme, to use in the forecast model. This parametrization scheme is an approximation — it gives the most likely impact of the sub-grid scales on the resolved scales, but does not represent the day-to-day variability. We can now explore what the two representations of model uncertainty look like in that system. In a perturbed-parameter approach, we take the uncertain parameters (physical constants) in a parametrization scheme and perturb them between ensemble members to explore the possible range in their values. In a stochastic parametrization scheme we introduce random numbers into our equations of motion to represent errors in our parametrization scheme. Instead of representing the most likely impact of the sub-grid scales on the resolved scales, a stochastic scheme represents one potential realization of the subgrid variables. Using the Lorenz '96 model, we perform a series of ensemble weather forecasts. All members are initialized from perfect initial conditions, removing initial-condition uncertainty. That allows for a clean test of the two representations of model uncertainty in the system. We find that, while the perturbed-parameter scheme improves on weather forecasts which do not represent model uncertainty, it is the stochastic approach which gives reliable forecasts. Some days, the ensemble spreads out, indicating high uncertainty, whereas on other days, the ensemble members stay close together, indicating little uncertainty in the forecast. So, returning to the title of the talk, in some cases, randomness can reduce uncertainty.

Having shown the potential of stochastic parametrization schemes in a simple model, we move to considering their impact in an operational weather-forecasting model — the Integrated Forecasting System (IFS) used at the European Centre for Medium Range Weather Forecasts (ECMWF). In particular, we are interested in the representation of uncertainty in the convection scheme, as this is the parametrization scheme to which models are most sensitive. The IFS contains two operational representations of model uncertainty, both stochastic. For comparison, we develop a perturbed-parameter scheme. A Bayesian parameter-estimation approach is used to measure the uncertainty in four of the parameters in the convection scheme — the resultant joint distribution in the parameters is used to determine the degree of perturbation between ensemble members. We also consider a generalization to one of the stochastic approaches to address the uncertainties in different atmospheric processes independently. This is in contrast to the current stochastic approaches, which are holistic in nature. We find that the perturbed-parameter scheme improves on the operational stochastic schemes — the resultant forecasts are more reliable. However, the new 'independent' stochastic approach performs the best, and produces reliable ten-day forecasts in areas of the world where convection is an important atmospheric process.

So it appears that stochastic parametrization schemes are a powerful tool for representing uncertainty in weather forecasts, but could they also be used to represent model uncertainty in climate prediction? There are good theoretical reasons for including a stochastic parametrization in a climate model. We hope that such a scheme will improve the short-time-scale 'weather' variability in the model. In turn this can improve the statistics of the modelled climate through noise-induced drift, noise-enhanced variability, and noise-activated régime transitions. In fact, in both the Lorenz '96 system and in coupled climate models, we do observe an improvement in the representation of the climate of the system when a stochastic scheme is included. In the Lorenz model, we find that including a stochastic parametrization scheme leads to an improvement in the régime behaviour of the system. In the climate model developed at the US National Center for Atmospheric Research, we see an improvement in the simulation of the El Niño–Southern Oscillation (ENSO). This is the name given to the irregular oscillation in sea-surface temperature observed in the Tropical Pacific, where it is the dominant mode of climate variability. In fact, we're currently experiencing a large 'El Niño' episode, with sea-surface temperatures approximately 3°C above normal.

To conclude, can randomness reduce uncertainty in forecasts? I would argue that in weather forecasts, the answer is "yes". Stochastic parametrization schemes allow us to produce reliable probabilistic forecasts, which indicate how predictable the coming weather is, and therefore how certain we can be. In the case of climate models, I would say the answer is "maybe". While stochastic parametrizations certainly improve the ability of a climate model to represent the real atmosphere, it is yet to be tested whether it will reduce or increase uncertainty about future climate change.

The President. We have time for a few questions.

Dr. G. Q. G. Stanley. Very fascinating. It would be lovely to know what the weather's going to be like for the weekend, so if you can tell us, we'd appreciate that. [Laughter.] I know there is a technique where you can introduce noise into a signal you're processing, and then what happens when you do the Fourier analysis is that it basically gets rid of the other noise. You put it back together and you get the crisp signal out of it — I guess that is roughly what you're doing at this point?

Dr. Christensen. That's very relevant for the discussion about ENSO — stochastic resonance is what you're referring to. The idea is that if you put a white-noise forcing into your system then the system picks up the particular frequency which is characteristic of the system and then resonates with that frequency. In that way you can magnify a signal among the noise. That would predict an enhancement of some of the variability in a system. If you put additive noise into a very simple model of ENSO, you see it enhancing ENSO, increasing the magnitude. But I suppose what we saw here was a reduction in power in ENSO when we put in a stochastic parameterization, and you can see that in terms of the standard deviation of the sea-surface temperatures as a function of month. It's very interesting — it doesn't seem to be a kind of classic stochastic resonance. I think in part that's because we're using the multiplicative noise term as opposed to an additive noise term and you tend to think of stochastic resonance for additive noise, but I think it's definitely very relevant.

Dr. Stanley. To follow on from that, when you've obtained results at the end, do you then post-process them and take out the randomness you've injected?

Dr. Christensen. No — for the randomness in a weather forecasting model, the time-scale of the randomness is about six hours and the spatial scale is about 500 km. Because we're perturbing the physics tendencies themselves, that in turn affects the flow of the model; there's no removal of the randomness at the end. I suppose what we do, however, is make a range of forecasts for the future. If you just want to work out your best-guess forecast, I like to think of a stochastic parameterization scheme as somehow inverting the order of your averaging. Thus you can explore the possible flow situations and then average to find your best guess, or if you use a deterministic parameterization scheme you're doing the averaging as you go along. You're putting into the model the best-guess representation of the cloud within a grid box, and then seeing how the model responds to that most-likely cloud. Whereas, in a stochastic scheme you explore possible clouds and then average at the end.

Dr. Stanley. I suppose the bad news for astronomers is that they don't need good seeing — the randomness there would help their results.

Professor P. G. Murdin. That was a very interesting talk indeed. It contained extremely subtle attitudes to communicating about probability and forecasting. I wondered if you'd given any thought as to how one would go about explaining this to the public at large and the politicians [laughter] and the people who are in charge, especially in relation to climate modelling, not to mention weather forecasting. Have you given any thought on how to get across the ideas that you've been talking about?

Dr. Christensen. That's a really important question. I think in the realm of climate modelling, communicating uncertainty is a little bit ahead of where it is in weather forecasting in the UK. I think that's because there are other very obvious things that are uncertain about predicting the future climate, such as what carbon-dioxide-emission track are we going to go along. Certainly I think that's communicated, or is being attempted to be communicated, fairly well to the policy makers, especially in the big International Panel on Climate Change reports. Those are very explicit in terms of what is very likely or possible or less likely in terms of impacts on the climate. For weather forecasting, I think it's a real shame that we don't actually give out more of this probabilistic information to the public. The Met Office have made some efforts in recent years to move towards that but I think they're worried that if they just present a PDF to the public that they'll think that they're hedging their bets in some way. [Laughter.]

Professor Murdin. They are, but that's the nature of the equations.

Dr. Christensen. Well, exactly, but I think if people communicate to the public that some days we only know that it will rain with, say, forty-percent certainty and other days we know it's not going to rain, and other days we're much more certain, I think that would be better. There were rumours that the Met. Office and the BBC fell out over the Met. Office wanting to put more probabilistic information into their forecasts.

The President. So is that why the BBC are about to give up using the Met. Office?

Dr. Christensen. That is the rumour, but it might be also a financial issue.

The President. Can we thank our speaker again? [Applause.]

For the final talk of the afternoon it's my pleasure to introduce our George Darwin Lecturer, Professor Katherine Blundell from the University of Oxford, who is going to talk about 'Rapid evolution in astronomy'.

Professor Katherine Blundell. [It is expected that a summary of this talk will appear in a future issue of *A & G*.]

The President. I think you'll all agree that that was a talk that had everything: high-quality science, low-cost instruments, public outreach — what more could you ask for?

Professor Blundell. A bit more sleep to be honest. [Laughter.]

The President. How faint an object can you actually observe with that network and get good data?

Professor Blundell. Do you mean good spectroscopy data, or good photometry?

The President. Good spectroscopy.

Professor Blundell. I haven't tried going immensely faint, but many in this room will know Phil Charles who has great skills in charming telescope time out of people. There was quite an important object that went into flare over the summer, V404 Cyg; Phil asked me to observe it for him, which I did. I handed over a few spectra to him a little while back; I think probably around the time that I was observing that object was about fourteenth magnitude. It was very useful, Phil said, to have those spectra. I haven't pushed it to the limits. There's so much that's relatively bright that can be explored just by the business of having the availability and continuity.

Professor Carole Jordan. Have you been able to get any X-ray spectra of that nova?

Professor Blundell. I haven't; I don't know whether there are any X-ray spectra out there. I know it was detected by *Fermi* in gamma rays a little while ago. I don't believe any spectroscopy was done. The *Hubble Space Telescope* observed it in the UV and the far UV on Monday or Tuesday but for X-ray spectroscopy, I'm not aware of any.

Professor Jordan. I'm not sure they're as good at changing their programmes to look at opportunities.

Mr. H. Regnart. My impression is that the means of determining the launch angle and launch velocity is momentous, but I wanted to ask you a question that departs a bit from that. Seeing the fascinating reaction from the school children in India, I wonder if we would get a similar enthusiastic reaction from all children in this country? Or might we be plagued with the tradition that learning isn't for everybody in this country? Which is a tragedy, of course, if true.

Professor Blundell. You raise a number of interesting points. For a start, an astronomical dome is not a formal learning environment, so it's possible it happens without trying. The students are jollied along, I hand over the controls to them, and I answer questions as they come up. I don't think that they think fundamentally what they're doing is learning, but of course we all know that they are. It's an interesting point whether it would happen over here. My first thought when you asked that was "no, they're not going to be enthusiastic when the rain drops fall on their heads", but I think that were there to be ideal conditions when they were doing it, I'd like to think there would be. The amazing thirst for knowledge that the kids in India have, for example, does go together with lives that are uncluttered by iPads, glossy magazines ...

The President. ... videogames ...

Professor Blundell. ... and all those things. Those kids have time on their hands, so I do wonder if the business of just being a little uncluttered and a little free to think makes it more possible for them just to lose themselves in the activity that they're doing and get very engrossed in it and thereby gain quite a few skills. I like to think that if you give any teenager a shiny telescope and the sky is clear, they'd probably have quite a lot of fun with it.

Professor D. W. Kurtz. I have several related questions: there must now be lots of micro-quasars known — is SS433 typical of the others? Are there any bright enough for you to observe and are you going to turn the network on to those?

Professor Blundell. I would not agree with the statement that SS433 is a typical micro-quasar.

Professor Kurtz. That was the question. [Laughter.]

Professor Blundell. In the following sense, the SS433 jets are unusual because they are on persistently. Many of the other micro-quasars, their jets switch on, eject plasma at a relativistic speed, and precess only intermittently, not persistently. So it's a good deal harder to study those, and the number that we know is actually only a dozen or twenty. Now I think there's a very neat way in which you could discover a whole lot more with a fairly modest investment in instrumentation, which is to take advantage of the fact that you have these moving lines: use a couple of little cameras, with just normal camera lenses, piggybacking on top of what I like to call the big telescopes — the telescopes in this network — with one wearing an Hα filter and one wearing an off-band filter. Then if you take successive photometry of wherever the telescopes are pointing, Fourier-transform those two data streams in amplitude and in phase, you ought to be able to lock on to objects that are doing this kind of thing in and out of the filters. But one of the reasons why we haven't already discovered such objects moving at more rapid speeds is that this figure here is just for something moving at thirty percent of the speed of light. We think that many of the active galactic jets that I showed you move rather faster, and the minute you start doing that or you move the angle round, you go out of the optical observing window.

Now admittedly Hβ then moves in, so I think you could still do this experiment. One of my next ambitions is precisely to equip the observatories with the kind of instrumentation that would lead us to discover a great many more micro-quasars.

The President. Any more questions?

Dr. Stanley. I've recently seen some fascinating presentations where they're using off-the-shelf equipment and making use of them for fantastic discoveries, *etc.* Do you see this as the other side of rapid evolution in astronomy? That we're seeing more and more observatories like this besides things like the *ELT*, *etc.*?

Professor Blundell. I think that's absolutely right. If you look at the *WASP* project, which is run by St. Andrews, Keele, and the Open University, they're using pretty much off-the-shelf lenses but they're doing a fantastic job of discovering a great many exoplanets. We need to make room for projects which have the kind of nimbleness that, of necessity, great big projects like *ALMA* can't have. So absolutely I think that we do need both if we're to capture the full picture of the rich, astronomical Universe that's out there.

The President. Final question.

Mr. B. Davis. Thank you for a wonderful exposition of your work — I found it fascinating. I'm Chairman of the amateur astronomical society on the Isle of Wight. We have weekly open evenings and we get school children, cubs, guides, WI members, townswomen's guilds coming out to our observatory and going "wow".

Professor Blundell. So that's an answer to Horace Regnart's question.

Mr. Davis. It's a very effective technique for introducing young people to science. Thank you very much indeed. [Applause.]

The President. I think that's a great note on which to finish, so I'd just like to close the meeting by reminding you of the usual drinks. And finally, I'd like to give notice that the next monthly A&G Open Meeting of the Society will be on Friday, December 11th 2015. And a round of applause for all our speakers please. [Applause.]

SPECTROSCOPIC BINARY ORBITS FROM PHOTOELECTRIC RADIAL VELOCITIES

PAPER 247: HD 30410, HD 62599, HD 127742, AND HD 171006

By R. F. Griffin
Cambridge Observatories

Orbits are given for four stars, two of which (HD 62599 and HD 171006) came to attention (like so many others) when they were observed as part of the 'Clube Selected Areas' programme.

All four are single-lined. HD 30410 and HD 62599 have circular orbits whose periods, relatively short in comparison with those of most stars treated in this series of papers, are about 83 and 65 days, respectively. The indications of the luminosity of the former are conflicting; the latter (for which *Simbad* retrieves *no* bibliography) has a projected rotational velocity of about 6 km s^{-1} and could well be a giant. HD 127742 and HD 171006 both have periods near 1200 days; their orbital eccentricities are near 0·3 and 0·2, respectively. HD 127742 is the brightest of the four stars and is the only one observed by *Hipparcos*; its distance and absolute magnitude are therefore reasonably well determined, and we know that it has the luminosity of a giant. HD 171006 is another object with no bibliography; its luminosity is uncertain. The mass functions of all four stars are small, and do not encourage any expectation that the secondary stars should be detectable, at least in radial-velocity traces.

Introduction

This paper, like many others published in this series in the last several years, offers orbits for four spectroscopic binaries. Two of them, HD 62599 and HD 171006, came to light in the course of the 'Clube Selected Areas' survey, which was described in the *Introduction* to the immediately previous paper[1] in this series, as well as (of course) in the papers[2,3] that have presented the results of that survey. The two stars referred to here, however, did not feature in the published results, but were included in a relatively recent and presently unpublished extension of the survey in the northern sky, made by increasing the sizes of the designated Areas while retaining the same centres. The intention was to increase the number of stars, and thereby the statistical precision of their mean radial velocity, in each of the northern Areas, roughly to match the numbers in the southern Areas. The density of stars, per unit area of sky, meeting the selection criteria for the survey was much higher in the southern hemisphere than the northern simply because the *Henry Draper Catalogue* itself (the source catalogue for the survey) is much richer there.

HD 30410

HD 30410 is a $7\frac{1}{2}^{m}$ star close to the eastern boundary of Perseus, the boundary that that constellation shares with Auriga. It is just two-thirds of the way from the famous 27-year eclipsing variable ε Aur to the 5^{m} star 59 Per that is some 3° preceding; it is also a little over 1° north-preceding the interesting visual/spectroscopic binary HD 30090 (COU 2031) whose 20-year orbit was recently published[4] by a syndicate that included the present author.

Only about 16′ south-preceding HD 30410 is the peculiar high-luminosity M-type star KS Per (HD 30353). The proximity of that star to the one of immediate interest here leads the writer to try to dispute and dispel the assignments, to be found in the literature, of HD 30410 to two different star clusters, the 'Double Cluster' and NGC 1664. The fact that Keenan & Pitts[5] assign KS Per to the Double Cluster (h & χ Per; called by them 'hφχ Per') would seem to imply that HD 30410, also, must be in the vicinity of that cluster, but actually both stars are about 25° away from it and are obviously not related to it at all. Another object that is within 1° of HD 30410 (it is nearly due west) is one that has been discussed in this *Magazine* previously, HDE 276743. That star was found by de Medeiros & Mayor[6] to show major variations in radial velocity; it was, however, later suggested (in a paper[7] not retrieved by *Simbad*) that the two velocities that were very discordant with the other 21 that were then available might have arisen through misidentification of the object with the adjacent star HD 29957, whose velocity seems more or less to match the discordant ones.

HD 30410 is listed as having spectral type G5 in the *Henry Draper Catalogue*[8]; it subsequently appears in the second volume of the *Bergedorfer Spektral-Durchmusterung*[9] (*BSD*) with a type of G8 V. Hoag *et al.* obtained photometry of the object in the course of a major project[10] concerning Galactic star clusters; it is one of 16 stars that they measured in the field of NGC 1664, and is listed with magnitudes $V = 7^{\mathrm{m}}{\cdot}50$, $(B-V) = 0^{\mathrm{m}}{\cdot}97$, $(U-B) = 0^{\mathrm{m}}{\cdot}64$. Their paper includes a photograph of the field and also a colour–magnitude diagram. The former shows that HD 30410 (designated NGC 1664–2) is far outside the obvious part of the cluster (nearly three times the apparent cluster radius from the centre) as well as being much brighter than all but one of the other stars in the field. The c–m diagram of NGC 1664 shows our star to be in a position three or four magnitudes above what appears to be the vestigial giant branch. In a later paper, Hoag & Applequist[11] report measurements of the strength of the Hγ absorption line in a lot of stars in clusters, but in spectra as late as that of HD 30410 the line is not strong enough* to be diagnostic of any interesting property or quantity. Those authors[11] do, however, quote for HD 30410 a spectral type of G5 III that they attribute to "J. Gibson, unpublished". The absolute magnitude is listed as $+0^{\mathrm{m}}{\cdot}3$ and the distance modulus as $7^{\mathrm{m}}{\cdot}0$; although the cluster modulus is proposed to be "$9^{\mathrm{m}}{\cdot}5$:" (smaller than the $10^{\mathrm{m}}{\cdot}2$ found by Johnson *et al.*[12] and the $10^{\mathrm{m}}{\cdot}5$ of Becker[13], to say nothing of the $11^{\mathrm{m}}{\cdot}5$ proposed by Schmidt[14]), HD 30410 is nevertheless noted as a cluster member. The class-III luminosity is not in accord with the dwarf type proposed in the *BSD*[9], or with the G5 V that was deduced by Sowell[15] from a spectral scan obtained with the 1·3-m *McGraw-Hill Telescope* at Kitt Peak.

The position of the star far from the centre of NGC 1664, plus the fact that not only does its proper motion disagree with that of NGC 1664 but actually has the opposite sign to that of cluster members[16] in both coordinates, argues conclusively against membership of HD 30410 in that cluster. As a *coup de grâce*, it may be noticed that, whereas NGC 1664 is listed[16] as having a radial velocity of +36·1 km s^{-1}, the γ-velocity of our star is shown below to be about −5. Thus we can say for certain that HD 30410 has nothing to do with NGC 1664, any more than it has with h & χ Per. The conclusion that the star is not a member of the cluster upon which it is (not at all accurately) projected was in fact reached on grounds of proper motion by Kerridge, Nelson & Mesrobian[17] as long ago as 1973, and subsequently on every other ground as well by Claria, Piatti & Osborn[18].

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*The measurements were not made on spectra, but by ordinary stellar photometry through interference filters.

Radial velocities and orbit of HD 30410

The first measurements of the radial velocity of HD 30410 appear to have been made in the 1950s by Boulon & Fehrenbach[19] by the French objective-prism method that was actively pursued at Haute-Provence for some years but had nothing like the precision and reliability of the cross-correlation spectrometers that were developed by the writer[20,21] about 50 years ago and of which an excellent example (made by others) was later installed[22] at Haute-Provence. Boulon & Fehrenbach gave the radial velocity of HD 30410 as -20 km s^{-1} as a mean of three measurements, and attributed to it 'quality A', meaning that it was supposed to have a 'probable error' less than 2·5 km s^{-1}.

Glushkova & Rastorguev[23] measured the radial velocities of nine stars in the field of NGC 1664*; they obtained a measurement of $-1{\cdot}31 \pm 0{\cdot}19$ km s^{-1} for HD 30410, and because of its conflict with the Haute-Provence value[19] they already suggested that the velocity might be variable. Some years later, in 1997, the same authors[24] (but with reversed seniority) gave two measurements of the star in a listing of velocities in some of the northern Selected Areas, but without seeming to recognize that they had already observed it previously under another identity. The two new measurements were discordant with one another, as well as with the forgotten one; all three are listed in Table I of the present paper, at the head of the list of radial velocities of HD 30410. The rest of the table consists of the 46 observations that have been made with the Cambridge *Coravel*, beginning in 2003 when the present writer took notice of Rastorguev & Glushkova's recognition[24] of the variable-velocity nature of the star. The early objective-prism velocities[19] cannot be listed because their dates were not published, but in any case they would not be likely to be of much assistance in the determination of the orbit.

The orbit is readily computed from the Cambridge observations; it is found to have a period of about 83 days. Zero eccentricity has been forced on the solution; it did not take much forcing, because when the eccentricity was allowed as a free parameter it took a value of only $0{\cdot}007 \pm 0{\cdot}007$ and the sum of the squares of the residuals fell only from 2·05 to 1·99 (km $s^{-1})^2$. Thus the two degrees of freedom represented by e and ω actually cost *less* per degree than the other 42 degrees remaining from the 45 accepted Cambridge observations when fitted by a circular orbit whose only free parameters were P, T, and K. The first Cambridge observation has been rejected in those calculations and in the orbital elements that are presented, with those of the other stars treated below, in Table V towards the end of this paper. That observation gives a residual double that of any other (though still only 0·8 km s^{-1}), but serious suspicion is cast on it by the fact that the radial-velocity 'dip' is shown considerably deeper than in any of the subsequent ones: it has an 'equivalent width' (defined in exact analogy with the well-known measure of spectral-line strength) of 6·21 km s^{-1} whereas the whole range of the other 45 observations is only from 4·38 to 5·11 km s^{-1}. It is possible that the wrong star was observed, or that the trace has been compromised in some way, although it would be surprising if a measurement of a random star were to give a residual, as the one being questioned does, of less than 1 km s^{-1}.

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*Worryingly, *none* of them gave a result anywhere near the cluster mean of +36·1 km s^{-1} given by Karchenko *et al.*[16].

TABLE I

Radial-velocity observations of HD 30410

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

Date (UT)			*MJD*	*Velocity* *km s^{-1}*	*Phase*	*(O–C)* *km s^{-1}*
1989	Jan.	22·64★	47548·64	−0·2	$\overline{62}$·137	−0·2
1990	Jan.	4·81†	47895·81	−6·8	$\overline{58}$·298	+0·2
	Dec.	26·91†	48251·91	−12·2	$\overline{54}$·567	−0·7
2003	Mar.	27·83‡	52725·83	−3·0	0·193	−0·8
	Nov.	4·17	947·17	−0·8	2·846	−0·2
2005	Sept.	29·19	53642·19	−1·6	11·177	0·0
	Oct.	10·17	653·17	−7·6	·309	−0·2
	Nov.	4·12	678·12	−10·5	·608	0·0
		10·08	684·08	−8·0	·679	−0·1
		13·10	687·10	−6·4	·715	0·0
		25·05	699·05	+0·1	·859	+0·3
		30·09	704·09	+1·9	·919	+0·3
	Dec.	10·94	714·94	+1·9	12·049	−0·3
		17·12	721·12	+0·1	·123	−0·3
2006	Jan.	28·89	53763·89	−9·7	12·636	−0·1
	Feb.	8·90	774·90	−4·2	·768	−0·2
	Nov.	1·14	54040·14	+2·1	15·947	0·0
	Dec.	6·14	075·14	−9·3	16·367	+0·4
		9·08	078·08	−10·4	·402	+0·4
		17·04	086·04	−12·0	·497	+0·1
2007	Jan.	25·87	54125·87	+2·3	16·975	−0·1
	Feb.	3·96	134·96	+1·8	17·084	+0·3
		14·89	145·89	−3·4	·215	−0·2
	Oct.	18·19	391·19	−0·7	20·155	0·0
	Nov.	3·18	407·18	−9·2	·347	−0·2
		9·10	413·10	−10·9	·418	+0·2
		12·10	416·10	−12·1	·454	−0·3
2008	Feb.	10·96	54506·96	−12·0	21·543	−0·2
	Sept.	28·17	737·17	−7·0	24·302	+0·1
2009	Mar.	5·91	54895·91	−2·7	26·205	0·0
	Oct.	12·18	55116·18	−0·7	28·845	0·0
2010	Dec.	19·03	55549·03	+2·2	34·033	−0·1
2011	Dec.	8·04	55903·04	−6·0	38·277	0·0
2012	Jan.	28·90	55954·90	+1·3	38·898	+0·2
	Sept.	19·19	56189·19	−6·4	41·707	+0·4
	Nov.	11·07	242·07	−8·8	42·340	−0·1
2013	Jan.	31·89	56323·89	−7·7	43·321	+0·3
	Oct.	30·20	595·20	−11·5	46·573	−0·2
	Nov.	9·15	605·15	−7·3	·693	+0·1
		13·15	609·15	−5·5	·740	−0·3
	Dec.	5·08	631·08	+2·4	47·003	−0·1

TABLE I (*concluded*)

Date (UT)	*MJD*	*Velocity km s⁻¹*	*Phase*	*(O – C) km s⁻¹*
2014 Jan. 9·98	56666·98	−11·7	47·434	−0·2
Feb. 11·95	699·95	−1·7	·829	−0·4
Mar. 7·85	723·85	+0·7	48·115	0·0
Nov. 24·05	985·05	−4·5	51·246	+0·1
Dec. 6·05	997·05	−10·7	·390	−0·3
29·93	57020·93	−7·7	·676	+0·4
2015 Jan. 16·94	57038·94	+1·1	51·892	+0·2
Feb. 17·84	070·84	−5·7	52·275	+0·2

*Observed by Glushkova & Rastorguev[23]
†Observed by Rastorguev & Glushkova[24]
‡Cambridge observation rejected (see text)

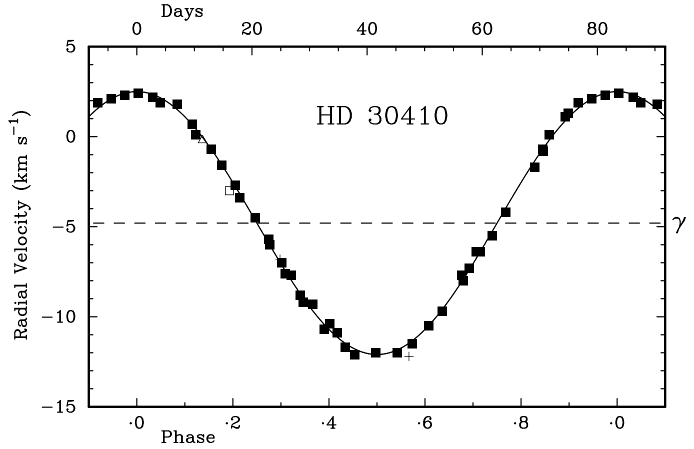

FIG. 1

The observed radial velocities of HD 30410 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The great majority of the observations (the ones upon which the orbit depends) were obtained with the Cambridge *Coravel* and are plotted as filled squares. Some misgivings have arisen over the first Cambridge measurement (see text); it has been plotted as an open square and not included in the solution of the orbit. Three published measurements, listed at the head of Table I, have also been zero-weighted in the solution; the earliest one was given by Glushkova & Rastorguev[23] and appears in the diagram as an open triangle; the other two are those of Rastorguev & Glushkova[24] and are represented by plusses (one of them partly hidden near phase ·3).

Radial velocities presented in this series of papers are usually listed 'as observed', without much effort being made to place them specifically upon a recognized absolute scale except when that is explicitly mentioned. A small investigation[25] of the zero-point of the Cambridge velocities as a function of stellar colour index indicated that, for a star having the colour of HD 30410, a correction of $-1{\cdot}1$ km s^{-1} might be warranted to place the velocities on the same scale as that adopted at that time at Haute-Provence, or $-0{\cdot}3$ km s^{-1} to place them on the zero-point established by the writer in an early work[26] and often adopted in this series of papers. No such correction has been made to the Cambridge velocities in this case, but the three velocities quoted from other papers[23,24] have been adjusted by $+1{\cdot}1$ km s^{-1} in an effort to make them more comparable with the Cambridge ones. They could well be included in the solution of the orbit, though they would need to be given quite low weight to make their weighted residuals equal to those of the Cambridge data. The resulting improvement in the standard errors of the orbital parameters is, however, so slight that the decision has been taken *not* to include them but to derive the orbit from the 45 accepted Cambridge observations alone. On that basis the orbit has the parameters listed in Table V; the corresponding plot is shown in Fig. 1.

The mass function is very small, and does not encourage any optimism that the secondary object might be seen in the radial-velocity traces. Most of the traces give rotational-velocity estimates of either zero or 0·5 km s^{-1} (the values are quantized in ½-km s^{-1} steps); that suggests that the observed star is a dwarf, since a giant with a period of only 83 days would be likely to rotate in synchronism with the orbital revolution, and as its radius would be at least comparable with the value of $a_1 \sin i$ found here it ought to exhibit a rotational velocity at least of the same order as K, which it certainly does not do. HD 30410 is unfortunate in not having been observed by *Hipparcos*, which would have given a reliable distance for it; few stars as bright as HD 30410's $7^{m}{\cdot}5$ escaped *Hipparcos*'s attention.

HD 62599

This is an $8½^{m}$ star that is to be found in the constellation Lynx, and has come to the writer's attention through being (as indicated in the summary above) in a presently unpublished extension of the area of sky assigned to Dr. S. V. M. Clube's 'Selected Area 4'. It lies a little over half a degree south-following the fifth-magnitude A-type star HR 2969. Information about it is scarce; *Simbad* carries no bibliography of it at all, but although it was not observed by *Hipparcos* itself we must be grateful to *Tycho* (actually *Tycho 2*[27]) both for the photometry $V = 8^{m}{\cdot}60$, $(B-V) = 1^{m}{\cdot}18$, and for the proper motion (which was, however, tolerably well determined previously) of about $0''{\cdot}054$ per annum. If the star were a main-sequence object its colour index would indicate its type to be about K5, which would imply a distance modulus of little more than one magnitude (distance 15–20 pc). At such a distance its proper motion would correspond to a transverse velocity of only 4–5 km s^{-1} — by no means impossible but unusually small, particularly in comparison with the radial γ-velocity which will be shown below to be nearly 50 km s^{-1}. On the basis just of its proper motion alone, therefore, the star could more naturally be considered to be a giant; its absolute magnitude would then be brighter by perhaps 5 to 7 magnitudes, so its distance (and accordingly its transverse velocity) would be larger by a factor of 10 to 25, putting it in the same range as the mean radial velocity, a situation that commends itself better subjectively.

The radial velocity of HD 62599 was first measured at Cambridge in early 2012, and next in a second round of observations of the stars that had been added to the programme in the extension to Area 4 in the spring of the

TABLE II

Radial-velocity observations of HD 62599

All the observations were made with the Cambridge Coravel

Date (UT)	*MJD*	*Velocity* *km s^{-1}*	*Phase*	*(O – C)* *km s^{-1}*
2012 Feb. 19·96	55976·96	+32·2	0·433	0·0
2013 Apr. 19·97	56401·97	66·4	6·999	−0·2
26·93	408·93	62·5	7·106	−0·2
29·86	411·86	59·2	·151	+0·2
May 3·86	415·86	52·4	·213	−0·3
4·94	416·94	50·4	·230	−0·5
6·88	418·88	47·5	·260	0·0
7·88	419·88	46·1	·275	+0·3
8·93	420·93	44·3	·291	+0·3
11·93	423·93	39·5	·338	+0·3
13·87	425·87	36·6	·368	+0·1
16·88	428·88	33·2	·414	0·0
June 3·90	446·90	42·2	·693	−0·1
5·90	448·90	45·1	·724	−0·5
Oct. 24·23	589·23	62·4	9·891	−0·1
29·22	594·22	66·2	·968	0·0
Nov. 9·23	605·23	59·5	10·138	−0·7
13·19	609·19	54·3	·200	+0·1
19·18	615·18	43·6	·292	−0·3
Dec. 1·16	627·16	30·5	·477	−0·3
5·14	631·14	30·9	·539	−0·3
20·09	646·09	50·6	·770	−0·2
29·07	655·07	63·8	·908	+0·1
2014 Jan. 5·06	56662·06	66·3	11·016	−0·2
7·04	664·04	65·9	·047	+0·1
10·03	667·03	63·5	·093	−0·1
12·02	669·02	61·2	·124	−0·2
27·03	684·03	37·4	·356	−0·1
Feb. 2·99	690·99	30·9	·463	−0·2
5·96	693·96	30·8	·509	+0·1
11·08	699·08	33·6	·588	+0·3
12·98	700·98	35·1	·618	−0·2
13·95	701·95	36·8	·633	+0·3
15·92	703·92	39·2	·663	−0·1
20·91	708·91	47·2	·740	−0·3
22·90	710·90	51·2	·771	+0·3
25·89	713·89	56·0	·817	+0·1
26·89	714·89	57·8	·832	+0·3
27·89	715·89	59·2	·848	+0·2
Mar. 1·88	717·88	61·5	·879	−0·1
4·88	720·88	65·1	·925	+0·5
5·97	721·97	65·3	·942	−0·1
8·87	724·87	66·5	·987	0·0
11·86	727·86	66·5	12·033	+0·3
12·85	728·85	66·0	·048	+0·3
13·85	729·85	65·3	·064	+0·2
19·84	735·84	58·7	·156	+0·1
21·83	737·83	55·8	·187	+0·3
23·06	739·06	53·2	·206	−0·3
24·03	740·03	51·8	·221	−0·1
25·96	741·96	+48·5	·251	0·0

TABLE II (*concluded*)

Date (UT)	*MJD*	*Velocity* *km s^{-1}*	*Phase*	*(O–C)* *km s^{-1}*
2014 Apr. 4·90	56751·90	+34·1	12·404	+0·3
7·98	754·98	31·8	·452	+0·3
14·84	761·84	31·9	·558	+0·1
15·85	762·85	32·8	·573	+0·3
18·85	765·85	35·3	·620	–0·2
19·84	766·84	36·9	·635	+0·2
26·93	773·93	47·8	·744	–0·2
28·88	775·88	51·2	·775	–0·2
May 2·89	779·89	58·1	·837	+0·2
18·88	795·88	64·2	13·084	+0·1
Nov. 6·21	967·21	46·5	15·730	+0·1
Dec. 14·10	57005·10	41·5	16·316	+0·1
2015 Jan. 11·05	57033·05	47·8	16·747	–0·5
Feb. 7·03	060·03	+57·8	17·164	0·0

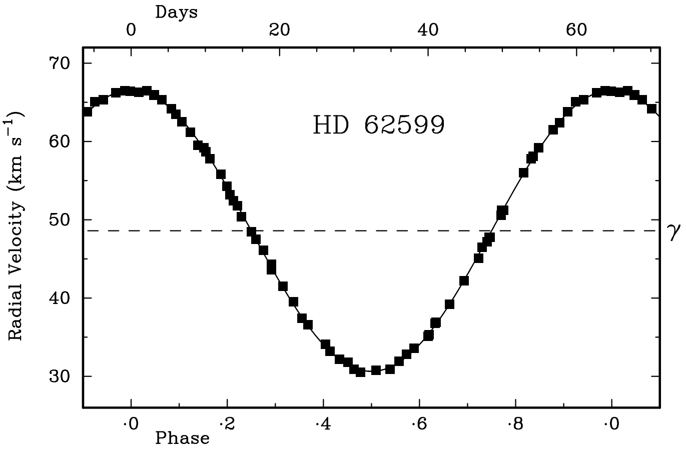

FIG. 2

The observed radial velocities of HD 62599 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations were made with the Cambridge *Coravel*.

following year. There was a large discrepancy of more than 30 km s^{-1} from the initial measurement, which galvanized immediate careful follow-up (12 more measurements during the seven weeks that remained of that observing season on the star). The following observing season, starting in 2013 October, as many as 47 further observations were made, and with just four more in the final season there are now 65 velocities altogether, all obtained with the Cambridge *Coravel* and listed in Table II. They readily yield a circular orbit (see Fig. 2) with a period of about 65 days; the elements are included in Table V below. The star is nearly as red as the 'reference stars' that were used originally to set up the scale of velocities adopted[26] in Cambridge, so the γ-velocity can be considered to be close to that scale without further correction.

The r.m.s. residual of the individual observations is 0·24 km s^{-1}, quite good for the *Coravel*, perhaps especially in view of the fact that the 'dips' in the radial-velocity traces are somewhat broadened, presumably by stellar rotation which they quantify at 6·3 km s^{-1} with a standard error of only 0·14 km s^{-1}. Despite the formal precision of that value, derived from the inter-agreement of the 65 independently determined values, the possibility of other minor line-broadening mechanisms leads to the view that the mean should not be attributed an absolute accuracy better than 1 km s^{-1}.

The $v \sin i$ number, taken at face value and considered in conjunction with the orbital period which, if HD 62599 has indeed giant-star luminosity, is very likely to be the same as the rotational period, yields for the star a projected radius of 8·0 $R_\odot$ — very reasonable for a late-type giant. The spectral type that would correspond to the measured $(B-V)$ colour index, in the case of a giant star, would be K2. The radius of a K2 III star is supposed[28] to be nearly double the projected radius that has just been estimated for HD 62599, but the uncertainties associated with the distance and luminosity of the star would make it unwise to place much credence in the mathematical implication that the orbital inclination is a little over 30°. It may be hoped and expected that *Gaia* will in due course provide an accurate parallax, luminosity, and astrometric orbit for the star, making the present effort to specify its properties appear at best to be in the nature of a preliminary speculation.

HD 127742

HD 127742 is the brightest of the stars discussed in this paper, having a V magnitude of 6·86. That value is listed by *Simbad* as having been derived from *Tycho 2* photometry; the corresponding $(B-V)$ colour index is 0$^{\mathrm{m}}$·92, which would ordinarily correspond in the case of a giant star to a spectral type of about G6 or G7. The type is given in the *Henry Draper Catalogue* as G5, and an actual MK classification of G5 III has been given by Harlan[29]. There is an *Hipparcos* parallax of 6·83 ± 0·74 arc-milliseconds, which translates to an absolute magnitude of +1·0 with an uncertainty of about a quarter of a magnitude. The star is to be found in an easterly excrescence of Virgo at a declination of about +5°; it is about 5° north-following the 3$^{\mathrm{m}}$·7 star 109 Vir.

There is surprisingly little else of much value in the literature about this relatively bright star. There is a short section of a low-resolution spectrum tracing in a paper[30] on *Red horizontal-branch stars in the galactic disk*, and there are four (mutually discordant) radial velocities given for the star by de Medeiros & Mayor[6]. There are also (as for practically all stars of such a magnitude as HD 127742) the usual two papers, whose references I refrain from citing again so as not to enhance further their citation history when what is needful is to reverse it, which give (*a*) a distance inverted from the parallax but with its implied precision enhanced by a factor of more than 10^4, and (*b*) several different numbers giving the ludicrously lax tolerance with which the radial velocity needs to be known (hundreds or thousands of times worse than is actually found here) in order not to impair the value of other measurements that have been, or might be, made of the object.

The star was placed on the Cambridge radial-velocity observing programme in 2002 in a somewhat belated response to the 1999 indications[6] of its spectroscopic-binary nature. Observations two months apart in the first observing season were in agreement with one another, but an unambiguous change had occurred by the next season, and thereafter for several years the object was systematically observed at an approximately monthly cadence during the season

TABLE III

Radial-velocity observations of HD 127742

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

Date (UT)	*MJD*	*Velocity* *km s*$^{-1}$	*Phase*	*(O – C)* *km s*$^{-1}$
1989 Aug. 24·97*	47762·97	+14·3	$\bar{4}$·210	+0·1
1990 Mar. 10·13*	47960·13	19·2	$\bar{4}$·372	+0·2
1991 July 3·88*	48440·88	20·4	$\bar{4}$·766	−0·6
1992 Mar. 21·98*	48702·98	10·6	$\bar{4}$·981	0·0
2002 May 29·94	52423·94	9·2	0·036	+0·3
July 14·93	469·93	9·0	·074	−0·2
2003 Feb. 18·19	52688·19	15·8	0·253	+0·1
Mar. 19·08	717·08	16·4	·277	−0·1
Apr. 16·07	745·07	17·1	·300	−0·1
May 26·04	785·04	17·9	·332	−0·1
June 19·99	809·99	18·4	·353	−0·1
24·96	814·96	19·0	·357	+0·4
July 20·89	840·89	19·2	·378	+0·1
2004 Jan. 9·29	53013·29	21·4	0·520	+0·1
Mar. 30·14	094·14	22·5	·586	+0·7
Apr. 22·12	117·12	21·6	·605	−0·3
May 19·03	144·03	22·0	·627	0·0
June 25·92	181·92	21·9	·658	−0·1
Aug. 1·87	218·87	21·8	·689	−0·1
Dec. 26·28	365·28	19·9	·809	−0·1
2005 Jan. 22·26	53392·26	19·3	0·831	+0·1
Mar. 12·21	441·21	17·7	·871	+0·2
Apr. 19·08	479·08	15·7	·902	0·0
May 9·05	499·05	14·9	·919	+0·2
27·98	517·98	13·5	·934	−0·1
June 22·94	543·94	12·5	·955	+0·3
July 16·91	567·91	10·8	·975	−0·2
2006 Jan. 29·26	53764·26	11·7	1·136	+0·5
Mar. 1·17	795·17	12·3	·162	0·0
23·15	817·15	12·8	·180	−0·2
Apr. 12·11	837·11	13·7	·196	0·0
May 6·09	861·09	14·2	·216	−0·2
30·00	885·00	14·9	·235	−0·2
2007 Jan. 14·29	54114·29	20·1	1·424	+0·1
Feb. 6·22	137·22	20·3	·442	0·0
Mar. 22·15	181·15	20·5	·478	−0·3
Apr. 16·05	206·05	21·1	·499	0·0
June 20·97	271·97	21·6	·553	0·0
July 12·91	293·91	21·8	·571	0·0
2008 Jan. 6·29	54471·29	21·7	1·717	0·0
Feb. 2·23	498·23	21·3	·739	−0·1
Mar. 5·19	530·19	21·2	·765	+0·2
31·14	556·14	20·6	·786	0·0
July 21·89	668·89	17·2	·879	+0·1
Aug. 2·87	680·87	+16·4	·889	−0·1

TABLE III (*concluded*)

Date (UT)	*MJD*	*Velocity* $km\ s^{-1}$	*Phase*	*(O–C)* $km\ s^{-1}$
2009 Mar. 6·20	54896·20	+8·9	2·065	−0·1
Apr. 2·09	923·09	9·6	·087	+0·1
May 7·03	958·03	10·4	·116	−0·1
24·02	975·02	11·0	·130	0·0
2010 June 27·96	55374·96	20·5	2·458	0·0
2012 Mar. 10·13	55996·13	11·3	2·968	−0·1
Apr. 30·05	56047·05	9·3	3·010	−0·1
2013 June 6·00	56449·00	18·3	3·340	+0·1
2014 Feb. 2·27	56690·27	21·6	3·538	+0·1
Apr. 8·13	755·13	21·7	·591	−0·2
May 15·06	792·06	22·0	·622	0·0
2015 May 27·04	57169·04	13·7	3·931	−0·1
June 11·98	184·98	13·2	·944	+0·2
July 5·92	208·92	+11·4	·964	−0·3

*Observed by de Medeiros & Mayor[6]

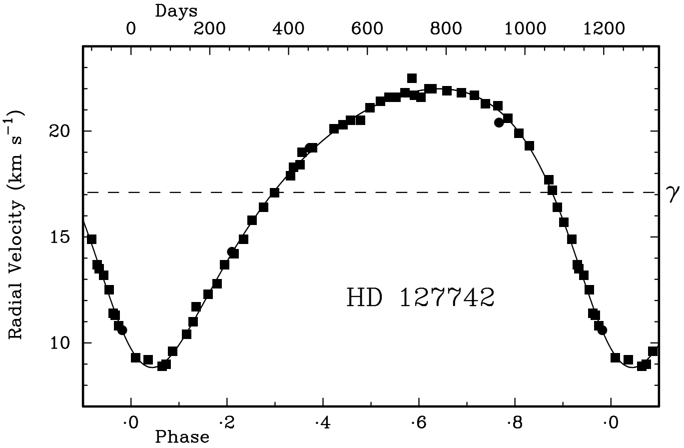

FIG. 3

The observed radial velocities of HD 127742 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. The four earliest measurements were made by de Medeiros & Mayor[6]; they are plotted as filled circles and were given half-weight in the solution of the orbit. The rest of the observations were made with the Cambridge *Coravel* and were given full (unit) weight.

when it was accessible (roughly January to July; the near-equatorial declination does not help). Later the observations became more scattered temporally, when the orbit was perfectly apparent but an effort was being made to improve the phase distribution of the data points. Table III lists the 55 Cambridge observations that are now available, following the four early velocities from the literature[6]. In an effort to keep near to the zero-point normally adopted in this series of papers, the literature velocities have been increased by 0·8 km s^{-1}, and the writer's data have been adjusted by –0·5 km s^{-1}, more or less in accord with the zero-point discrepancy found[25] between those two sources for a star of the relevant colour index. The observations readily yield the orbit that is plotted here as Fig. 3 and whose elements are included in Table V below. The r.m.s. residual is just 0·19 km s^{-1} — not in the same league absolutely as the planet enthusiasts manage, but being less than one-sixtieth of the range of variation that it charts it actually offers considerably better signal/noise ratio than in most planetary studies.

If we took the mass of the primary star as 2 $M_\odot$, then the mass function requires the secondary to have a mass not less than about 0·6 $M_\odot$ — the mass of a main-sequence star of very-late-K type, whose absolute magnitude could be expected to be about 7 magnitudes fainter than the primary. The actual mass and luminosity of the companion star could be larger to any degree, depending as they do upon the unknown orbital inclination, but there is no reason for concern over the absence of any sign of the secondary in radial-velocity traces.

HD 171006

This is a star a little brighter than the ninth magnitude, to be found in Draco at a declination of nearly 70°, just about 1° following the sixth-magnitude star 37 Dra (HR 6865). 38 Dra (HD 169027; at $6^{m}·78$ it is too faint to have a *Bright Star* designation), about 9′ following 37, acts as quite an accurate pointer to it. Once again we are indebted to *Tycho* (actually *Tycho 2*) for its photometry: $V = 8^{m}·75$, $(B - V) = 0^{m}·86$. The interest of HD 171006 came to light when it was observed as a 'Clube Selected Areas' star, in Area 2, when the northern Areas were increased in size in order to make the numbers of stars in them comparable with those in the southern hemisphere.

An initial radial-velocity observation was made with the Haute-Provence *Coravel* in 1998; it was four years before another one was obtained, at Cambridge, and a discordance was immediately apparent. The new velocity was confirmed on the very next night, but after that the observations were mostly made monthly. The high declination of the star and the fact that it is in opposition near the summer solstice (in fact it is situated only about 3° from the pole of the ecliptic) mean that it is accessible almost throughout the year, though only at heroic hour angles near the winter solstice. It has been observed as an evening star until nearly Christmas and as a morning one from early in the New Year. There are 60 Cambridge radial velocities as well as the initial Haute-Provence one. In an effort to maintain the usual zero-point of this series of papers, the latter has been adjusted by +0·8 km s^{-1}, and the former by –0·4 km s^{-1} in accordance with the colour term demonstrated in ref. 25. They are all listed in Table IV, and yield the orbit that is plotted in Fig. 4 and whose elements appear in the final column of Table V.

The 3·2-year orbit is of very moderate eccentricity, and the mass function is too small to hold out much hope that the companion star should be observable in the radial-velocity traces. Unfortunately there is no information on the luminosity of the principal star. The proper motion was determined at about 0″·038 per annum by *Tycho 2* — less even than that of HD 62599, in whose case it was argued above that its smallness favoured a conclusion that the star is a giant. In the present case, the argument would be slightly strengthened by the

TABLE IV

Radial-velocity observations of HD 171006

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

Date (UT)	*MJD*	*Velocity* *km s^{-1}*	*Phase*	*(O – C)* *km s^{-1}*
1998 July 26·02*	51020·02	−38·0	0·056	+0·2
2002 Sept. 9·99	52526·99	−34·9	1·347	−0·1
10·92	527·92	−34·8	·347	0·0
Oct. 21·92	568·92	−34·8	·382	−0·5
Dec. 19·75	627·75	−33·2	·433	+0·3
2003 May 8·05	52767·05	−32·6	1·552	−0·5
June 13·04	803·04	−32·0	·583	−0·1
July 13·05	833·05	−31·4	·609	+0·3
Aug. 14·96	865·96	−31·7	·637	−0·2
Sept. 14·88	896·88	−31·5	·663	−0·1
17·93	899·93	−31·8	·666	−0·4
Oct. 17·85	929·85	−31·3	·691	+0·1
Dec. 7·74	980·74	−31·0	·735	+0·4
2004 Mar. 2·24	53066·24	−32·1	1·808	−0·1
Apr. 7·16	102·16	−32·2	·839	+0·3
May 19·10	144·10	−33·8	·875	−0·6
June 15·06	171·06	−34·1	·898	−0·2
July 9·98	195·98	−34·8	·919	−0·3
Aug. 8·03	225·03	−35·2	·944	+0·1
Sept. 1·00	249·00	−36·1	·965	−0·1
Oct. 18·88	296·88	−37·4	2·006	−0·2
Nov. 4·82	313·82	−37·5	·020	+0·1
2005 Jan. 11·25	53381·25	−38·7	2·078	−0·4
Mar. 25·17	454·17	−38·4	·140	−0·3
Apr. 22·13	482·13	−37·4	·164	+0·5
May 15·08	505·08	−37·8	·184	−0·2
June 11·04	532·04	−37·3	·207	−0·1
July 17·01	568·01	−36·6	·238	+0·1
Aug. 15·02	597·02	−36·2	·263	+0·1
Sept. 7·88	620·88	−36·1	·283	−0·2
Oct. 4·81	647·81	−35·6	·306	−0·1
31·77	674·77	−35·0	·329	+0·1
Dec. 17·71	721·71	−34·4	·369	+0·1
2006 Mar. 1·24	53795·24	−33·4	2·432	+0·1
Apr. 4·16	829·16	−33·4	·461	−0·3
May 3·12	858·12	−32·9	·486	−0·1
June 4·06	890·06	−32·1	·514	+0·4
July 4·02	920·02	−31·9	·539	+0·4
Aug. 7·99	954·99	−32·0	·569	0·0
Sept. 7·98	985·98	−31·5	·596	+0·3
Oct. 4·91	54012·91	−31·7	·619	−0·1
2007 Apr. 2·18	54192·18	−31·5	2·772	+0·1
May 1·14	221·14	−32·3	·797	−0·5
June 1·07	252·07	−32·6	·824	−0·4
July 7·04	288·04	−32·8	·854	0·0
18·99	299·99	−32·7	·865	+0·3
31·98	312·98	−32·9	·876	+0·4
Aug. 30·98	342·98	−33·1	·901	+0·9
Sept. 22·89	365·89	−34·6	·921	0·0
Nov. 14·75	418·75	−35·8	·966	+0·2
Dec. 15·71	449·71	−36·9	·993	−0·1

TABLE IV (*concluded*)

Date (UT)	*MJD*	*Velocity* $km\ s^{-1}$	*Phase*	*(O–C)* $km\ s^{-1}$
2008 Aug. 13·00	54691·00	−37·3	3·199	+0·1
2009 Apr. 22·13	54943·13	−33·9	3·415	−0·1
Aug. 12·00	55055·00	−32·4	·511	+0·2
2010 Apr. 13·15	55299·15	−31·0	3·720	+0·4
2011 July 29·05	55771·05	−38·2	4·124	+0·1
Sept. 10·93	814·93	−37·7	·162	+0·2
Nov. 27·77	892·77	−37·1	·228	−0·2
2013 Sept. 16·92	56551·92	−32·1	4·793	−0·3
2014 July 3·98	56841·98	−38·2	5·041	−0·2
Sept. 9·93	909·93	−38·0	·099	+0·4

*Observed by de Medeiros & Mayor[6]

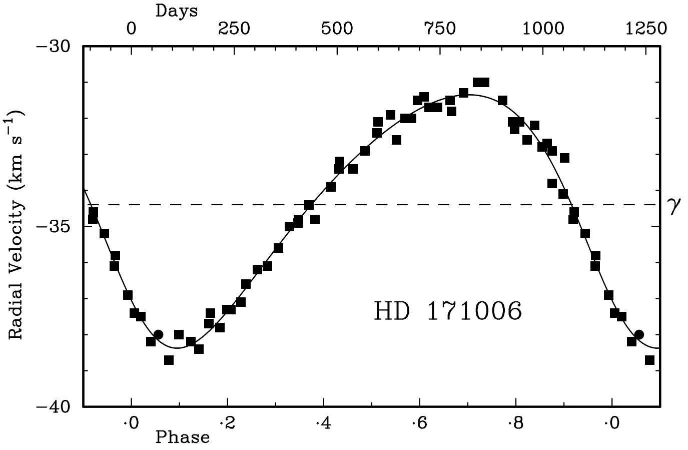

FIG. 4

The observed radial velocities of HD 171006 plotted as a function of phase, with the velocity curve corresponding to the adopted orbital elements drawn through them. All the observations were made by the writer with *Coravel* instruments and weighted equally in the orbit. The first one (plotted as a filled circle near phase ·06) was made at Haute-Provence, and all the rest at Cambridge.

proper motion being smaller, but would be weakened because (*a*) the star is slightly fainter than HD 62599 and quite a lot bluer, so if it is a main-sequence star it is considerably further away than HD 62599 and therefore its proper motion would in any case be correspondingly reduced, and (*b*) the γ-velocity is not so high and does not contrast so greatly with the transverse velocity that would be implied by the proper motion on the hypothesis that the star is a dwarf. All but three of the Cambridge radial-velocity traces yield non-zero rotational velocities for HD 171006, the formal mean value being 2·7 ± 0·3 km s^{-1}; since, however, there is no expectation of synchronous rotation when the orbit has a period as long as the one found here, the rotational velocity does not cast any light on the question of the star's luminosity.

TABLE V

Orbital elements for HD 30410, 62599, 127742, and 171006

Element	*HD 30410*	*HD 62599*	*HD 127742*	*HD 171006*
P (days)	83·427 ± 0·005	64·735 ± 0·009	1218·2 ± 0·6	1168·0 ± 3·6
T (MJD)	55045·68 ± 0·08	56661·003 ± 0·025	53598·3 ± 3·5	53290 ± 13
γ (km s^{-1})	−4·80 ± 0·03	+48·60 ± 0·03	+17·11 ± 0·03	−34·40 ± 0·04
K_1 (km s^{-1})	7·30 ± 0·05	17·96 ± 0·05	6·58 ± 0·04	3·51 ± 0·06
e	0	0	0·298 ± 0·006	0·213 ± 0·015
ω (degrees)	—	—	149·5 ± 1·2	128 ± 4
$a_1 \sin i$ (Gm)	8·37 ± 0·06	15·98 ± 0·04	105·3 ± 0·7	55·2 ± 0·9
$f(m)$ ($M_\odot$)	0·00337 ± 0·00007	0·0389 ± 0·0003	0·0314 ± 0·0007	0·00491 ± 0·00025
R.m.s. residual (wt. 1) (km s^{-1})	0·21	0·24	0·19	0·28

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REVIEWS

Kepler and the Universe: How One Man Revolutionized Astronomy, by D. K. Love (Prometheus, Amherst), 2015. Pp. 253, 23·5 × 16 cm. Price $24 (about £16) (hardbound; ISBN 978 1 63388 106 8).

I have been an admirer of Kepler for almost as long as I can remember. It was Arthur Koestler's book the *The Sleepwalkers* (Pelican edition, 1968) that first brought him to life as a flesh-and-blood human being rather than just a historical cipher responsible for describing the orbits of the planets. I must have read that book in those heady days when I was first coming to grips with physics, while society all around was becoming less appreciative of the benefits of science; as Bob Dylan so memorably put it, "There was music in the cafés at night and revolution in the air". So it was a joyful experience to find that Koestler revealed a man who struggled with concepts and calculation, and who followed mad, half-thought-through schemes to their ridiculous conclusions — like the model of the Solar System made from precious metals to be used as a drinks dispenser. Kepler is often seen as the transitional man, with one foot in the mediaeval camp of mystics and alchemists and the other firmly with the cohort of mathematical physics. Over the years my collection or books about Kepler has grown, and without turning my head I can see half a dozen or so on the shelf in front of me now. And yet David Love's book has introduced me to the man, as human, all over again and told me things I didn't already know; for example, that Kepler wore glasses to correct myopia and astigmatism. If anything, Love makes Kepler even more human than Koestler did — "Love makes Kepler human" could almost be a greetings card aphorism — but make no mistake, this is a serious scholarly work which over eight chapters chronologically details Kepler's life, with numerous illustrations and photographs, and includes 25 pages of notes, a section for each chapter, an extensive bibliography, and a useful index.

David Love is very good on the state of society during Kepler's lifetime, and also the details of his family and personal life — there is a family tree showing the mostly sad fate of his nine children and two wives. A useful appendix summarizes Kepler's travels through Europe in his pursuit of employment, and the text details some of the many letters written to potential patrons — including a possibility of working in England under King James I. Two maps illustrate the extent of those travels which, undertaken in the early 1600s, must have been quite taxing. Prague to Graz, for example, is a distance of over 200 miles, which may have been quite an adventure for Kepler as a young man of 29 with his new wife and stepdaughter — but in the winter of 1630, across Germany from Sagan to Regensburg, when he was now an elderly man of 59 in poor health, may have been a bit more challenging. Kepler spent his working life in a society almost constantly at war, and one in which casual state brutality was an everyday occurrence. One of his best friends was beheaded after first having his tongue ripped out; his mother, on trial for witchcraft, was threatened with torture and in the context of the day that was not an idle threat. Kepler, towards the end of his life, as an eminent establishment person, the imperial mathematician, was to some extent shielded from the worst excesses, but none the less even he had frequently to move out of harm's way, and his library was impounded and some of his cherished collection of books burned.

The science is well described in Love's book. The process by which Kepler arrived at his laws is well explained. Not as a sudden flash of brilliant insight but the result of hard methodical work, cranking through the observations (Tycho's and others') and trying various hypotheses until the only remaining possibility results in one or other of the laws — planets move in elliptical orbits around the stationary Sun, and in those orbits equal areas are swept out in equal times.

As well as Kepler, Love briefly mentions some of his contemporaries, some well-known, others less so, and, in passing, notes the debt of gratitude that we in later generations owe to an unlikely scientific hero, the Emperor Rudolph, for his support of Kepler, not only in providing him with a salary and respectable position but crucially the freedom from religious persecution which gave him the time to think about and ultimately derive his planetary laws.

In summary, this is a well-written easily-assimilated description of Kepler the man and his hard-won, game-changing, role in understanding the motions of the planets. But more than that it is one of the better books at putting Kepler the scientist in the context of his society and revealing the character of a driven individual, who without the benefit of independent means seeks scientific truth whilst negotiating the hurly burly of funding patronage and family life. In providing some heavy hints to Newton on the theory of gravity as well as optics, Kepler was important to physics as a whole, and this book is an excellent primer on this important scientist. For physics and astronomy scholars of all ages this is a very enlightening and enjoyable read. — Barry Kent.

It Came from Outer Space Wearing an RAF Blazer, by Martin Mobberley (Springer, Heidelberg), 2013. Pp. 655, 23·5 × 15·5 cm. Price £22·96/$39·99 (paperback; ISBN 978 3 319 00608 6), and **Return to the Far Side of Planet Moore**, by Martin Mobberley (Springer, Heidelberg), 2015. Pp. 419, 23·5 × 15·5 cm. Price £22·96/$39·99 (paperback; ISBN 978 3 319 15779 5).

Sir Patrick Alfred Moore CBE, FRS, FRAS (1923 March 4 – 2012 December 9) was a famous, enthusiastic, amateur astronomer. Those three adjectives need stressing. Not only was Patrick *enthusiastic* but he had the happy knack of passing that enthusiasm on to many millions of others through his books, lectures, and television programmes. And the word *amateur* is important too, in its rather Victorian meaning: Moore loved astronomy, lived for astronomy, and devoted his life to the subject. The word *famous* needs little embellishment: for well over sixty years Moore was at the heart of British astronomy.

His monthly *The Sky at Night* BBC programme (the world's longest-running TV series) started in 1957 April, and Patrick was still there, aged 89, on 2012 December 3, over 720 programmes later. Patrick was able to speak live to camera with faultless, speedy, concise, and error-free delivery. He had an enviable knack of getting complex concepts across to the layman. He encouraged more human beings to look up into the night sky than any other man in history. The programme was a low-budget affair. Patrick had no contract with the BBC — it was just a gentleman's agreement. The fame of Patrick and his *Sky at Night* programme was greatly enhanced by the fortuitous and timely launch of the Soviet's *Sputnik 1* on 1957 October 4, and by the huge success of the USA's Apollo mission to the Moon in the late 1960s. Most of the guests on the programme were fellow amateur astronomers discussing their observations. It was a rare honour for a professional astronomer to receive an invitation. I managed it a few times. On one hilarious occasion we were discussing the largest four asteroids. These were represented in the studio by large wooden balls, of the correct scale size. The programme was recorded 'as live' at the BBC's White City studios. During filming Patrick lifted the asteroid balls from the floor and placed them on the glass-topped coffee table that separated him from his guest. Unfortunately the asteroidal balls did not stay put; they spectacularly rolled from the table and bounced across the floor. "Will someone come and saw the bottom off my balls?", shouted Patrick. Then followed two minutes of laughter, scampering, and efficient sawing noises. The recording restarted with Patrick talking faultlessly but now assisted by balls that stayed put.

At heart Patrick was an overgrown, and rather untidy mother's boy. His Churchillian physical presence somewhat resembled Billy Bunter of Greyfriars School. He had a steadfast belief that vegetables and fruit and brown bread were unhealthy, and he was a strong supporter of the restorative properties of gin and tonic and good claret. He channelled all his energy into observing the sky, writing books on astronomy, and talking about astronomy. He was not burdened by the normal societal millstones like a day job, gardening, cooking, washing, cleaning, DIY, or a mother-in-law. Patrick certainly had some blind spots. He had an abiding belief that the lunar craters were volcanic in origin, and that occasional gas emissions from volcanic vents caused transient lunar phenomena. Politically he was somewhat to the right of Attila the Hun, and his views on the abilities and advantages of the female sex were usually unprintable. He was also a great believer that Englishmen, like his good self, had drawn the ace of trumps from the pack of life. Xenophobia coloured his world outlook. But at heart there lay a man of huge generosity, and great loyalty to his friends. It must be said, however, that Patrick did not enjoy criticism, and anyone who had crossed him was termed a 'serpent' and cast into outer darkness for the rest of his life. There were certain mysterious episodes in Patrick's biography. What he actually got up to in his RAF days in the Second World War remains somewhat hazy, and there was also his enigmatic fiancée Lorna — was she fact or fiction?

Martin Mobberley's two biographical volumes, all 1074 pages of them, are 'page-turners'. I enjoyed reading them hugely. Mobberley was one of Patrick's great friends and at heart a life-long fan. But he has provided us with a revealing, none-too-hagiographic, warts-and-all insight into Britain's most famous recent astronomer. He also draws back the curtain on some of the minor machinations of the British Broadcasting Corporation, the British Astronomical Association, and amateur astronomy in general. Patrick joined the BAA when he was eleven and was president from 1982 to 1984. He was a stalwart observer of the Moon, and for many years he claimed to be the discoverer of Mare Orientale, which was rather unfair to the German professional astronomer Julius Heinrich Franz who described it in 1906, nearly two decades before Patrick was born.

I unreservedly recommend the two books under review. They provide an eye-opening overview into what it means to be an amateur astronomer. I was honoured and proud to know Patrick Moore, and Mobberley's books do him credit. — DAVID W. HUGHES.

To Explain the World: The Discovery of Modern Science, by Steven Weinberg (Allen Lane, London), 2015. Pp. 432, 16·2 × 24 cm. Price £20 (hardbound; ISBN 978 0 241 19662 5).

"I am a physicist, not a historian", states Weinberg at the outset. As such, this is not a typical history-of-science book which describes discoveries within the mindset of the time of discovery (or, perhaps unintentionally, the time of writing) but, as the subtitle indicates, concentrates on events which led to the discovery of modern science. The word 'discovery' is also important, since Weinberg, as he states in the preface, believes science to be something objective which is discovered and not (as some historians of science hold) some sort of social construct. The book grew out of lectures which Weinberg (retired, but still active) gave at the University of Texas, where he has been since 1982. His approach has been criticized as Whiggish by some, who apparently don't understand Weinberg's objective in the book. (As Weinberg points out, Butterfield, who coined the usually pejorative term "the Whig interpretation of history", was himself Whiggish, as is Weinberg, when it comes to the scientific revolution.)

Weinberg is one of the few physicists to have made important contributions to both (traditional) cosmology and particle physics. (Many people work in the field of astroparticle physics or the early Universe, but such work is essentially particle physics applied to cosmology, whereas Weinberg has worked in traditional astronomical cosmology as well as traditional particle physics.) He coined the term "standard model" in the context of cosmology and was one of several who later started using the same term in the context of particle physics. This breadth of expertise also broadens the perspective compared to most history-of-science and/or popular-science books, even those written by professional scientists. Weinberg has written many popular books, and his skills as a writer are better than those of most other scientists who write popular books, and even better than those of some professional historians and writers. The book is thus much more than a book intended to be bought mainly because of a famous name on the cover.

Despite the wide-ranging title, much or most of the book is about astronomy, simply for the reason that astronomy was often the driving force in the saga of the discovery and development of modern science. The first five chapters make up the part 'Greek physics', which sets the stage for the second part, three chapters on 'Greek astronomy'. The third part, 'The Middle Ages', has a chapter each on 'The Arabs' and 'Medieval Europe'; much of the former is about astronomy, while most of the latter is about physics and philosophy. The fourth part, 'The scientific revolution', consists of four chapters and an epilogue, starting with the understanding of the Solar System and ending with Newtonian physics. The fact that *The Discovery of Modern Science* ends with Newton is no mistake, but rather expresses the fact that the machinery of science was in place by the time of Newton; subsequent advances (mentioned in the epilogue) are 'merely' the use of this machinery.

Weinberg is selective, intentionally (a point missed or misunderstood by some critics) concentrating on events which led to modern science rather than blind alleys, and on the ideas rather than the people who first discovered them or the society in which they lived. At the same time, in many cases more detail is provided than in other books which cover similar ground: for example, the quite extensive differences between the world models of Eudoxus and Ptolemy. Arabic science (including but not limited to astronomy) during the mediaeval period is also explored in considerable depth for a book of this sort; the same is true for mediaeval ideas about motion. While many authors often interpret ideas of the ancients in the light of modern knowledge (ironically, something many of Weinberg's detractors accuse him of doing), Weinberg is quite clear as to whether ideas are scientific in the modern sense of the term, relegating much of Ancient Greek thought to 'poetry', including early 'scientists' such as Thales. He also sees religion in its role in hindering scientific progress (although he notes that "it is not easy to determine in just what sense the pagans actually believed in their own religion"), glossing over cases where it played a role in the development of an idea (in the case of Kepler, for example). However, this is in keeping with his theme of concentrating on objective reality and not the contingent events which led to its discovery.

There are just a few factual mistakes; the correct versions are: "geometry" rather than "geography" is a component of the quadrivium; Snell was a Dutchman, not a Dane; and it was not a "comet or meteor", but rather an asteroid or perhaps a large comet whose impact probably made a large contribution to the demise of the dinosaurs, though some meteors were certainly produced in the process. Weinberg's question as to how Copernicus could know anything about the shape of the stars is probably due to the fact that Weinberg realizes that the apparent shape depends on wave optics and the physiology of the eye, and doesn't take into account the fact that Copernicus, assuming that their apparent shape represents their true shape, lived before the discovery of wave optics and when less was known about the eye than today.

There are only about half a dozen typographical errors, far fewer than is the case for many or even most books I have reviewed in these pages, where one every page or two is not uncommon. I also have no complaints about the style, again a rarity. Weinberg describes himself as having "no Latin and less Greek, let alone Arabic", but all that is needed to write a good book on the history of science is good knowledge of the subject, good skills in the language in which the book is written, and an occasional allusion to the Bard. (Of course, Weinberg relies on, and acknowledges, sources whose authors do need good knowledge of several languages, but division of labour is a good thing.)

The main text is followed by extensive technical notes, many of which contain line drawings (such as a professor might draw on a blackboard during a lecture), intended to give some technical background for readers who are not scientists. (Weinberg points out that these are modern explanations, often taking a different route than those who discovered them first.) Rather than proper footnotes, the text is complemented by 'footnotes' (so the title of the corresponding section) collected at the end of the book (after the acknowledgements). Between the technical notes and the extensive bibliography (split into original sources, collections of original sources, and secondary sources) are 'endnotes'; these are essentially literature references, many including comments as well. While I like the distinction between notes which are essentially references and those which provide more detailed information, I prefer the latter to be proper footnotes, so that one does not have to flip back and forth. Other than that, I have no complaints about the layout and production of the book, though an index would have been nice.

I recommend the book to anyone interested in the topic, whatever his or her level of expertise; there is something for everyone here. This is not a conventional history of science, but that is an advantage. While Weinberg departs from the conventional approach in many respects, I think he is correct in doing so, and he states clearly where he differs from convention. — PHILLIP HELBIG.

The Fundamentals of Modern Astrophysics, by M. Ya. Marov (Springer, Heidelberg), 2015. Pp. 336, 24 × 16 cm. Price £90/$129 (hardbound; ISBN 978 1 4614 8729 6).

Mikhail Marov works at the M. V. Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, Moscow, and is a Professor of Planetary Physics at Moscow State University. He was involved in the exploration of Venus with the *Venera* series of interplanetary spacecraft in the 1960s. He has the relevant background to write a book about Solar System exploration and planetary science. This is in principle what he has done, with eight of 11 chapters in the book being dedicated to the Solar System and extrasolar planets. The title of the book is thus quite misleading, as the rest of astrophysics is briefly covered in three chapters on 'Stars', 'Galaxies', and 'Cosmology' in a total of just 40 pages. Those topics are better and more rigorously covered in other textbooks. Furthermore, the focus is not so much on underlying physics but more on observational properties. There are virtually no equations in the book but rather methods, facts, and findings are laid out in a story-telling fashion.

I found the eight chapters on planetary science quite well written, although there is little here not covered in similar manners in standard textbooks. The book has a reasonable balance between text, pictures, and diagrams, and is quite well narrated. There are plenty of colour pictures and illustrations. As the chapters are quite short a possible target reader would be one who wants a quick overview of the history and current status of planetary-science research. — ANDERS JERKSTRAND.

An Introduction to the Sun and Stars, 2nd Edition, edited by S. F. Green & M. H. Jones (Cambridge University Press), 2015, Pp. 372, 26·5 × 21 cm. Price £39·99/$74·99 (paperback; ISBN 978 1 107 49623 9).

An Introduction to the Sun and Stars is the second edition of an Open University textbook, suitable for beginning undergraduates, post-16 high-school students, or interested amateurs. It discusses the structure and properties of the Sun, before moving on to the Hertzsprung–Russell diagram and the properties and evolution of other stars; there is also a fairly detailed discussion of the interstellar medium. Very little prior knowledge is assumed, with necessary physics being introduced in 'boxes' as required, and no calculus; however, the authors integrate the mathematics that they do use into the main text, leaving the reader in no doubt that the maths is essential to the subject — a refreshing change from many American freshman texts. There are numerous problems, some answered immediately in the text, and others at the back of the book.

The book is lavishly illustrated in colour, and enlivened with biographies of relevant scientists. I thought it a pity that these did not include Cecilia Payne-Gaposhkin, the first person to deduce the chemical compositions of stars (her inclusion would have improved the male-to-female ratio slightly!), and odd to include Robert Oppenheimer in the context of neutron stars, when Walter Baade (who made many other contributions to stellar astrophysics) or Fritz Zwicky would have been a more natural choice.

Overall, this is a nice text, very suitable for self-study or for a beginning undergraduate course. My principal criticism is that the hydrogen-shell-fusion stage of stellar evolution is seriously under-emphasized: although it is present and labelled in all the diagrams, in the text it gets just one paragraph. A student reading this book would get the impression that the star goes straight from the main sequence to helium burning, with the hydrogen-shell source as merely a fleeting transition. This is a misconception that many students have; it is a pity to have it reinforced here.

A few minor gripes: the plots all have purple borders, and in one or two cases where there is a second axis with red or orange print, the reading contrast was not good; Tycho Brahe used *diurnal* parallax to infer the great distance of SN

1572, not annual parallax as implied, and SN 1572 was *not* the explosion of a massive star (we know, from observing an echo of its spectrum, that it was a type Ia). Overall though, a book that students will both enjoy and learn from! — SUSAN CARTWRIGHT.

Annual Review of Astronomy and Astrophysics, Volume 53, 2015, edited by S. M. Faber & E. van Dishoeck (Annual Reviews, Palo Alto), 2015. Pp. 699, 24 × 19·5 cm. Price $255 (print only for institutions; about £167), $99 (print and on-line for individuals; about £65) (hardbound; ISBN 978 0 8243 0953 4).

In spite of being one editor short of the usual triumvirate, volume 53 of the *Annual Review* has appeared on time and with the familiar, full complement of definitive reviews of a wide range of topics. And, also as usual, the book starts with an autobiographical essay from one of the subject's grandees: Maarten Schmidt, who outlines his life from the very start, through the Second World War, and on through a number of astronomical interests, including of course his discovery with Greenstein of the enormously redshifted lines in quasars.

Starting close to home, we learn from P. J. Marshall *et al.* (including Chris Lintott) of the enormous potential of 'citizen science' *via* the Web, whereby anyone with a computer and an interest can join in various projects to bring order to the mountains of data accruing from large-scale surveys in astronomy, already familiar to readers of this *Magazine* through the Galaxy Zoo. More-traditional 'pro–am' projects are also covered. Perhaps next we need to consider 'crowd funding' for astronomy!

Further away from Sun and Earth we examine the boundary of the heliosphere with G. P. Zank utilizing data from the *Voyager* spacecraft already out in those remote places, and from *IBEX* observing from 1 AU and watching the interaction with the interstellar medium (ISM) at the heliopause. In fact, the ISM gets more attention in this volume with articles on dust-grain alignment, by B.-G. Andersson *et al.*, with polarization measurements showing the structure of ambient magnetic fields; a fascinating study of icy interstellar grains by A. C. A. Boogert *et al.*; and a look at the interaction of cosmic rays and the ISM by I. A. Grenier *et al.* And this leads naturally to the CO surveys of our Galaxy examined by M. Heyer & T. M. Dame which provide data on cloud masses and kinematics (a subject where, as a very green undergraduate, I took my first steps in research under the inspiring supervision of the late Michael Penston — see *MNRAS*, **142**, 355, 1969).

Before leaving the Solar System we should note its general structure for comparison with the architecture of exoplanetary systems, considered by J. N. Winn & D. C. Fabrycky, who by now have sufficient data to prepare a summary (on p. 437) for theoreticians to work on. That said, stars, with or without planets, are encouraged not to stray too close to black holes at the centres of galaxies if they don't fancy being ejected at the 'hypervelocities' discussed by W. R. Brown; and we are not talking of runaway stars with velocities of ~100 km s^{-1} but rather the ~1000 km s^{-1} that will throw them out of the galaxy altogether. And for those 'failed stars', brown dwarfs, and giant planets that may or may not be dangerously close to a black hole, the complex molecular chemistry of their atmospheres is considered by M. S. Marley & T. D. Robinson, while the hydrodynamics of those atmospheres may incorporate the processes described by R. Teyssier.

Then on to the grander scale where Hagai Netzer reviews the perhaps-not-so-unified models of AGN revealed by IR interferometry, while ex-Editor of *The Observatory* Andrew King and Ken Pounds examine outflows and feedback from AGN. And finally to galaxy formation in the cosmological time frame (R. S. Somerville & R. Davé) and the information about those distant eras that can be gleaned from the oldest, extremely metal-poor stars described by A. Frebel & J. E. Norris.

Of course, progress would not go far without new instrumentation, and some wonderful techniques for optical and IR imaging spectroscopy and energy-resolving detectors using superconducting thin films are displayed by F. Eisenhauer & W. Raab. All in all, a very encouraging picture of progress in our subject. — DAVID STICKLAND.

Annual Review of Earth and Planetary Sciences, Volume 43, 2015, edited by R. Jeanloz & K. H. Freeman (Annual Reviews Inc., Palo Alto), 2015. Pp. 649, 24 × 19·5 cm. Price $278 (institutions, about £178), $105 (individual, about £67) (hardbound; ISBN 978 0 8243 2043 0).

Annual Review is slightly slimmed down this year, with a mere 649 pages. The volume kicks off with an interesting new experimental format of material — the transcript (or, presumably, an edited version!) of a conversation with Caltech emeritus professor in environmental-engineering science, James J. Morgan. It is nice to see a novel form in scientific literature but I suspect that this 27-page piece will be of most interest to people who know Prof. Morgan already.

The scientific part of the book is somewhat less broad than previous volumes, but still provides excellent reviews of a number of subjects. Environmental change is particularly well represented this year. Papers in that category deal with global monsoon behaviour, conservation palaeobiology, ice-sheet retreat, the carbon cycle, palaeosols, palaeoenvironments and palaeoclimate, the palaeo-sulphur cycle, and the environment of early hominid evolution. I don't usually make favourites, but in this case I simply must highlight the latter chapter. It elegantly builds bridges between geology, archaeology, and environment to relate beautifully not just humans to their environment but the evolution of hominids to evolution of the environment.

The solid Earth is also represented with several chapters, though with some duplication of theme. Several chapters deal with the continental crust. One concentrates on the continental lower crust, highlighting the fact that this is a region that is still poorly known. A wide range of compositions is possible, from quite felsic to quite mafic. The paper nicely includes cross-disciplinary information from seismic, heat-flow, and dynamic-modelling work. Some lower continental crust may be gravitationally unstable and contribute to delamination recycling — a subject of considerable interest to those working in intraplate volcanism (*e.g.*, me!). Two additional chapters review the role of magmatic arcs in the formation and recycling of continental crust.

Subduction zones are also spotlighted by more than one chapter. A chapter on jadeitites and plate tectonics make the point that the former can be viewed as a marker of fluid transport in subduction regions. Sadly, this beautiful rock (pictures of lovely jadeite carvings included) is rarer than expected — a challenge to explain. A few additional chapters touch on other branches of Earth science, including palaeontology (planktic foraminifera) and earthquakes and the seismic-deformation cycle, a chapter that contains some nice case histories and beautiful figures and could usefully embellish graduate and undergraduate courses. Other celestial bodies are touched upon briefly with chapters on the atmospheres of both Solar System bodies and exoplanets.

As usual, this year's *Review* is beautifully produced on high-quality paper and with wonderful figures and summary boxes making for a pleasurable read. Buy a copy and keep your collection complete! — GILLIAN FOULGER.

The Twenty-First Century in Space, by B. Evans (Springer, Heidelberg), 2015. Pp. 519, 23·4 × 17 cm. Price £24·99/$44·99 (paperback; ISBN 978 1 4939 1306 0).

This is the sixth and final book in the series of *History of Human Space Exploration* volumes written by the same author. As such, I expected this latest effort to bring the story up to date, with in-depth discussion of the final construction and utilization of the *International Space Station* (*ISS*). Instead, I discovered that this volume has little to do with the 21st Century in space. Indeed, events that occurred during this century are barely mentioned.

The book has no obvious start and end point. The first chapter begins, for no obvious reason, in 1995 May, with woodpeckers digging away at the exterior of the Shuttle's giant fuel tank. Almost 500 pages later, the main text concludes with STS-88, a 12-day mission that began assembly of the *ISS* mission in 1998 December. The only reference to the 21st Century comes in a short epilogue.

The author provides plenty of well-written detail about the backgrounds of each of the crew members and the key events during the period of US–Russian cooperation during the Shuttle–Mir programme, the forerunner of the *ISS* collaboration. However, most of the source material is limited, comprising NASA press releases and articles from a well-known aerospace magazine.

I found the title and the cover picture of the completed *ISS* totally misleading, while the index is very short and incomplete. In the foreword, the author explains that this book only exists because a previous volume in the series was becoming too long to include all of the text he had produced. Unfortunately, this book now appears as an afterthought with no obvious purpose. Some judicious editorial intervention would have been advisable. — PETER BOND.

Robotic Exploration of the Solar System, Part 4: The Modern Era 2004–2013, by P. Ulivi & D. M. Harland (Springer, Heidelberg), 2015. Pp. 567, 24 × 17 cm. Price £24·99/$44·99 (paperback; ISBN 978 1 4614 4811 2).

Preceded by three, equally weighty, volumes this work completes the authors' review of Solar System missions up to about 2013. It is undoubtedly one for the engineering geeks as it packs masses of technological background detail around the story of each mission it describes. Those working in the space field will be familiar with the concept studies, pre-phase-A reports, and down-selects along the road which most missions travel *en route* to their targets. True to reality this work details the stillborn siblings and blind alleys of *Rosetta/Philae*, *New Horizons*, and the like. While the technology and mission-operations coverage is very full, almost to the point of obsessional, the descriptions of the scientific results are less deep, perhaps reflecting the skills and interests of the authors who are not practising scientists. Nonetheless the 40 pages of references, amounting to about 900 citations, leave plenty of opportunity for follow-up. I particularly liked the selection of photographs, both technological and scientific, many of which I had never seen before.

The final chapter reviews future missions, not all yet approved, which illustrate the possibilities for the younger generation of planetary scientists. There are comprehensive appendices of past missions and a 'checklist' of exciting launches, landings, and flybys which are expected (or at least half expected) between now and 2033. It will be interesting to tick them off, or cross them out, over my retirement.

This is not a book for holiday reading from cover to cover, but as source of detailed descriptions of any planetary mission you have heard of, and possibly a few you haven't, it is an excellent reference source. — JOHN DAVIES.

Basics of Plasma Astrophysics, by C. Chiuderi & M. Velli (Springer, Heidelberg), 2015. Pp. 279, 24 × 16 cm. Price £53·99/$79·99 (hardbound: ISBN 978 88 470 5279 6).

This is a well-presented and well-written book that aims not only to take the reader through the basics of the plasma physics needed to understand astrophysical plasmas but also to give them a taste of some of the topics of current research. It is suitable for both advanced undergraduates as well as introductory post-graduate courses. It requires a reasonable level of mathematical skill, but does not dwell too much on algebraic manipulation. The first few chapters take the reader through the basics of particle-orbit theory, then elementary kinetic theory, which allows the standard fluid and magnetohydrodynamical picture to be developed logically. Plasma instabilities and plasma waves then receive a chapter each. Waves are not only treated from a fluid standpoint, but kinetic theory is included to treat Landau damping. The style is clear and succinct throughout, which allows this relatively small book to be remarkably comprehensive. One particularly attractive element is the way the authors systematically and explicitly use characteristic scaled parameters to assess the relative importance of terms in equations, that then lead to clear explanations of what approximations are possible.

The final four chapters cover the more-advanced and more-research-level topics of shocks, magnetic reconnection, turbulence, and magnetic-field production. Although this is done in a brief fashion, it does not give the impression of being simply qualitative or cursory. This book can be strongly recommended to students of physics and astrophysics who want to find out about the plasma processes in stars and planetary magnetospheres to a level where they can get a feel for modern research in the field. As is common with many astrophysics texts, the book does not use SI units, so probably is not quite as recommendable across the whole plasma-physics spectrum. — TERRY ROBINSON.

An Introduction to Space Plasma Complexity, by T. Tien Sun Chang (Cambridge University Press), 2015. Pp. 160, 26 × 18 cm. Price £65/$99 (hardbound: ISBN 978 0 521 64262 0).

There was a time, not all that long ago, when time-series analysis meant Fourier analysis. However, over the past few decades, space-plasma physicists have gathered a wealth of data from spacecraft instrumentation and from radar systems that cannot simply be interpreted in terms of the linear superposition of spectral components and hence where Fourier analysis is inappropriate. The fluctuations seen in many space-plasma pheonomena are turbulent in nature and are characterized by non-linear interactions. This monograph is ideal for anyone who wishes to learn about the underlying mechanisms involved in such processes, as well as the analysis techniques that can reveal them from the data.

The first chapter is a general introduction to the basic concepts of complexity, scaling, self-organized criticality, intermittency, and multifractals, as well as the use of wavelet transforms as an analysis methodology. There follow more-detailed descriptions of the use of well-established analysis techniques such as sand-pile and forest-fire modelling of plasma processes in the solar corona and in the ionosphere. The physical mechanisms behind complexity are examined in the context of Alfvénic dyamics, and the use of probability distributions and the structure function are also dealt with. The last two chapters of the book outline more recent developments including Rank Ordered Multifractal Analysis and an approach based on renormalization group methods.

Overall, the book is both readable and authoritative. It is written by an expert practitioner and provides a challenging and rewarding read for students as well as for professionals who wish to apply these important ways of understanding space-plasma data to their research. — TERRY ROBINSON.

The Solar Activity Cycle, edited by A. Balogh, H. Hudson, K. Petrovay & R. von Steiger (Springer, Heidelberg), 2015. Pp. 602, 24 × 16 cm. Price £153/$229 (hardbound; ISBN 978 1 4939 2583 4). Previously published in *Space Science Reviews*, Volume **186**, Issues 1–4, 2014.

Initially I found this densely-packed 600-page volume fascinating, exciting, and baffling: I was fascinated by the wealth of observational detail and complexity of modelling, excited by the well-balanced combination of historic and present-day data that outline the tentative beginnings and the developments from them, but baffled by the appearance in marketable book form of a special issue of a regular science journal. As its title page states, the 20 review papers reproduced here were all previously published in an astronomy journal; it is available on-line for free — in Volume 186 of *Space Science Reviews* one can find the whole book, in exactly the form reproduced here, without having to pay the rather steep price of £153. Since the papers were apparently intended for a peer-level readership and not the general public, it is not at all clear where the book could be marketed — but that is Springer's problem. And although we do not normally review issues of journals, some brief reflections are given here of this one.

While retaining that initial excitement and fascination with the diversity and scope which even this one aspect of one object revealed, I then became a little disillusioned, not because of any failure by the papers to describe or convey their chosen topics well, but rather because if this one nearby star — one that we can now resolve into minute detail, video-photo in real time, watch simultaneously from the ground and from space at many different frequencies, and which is the sole target of a number of special observatories — presents so many unanswered questions, suggests so many ill-understood features, and is the unbending guardian of so many closely-guarded secrets, what hope is there that we will ever understand its more distant neighbours, 'the stars', at all well, or even slightly well? Without doubt, the more details one observes the more puzzling the problem, and the papers were candidly honest about that, each admitting to work very much in progress and to being a long way from confirmed solutions. In that respect it was refreshingly more realistic than the rest of our astronomical literature, which tends to be over-confident that models are 'correct', explanations water-tight, and only some tiny details 'not yet fully understood'. Here is a large international body of highly-skilled scientists, all questioning the physical phenomena shown by an easily-observable object, yet all struggling to model convincingly the various features of its activity cycle, whether the varying patterns of sunspots, the multiplexity of its magnetic properties and their interactions, or why and how the interplay between them is influenced and triggered. For example, while some of the most difficult aspects to tackle, the magnetic properties, seem to be understood at the local level, modelling the bigger picture remains the harder challenge. Is the basic need for more computing and people power, rather than more instrumentation? Will not the latter throw up even more baffling details? If so, what message does this have for the other 10^{11} objects in our Galaxy alone? — ELIZABETH GRIFFIN.

Unlocking the Secrets of White Dwarf Stars, by H. M. van Horn (Springer, Heidelberg), 2015. Pp. 324, 23·5 × 15·5 cm. Price £26·99/$29·99 (paperback; ISBN 978 3 319 09368 0).

When I first offered to review this book, I was expecting to receive a copy of a long-awaited major monograph on white dwarfs. So, initially, I was disappointed to receive a rather thinner paperback in Springer's *Astronomer's Universe* series. This volume is really a history of the development of our understanding of these enigmatic objects for the lay reader rather than a book for researchers. Written very much from the personal perspective of a scientist who has been intimately involved in a substantial part of that story, Hugh van Horn has produced a very interesting and readable volume by focussing on key individuals in white-dwarf research and the contributions they have made. Inevitably, there is an element of subjectivity in the choice, and there are other contributors I would have liked to see included. However, a book like this should not be too long and every scientist within its pages is certainly worthy of the attention given. While the white-dwarf story is largely up to date, there is one quite important omission: the recent work on debris discs and the emerging view that white dwarfs are actively accreting material from rocky extra-solar planetary debris. To me, that is one of the most exciting discoveries in decades and I am somewhat mystified that it is not mentioned. I hope that will be rectified in a future edition.

Although, perhaps, not part of the main target readership, I found the book both enjoyable and enlightening. I would certainly recommend it to all researchers in the field. With luck, this will be a precursor to a more substantial work! — MARTIN BARSTOW.

Why Galaxies Care About AGB Stars III: A Closer Look in Space and Time (ASP Conference Series, Vol. 497), edited by F. Kerschbaum, R. F. Wing & J. Hron (Astronomical Society of the Pacific, San Francisco), 2015. Pp. 564, 23·5 × 15·5 cm. Price $88 (about £58) (hardbound; ISBN 978 1 58381 878 7).

'Why Galaxies Care ...' has become a quadrennial meeting to explore the role of asymptotic-giant-branch (AGB) stars in the life cycle of galaxies. AGB stars are factories where carbon, oxygen, and many heavy nuclides are manufactured. Ejected as dust, these nuclides are re-cycled into the interstellar medium to provide the raw material for the next generation of star formation, planet building and, so it is believed, creating life. As these proceedings of the 2014 meeting held in Vienna demonstrate, the broad view hides an enormous amount of detail. AGB stars are complicated. Dust formation, convection, pulsation, and rotation are all challenging topics, but progress is rapid. Broad subject areas covered by the meeting include the structure of AGB-star atmospheres, the roles of binary companions, nucleosynthesis, dust, the variety of AGB stars in different environments, and the outlook for future observations with new instruments.

Roughly a dozen ten-page review papers and some 45 five-page contributed talks are presented, along with a large number of two-page posters. It is nice that the after-talk discussions have been recorded, along with photographs of speakers; these provide a lot of extra colour not found in formal journals. However, publishers need to find more space-efficient ways to handle poster papers (CUP do this better than ASP). At a modest price, this well-edited book represents a valuable resource. It might also persuade me to attend meeting IV in 2018. — C. SIMON JEFFERY.

Extraterrestrial Seismology, edited by V. C. H. Tong & R. A. García (Cambridge University Press), 2015. Pp. 441, 25 × 18 cm. Price £80/$140 (hardbound; ISBN 978 1 107 04172 1).

This multi-author book is an extensive, interesting, and useful compilation of loosely connected review chapters, some wide-ranging, others explicitly narrow, describing the gamut of seismological studies, both realized and proposed, of condensed extraterrestrial bodies, from planets and (some of) their satellites to giant stars. There are also some brief discussions of geoseismology, from which the wider discipline covered in this book was spawned. What the objects under study have in common is a relatively simple structure: they are (nearly) all close to being spherically symmetric; asphericity, where it is explicitly considered, is always weak, having been caused either by a magnetic field or by slow rotation. (There is, however, in addition, a short discussion of the seismology of accretion discs.) Therefore, on the whole, the physics of seismic waves is understood more reliably than is the detailed nature of the objects through which they propagate, so that observed properties of those waves can be used to make relatively reliable inferences about the structures of the host objects. This book describes the techniques that have been developed to accomplish that goal, and summarizes the results that have been obtained. All the reviews are non-technical, so that any interested physical scientist can readily understand them; an extensive list of references provides the reader with an entry to pertinent technical, and in some instances historical, detail.

This is the most widely embracing discussion of the subject between two covers, and can be useful to anyone involved in extraterrestrial seismology who wishes to improve their expertise by extending the arena of their knowledge beyond their own subdiscipline. It would be of lesser interest to the general scientist, who is more likely to prefer emphasis on scientific achievements than advances in techniques. — DOUGLAS GOUGH.

Myths, Symbols and Legends of Solar System Bodies, by Rachel Alexander (Springer, Heidelberg), 2015. Pp. 234, 23·5 × 15·5 cm. Price £22·99/$39·99 (paperback; ISBN 978 1 4614 7066 3).

Ancient astronomy has always been associated with the three Cs: clock, calendar, and compass. But there was a fourth aspect — mythology. Our ancestors looked up at the sky, and at the planets that moved against the fixed stellar background, and they invented names, and characteristics, and made up stories. In certain societies this went as far as deification. The Sun and the Moon were worshipped. The solar influence on early society was obvious. The Sun brought light to the day, and high temperatures to the Northern Hemisphere summer, and energy for all growth. Life depended on its continued existence. And the Moon periodically provided a night light for the times when the Sun was set, and was soon found to be responsible for the differences between spring and neap tides, and thus influenced food gathering and early travel. Some societies went further and associated the Moon with fertility and femininity and virginity. But why?

Here we hit one of the snags with Rachel Alexander's book. She happily trawls through an array of Solar System bodies and provides the reader with a large collection of mythological facts gleaned from a host of different civilizations. But the book is just a collection of statements with far too little explanation. The many opportunities for cross-correlation between the planetary mythologies of different anthropological groups and different eras of history are missed. It is all very well stating, for example, that "Venus is associated with the metal copper and the weekday Friday", but did everyone think that; and what was the reason? To get answers I had to start doing some research for myself — which might not be a bad thing. — DAVID W. HUGHES.

Astrobiological Neurosystems, by J. L. Cranford (Springer, Heidelberg), 2015. Pp. 204, 23·5 × 15·5 cm. Price £19·99/$34·99 (paperback; ISBN 978 3 319 10418 8).

The quintessence of this book is whether there possibly exist brains (central nervous systems) on other planets that might work the same or entirely differently from those found on Earth. On pursuing these thoughts the author, Jerry Cranford, touches upon the pivotal problem of defining what form or forms of extraterrestrial life might exist — whether the same but not identical to terrestrial life-forms, or entirely different (some bizarre and baffling chemical combination).

As it is possible that extraterrestrial traces of life could have had an independent evolution to forms of life that have occurred on Earth, the author is in the field of what our species cannot image or discern. This distinction between two levels of evolution — in the context of brain, mind, and body — poses different propositions for the key to exploring living matter not of this Earth. The author recognizes the limits of this, and the fact of any discussion being narrowed by what we have culturally, socially, and philosophically inherited. In other words, whether in the field of neuroscience or astrobiology, there is the enormous problem of being confronted by our own understanding of the nature of life, and who and what we are.

Should carbon-and-water-based thinking beings exist on other worlds, in which Jerry Cranford has confidence, there is the unknown of the philosophies, beliefs, ways, and languages of such species. LINCOS[1] — 'a language for cosmic intercourse' — in 1960 came about to meet this situation. LINCOS admits the proposition that life and science as we know it enable communication with extraterrestrial species. Seemingly, it does not take into account alien philosophy and psychology — the driving powers of language and communication.

As to whether extraterrestrial beings are predatory and belligerent, the author leans towards Stephen Hawking, who believes they may be threatening. This rests upon what we know about our species and the long history of predatory as well as warring life styles. In a similar context, Cranford refers to the self-destructive mentality of our species and correlates it with global warming and the development of technologies that could end all life on our planet. By extension, self-destruction could also apply on other worlds, where similar or entirely different biological species use perilous technologies — one of the reasons for wanting no contact. Among other reasons, as pointed out by the author, it may well be that such species do not want contact with us.

For astro-neurobiological educated guesses, surmises, and ideas, this book is the first of its kind and offers a good read. — P. CHAPMAN-RIETSCHI.

References

(1) H. Freudenthal, *LINCOS: design of a language for cosmic intercourse, Part 1* (North-Holland, Amsterdam), 1960.

Alpha Centauri: Unveiling the Secrets of Our Nearest Stellar Neighbor, by M. Beech (Springer, Heidelberg), 2015. Pp. 297, 23·5 × 15·5 cm. Price £22·99/$39·99 (paperback; ISBN 978 3 319 09371 0).

On several occasions over the last seven years I have made micrometer measurements of double stars with the 26·5-inch refractor at Johannesburg, and one of the highlights of those sessions was to observe alpha Centauri. Seeing the two deep-yellow suns shine out in the eyepiece was like looking at a pair of car headlights — almost too bright to behold. Even without the micrometer the orbital motion over that period was obvious — amounting to 32 degrees in position angle with the angular separation of the two stars closing from 8·2 to 4·8 arc seconds. This magnificent binary now has, and deservedly so, a book all to itself. (There is a slim volume, published by Ian Glass[1] and available from him, which deals primarily with Proxima Centauri but does contain a significant amount about alpha itself.)

The book is divided up into three sections: the first describes the history of observation of alpha and Proxima Cen, summarizes what is known about the physical characteristics of the stars in the system, and places it in context with respect to the stars in the solar neighbourhood.

The middle section deals with stellar properties and the making of planets. The dynamics of the alpha Cen system mean that there are only limited zones in which planets could conceivably be in stable orbits, and to date observations seem to have ruled out families of Jupiter-mass bodies around alpha Cen A and B, and if they exist around Proxima then they will be far out and therefore less easy to detect. The announcement that a planet orbiting the B component (and called Bb) had been found was made by Dumusque *et al.*[2] and is covered thoroughly. The scatter in the radial velocities shows just how marginal that detection is, and at the time of writing it had not been confirmed. It was to be hoped that an *HST* programme of photometric monitoring would settle the issue. The result of that work (Demory *et al.*[3]) appeared in 2015 and could not confirm any transit events that might be associated with Bb — which could just mean that its orbital plane is tilted to our line of sight — but they did find evidence in the form of a single transit of another putative exoplanetary body. Now we wait for someone to confirm *that* observation, but the amount of observing time needed on *HST* to do this work (40 hours in this case) is such that a follow-up project is unlikely to be attempted soon. Another possibly fruitful field of research is to monitor the considerable proper motion of Proxima and look for gravitational-lensing effects as it passes in front of background stars. There is such an event expected for 2016.

Another question that is often asked and which is still hanging in the air: is Proxima gravitationally bound to alpha Cen A and B? Unfortunately the result depends on a substantially more accurate radial velocity for Proxima than we currently have. It's clear that this fascinating group of stars is not giving up its secrets easily. But one thing is for sure: the impressive number of planned missions specifically designed to detect exoplanets by transit photometry, radial velocity, or astrometry is bound to reveal much more about the alpha Cen system.

In the final, speculative section, the author looks into the future — possible propulsion mechanisms, the possibility of exploring the stellar neighbourhood *via* an unmanned probe on a 65-year mission to tour some of the stars in the solar neighbourhood less than 12·5 light years away, the consequences of future stellar encounters especially if they are close enough to perturb the Oort cloud, and the expected future of the alpha Cen system.

I found this to be a thoroughly fascinating, thought-provoking, and engaging volume and can recommend it. The text is well-written and draws the reader in, and, speaking personally, the slightly larger font makes it easier on the eyes. There are one or two factual errors, the most glaring of which is that Henderson and John Herschel observed from Johannesburg instead of Cape Town (or its environs) but there are quite a lot of misprints which a proof-reader might well have picked up. — ROBERT ARGYLE.

References

(1) I. S. Glass, *Proxima: The Nearest Star* (*Other Than the Sun!*) (Mons Mensa, Cape Town), 2008.
(2) X. Dumusque *et al.*, *Nature*, **491**, 207, 2012.
(3) B.-O. Demory *et al.*, *MNRAS*, **450**, 2043, 2015.

Astrophotography on the Go, by J. Ashley (Springer, Heidelberg), 2015. Pp. 320, 23·5 × 15·5 cm. Price £22·99/$39·99 (paperback; ISBN 978 3 319 09830 2).

Modern equipment means that you can get pretty spectacular deep-sky images by using DSLR cameras coupled to inexpensive mounts and telescopes. The equipment used is relatively portable, which is important for those of us who have to travel away from home to escape light pollution. The author of this book is aiming at people who live in light-polluted towns and who have little experience but who aspire to produce the colourful astro-photos of deep-sky objects that we see on-line or in magazines. This is a laudable objective but I think the author fails in many ways.

One of the problems, which is not of the author's making, is that modern on-demand book publishing encourages quantity rather than quality. This particular publisher has a huge range of astronomy titles but most have very short print runs. This means that copy-editing is minimal or non-existent so stupid errors get through to the final book. Most of these errors are obvious and so amuse rather than confuse (I liked the vision of an "armed chair astronomer" on p. 92 — perhaps there are such things in Texas?), but others are more significant, such as the description of software planetarium programs as "planetary programs" on p. 154. Other errors are the fault of the author and fall into the 'very confusing' category. His description of signal-to-noise in short-exposure imaging is very muddled and the author continually confuses the PC processor's word size (32- or 64-bit) with the ability of a graphics program to open images with 16- or 32-bit pixel representation. Other errors in the description of noise in image sensors imply that the author's understanding of that technology is rather tenuous.

My main problem, though, is that much of the book reads as if it has been strung together from out-of-date web blogs. In this field most of the technology is advancing so rapidly that attempting to give specific instructions on equipment or software in a hard-copy book is pointless. That is what the web, with its much more dynamic format, is good at. Books should concentrate on background and principles. If they don't they can be out of date before they are published.

Apart from light pollution, we are living in a golden age when it comes to the availability and effectiveness of astro-imaging equipment and software. I applaud the principles of this book but I would not recommend it to anyone that I know who forms its target readership. Far better to scour the web, read some magazines, and join a local astronomy club. — NICK JAMES.

Universe Unveiled: The Cosmos in My Bubble Bath, by C. V. Vishveshwara (Springer, Heidelberg), 2015. Pp. 243, 23·5 × 15·5 cm. Price £31·99/$34·99 (paperback; ISBN 978 3 319 08212 7).

This is basically a short history of astronomy and cosmology, though told in a somewhat roundabout way. Though it is self-contained, it is in some sense a sequel to the author's *Einstein's Enigma or Black Holes in My Bubble Bath*. The material covered is essentially the same as in the book by Rhodri Evans recently reviewed in this *Magazine*[1], though the level is somewhat lower; no equations or graphs are included, but there are a few drawings — and one figure, consisting of several photographs and illustrating redshifts of five different galaxies, which I have seen in many other books. Both books are part of Springer's *Astronomers' Universe* series, but *Universe Unveiled* is pitched a bit lower than the level described in Springer's own description[2] of the series.

The main text is told by the narrator within the framework of conversations with his talking bath(!); visions involving historical figures; and conversations with other people, principally Bruno, who owns an Italian restaurant which is the scene of some of the conversations, and George, who is writing a book on cosmology, parts of which appear in *Universe Unveiled*. I find this rather distracting and somewhat camp; nevertheless the conversations with the ghosts of astronomers can be effective when used to give an impression of their personalities, though I think it is worth the trouble only in the case of Hubble (where it is hilarious). Not all of the historical figures are (well known as) astronomers: one can make a case for including Omar Khayyam, but Casanova seems a bit of a stretch. These plays within plays don't really add to the narrative and there is no payoff, only confusion (such as the question of whether *Universe Unveiled* was written by George, at least in the context of the narrative). Related to this is the question of the target demographic. I can imagine that something like this framework might work in the context of a television programme, at least for a certain audience, but anyone with the patience to read the book is likely to find it too distracting.

Apart from those issues, the book does provide a reasonably good historical overview of astronomy and cosmology (with the balance shifting towards the latter as the present is approached), but offers nothing really new. That some chapters share their titles with other works (certainly homage and not plagiarism) will probably be lost on most readers. My only real complaints about the scientific approach are that the author sometimes just mentions relatively new topics, such as the flatness problem, without really explaining them: the reader has then heard the terms but is none the wiser; and that the author dismisses the entire concept of multiverses — certainly a valid position in a debate, but a popular book should concentrate on well-established consensus, or at least not take sides. At best highly misleading is a detailed discussion of the geometry and fate of the Universe in the case of a vanishing cosmological constant — depending on the value of the density parameter, the Universe is either spatially finite with positive curvature and will collapse, is spatially infinite with negative curvature and will expand forever, or is at the border between the two cases in both respects, spatially infinite with zero curvature (flat) and will expand forever — which is fine as far as it goes. However, it seems rather out of place since the cosmological constant is mentioned before this description and recent results supporting a positive cosmological constant are described in some detail after it, though ignoring the important fact that our Universe will definitely expand forever even though it is not yet clear whether or not it is spatially finite (and accordingly the question of the presence and if so the sign of non-zero curvature). Definitely misleading is the explanation of evidence for a positive cosmological constant from the Hubble diagram for type-Ia supernovae, where allegedly "their velocities could be determined from their redshifts". The evidence comes from comparing the observed relation between redshift and apparent magnitude to theoretical predictions for various cosmological models. Velocity does not follow from redshift unless the cosmological model is already known, and in any case is a derived quantity, not measurable in any meaningful sense, and played no role in this discovery. While "if firmly established" is mentioned, in retrospect it was premature even to mention *BICEP2* at all; in general, popular books should avoid mentioning recent results unless they have been confirmed. Apart from those, I didn't notice any factual mistakes.

The general production is similar to other books in the *Astronomers' Universe* series, though details differ. Somewhat strange are the varying sizes of the lower margins, apparently to avoid, as far as possible, breaking a paragraph across facing pages (which is usually done by adjusting inter-word and/or inter-line spacing), though if at all this would be more important for breaks coinciding with turning the page. There are fewer typographical errors (most of which are probably not typing mistakes as such but rather bad style) than in some books I have reviewed in these pages, though still far too many. There are no footnotes, endnotes, index, or references, and none are needed. There is a "List of Some Selected Books", apparently a mix of sources and suggestions for further reading.

Despite the shortcomings, I recommend the book, which the author obviously enjoyed writing, though as mentioned above I'm not sure if the target demographic exists. Stripped of the conversational framework, there is really nothing new, but it could serve as a short introduction to the topics for someone who would enjoy the way in which they are packaged. — PHILLIP HELBIG.

References

(1) P. Helbig, *The Observatory*, **135**, 237, 2015.
(2) http://www.springer.com/series/6960

Extragalactic Astronomy and Cosmology: An Introduction, 2nd Edition, by P. Schneider (Springer, Heidelberg), 2015. Pp. 644, 28·5 × 21·5 cm. Price £62·99/$89·99 (hardbound; ISBN 978 3 642 54082 0).

The number and size of pages definitely qualifies this book as a massive tome. It is the second edition, the first (a translation from the German original) having appeared in 2006. That a new and expanded edition is needed after less than a decade indicates the rapid progress in the fields covered. The book grew out of lectures by the author (who is known primarily for his work in gravitational lensing) at the University of Bonn. Topics covered (one chapter each unless otherwise indicated) are the Milky Way, galaxies in general, cosmology (three chapters), AGNs, clusters and groups of galaxies, the Universe at high redshift, and galaxy evolution.

Somewhat unusual is the ordering of chapters not by scale (as in many similar textbooks), nor by epoch (starting with the Big Bang and working forwards in the history of the Universe (or in the reverse direction)), nor historically (common in books with more emphasis on the history and development of the field), but according to difficulty, from easiest to hardest, at least in the view of the author. All chapters are roughly the same length, but since some topics cover more than one chapter, this doesn't indicate that all topics are treated with the same amount of detail. There is a difference even for one-topic chapters, since some topics need more detail to provide the same level of introduction. Giving all chapters the same amount of detail as the most detailed chapters would have made the book too long; the reverse would have made the book less useful, since there are other books covering the basics. It is a good idea to study at least two or three textbooks when learning about a field, and this is complemented by different emphases in different books. Readers who read just one book (this or another one), though, should be aware that the choice of which topics to emphasize varies from author to author. The book is aimed at students of astronomy (as opposed to other students taking an introductory course in astronomy, for whom this book is too detailed), who would presumably cover the material in this book after a similar introductory course on other aspects of astronomy, perhaps before moving on to more specialized courses.

An obvious difference from many other roughly similar books is the large number of illustrations, many in colour. Most are exact reproductions from the literature (with references* provided in the captions), though the captions have been written for the book and are quite detailed. (In such cases, the 'source' is given at the end of the caption; otherwise, 'credit' is given to the producer of the figure. This ameliorates to some extent the notorious lack of a full stop at the end of captions in Springer publications.) Another difference is that there is little emphasis on history and people: there are no pictures of astronomers, and most topics are presented fully formed, with little if any historical background. Of course, providing such background without sacrificing depth would have made the book too long, or required splitting it into two volumes. (There are other books on the history of extragalactic astronomy and especially cosmology; with the exception of rare cases where something important has been discovered since publication, these remain up-to-date, though of course only with respect to the period before their publication.)

I have read neither the first edition nor the German original. Basing my knowledge of the first edition on a review[1], a change introduced in the second

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*The reference style is somewhat unusual, *e.g.*, ApJ 692, 277, p. 682. The first number is the volume, the second, the first page of the article, and the third, the page from which the figure was taken.

edition is problems at the end of each chapter, with solutions at the end of the book. A comparison with the review of the German original[2] indicates that Chapter 10, on galaxy evolution, didn't exist prior to this edition. In common with the previous edition, there is little discussion of 'hot topics'. I think that that is good, since the inclusion of such topics tends to date a textbook quickly. Also, almost by definition such topics are at the forefront of knowledge, so any useful description would assume more background information than the book itself covers. An improvement is moving the picture credits from the end of the book to the individual figures.

An obvious point of comparison is *Introduction to Galaxies and Cosmology*, reviewed recently in this *Magazine*[3]. That book is also recommended in Schneider's book, noting correctly that the level is somewhat lower. However, there are several other differences: the former includes more historical information, has a more uniform feel since figures were produced or adapted for the book, is 'busier' in a positive sense, and has more emphasis on cosmology; I also found it somewhat easier to read, probably because both the authors and I are native speakers of English. (Nevertheless, despite a few 'Germanisms', the English in Schneider's text is in general quite good.) Useful in Schneider's book is the first chapter, which includes an overview of what follows as well as an introduction to telescopes for various wavelengths. Readers interested in more detail will be better served by Schneider, while the other book is more suited to beginning- or non-astronomers interested in the topics covered.

There are no real factual mistakes, but somewhat confusing is the suggestion that the Hubble radius is a characteristic length scale of the observable Universe: this is true in most, but not all, cosmological models (though they are rarely identical). Similarly, the relevance of the Hubble radius to the discussion of Newtonian cosmology is at best confusing. It is essentially an issue of semantics to what extent one speaks of the cosmological redshift as being due to a recession velocity, though this velocity should never be referred to as "escape velocity" (which has another, well defined, meaning in astrophysics) as in the caption to Fig. 4.12. Here it is also mentioned that the curves assume $q = 0$ whereas they additionally they assume $\lambda = 0$, *i.e.*, a vanishing cosmological constant. To be fair, this is not mentioned (but implicitly assumed) in the original paper, even though it is as recent as 1998. However, the reader is referred to Eq. 4.35 for the definition of q, which is given as $\Omega/2 - \lambda$, which is the correct general definition but most certainly does not assume $\lambda = 0$. Also, using Ω_m and Ω_Λ (instead of, say, Ω and λ) leads to the neglect of the subscript 0 to refer to the present epoch, *e.g.*, Eq. 4.35 is actually $q_0 = \Omega_\mathrm{m}/2 - \Omega_\Lambda$; either all of the terms should have the subscript 0 or none of them should. Rather bizarre is h_P to denote Plank's constant, though no subscript is used for $\hbar$. This is probably to avoid confusion with the symbol h for the dimensionless Hubble constant ($\mathrm{H}_0/100$, both terms in the usual units), though there is little possibility of confusion and no distinction is made between the latter and h used to represent the height from which a stone falls.

It is arguably a matter of taste to use cgs rather than SI units where astronomy-specific units, including the astronomical unit, would be out of place, though I (and some standards bodies) prefer the latter. There are several references to arXiv preprints, *e.g.*, astro-ph/0503176. Most or all of these have probably been published by now (some are older than fifteen years), and in at least some cases the arXiv abstract has been updated, so it would be nice to have proper publication information where it exists. There are few actual misprints, but many typographical errors with respect to style, punctuation, and so on, including but not limited to my two pet peeves: missing hyphens in two-word adjectives and wrong placement of "only" in sentences where it has the intended meaning only when placed correctly. There are over 500 figures, many or even most in colour (black-and-white figures are almost always reproductions of black-and-white originals).

The final chapter looks towards the future with respect to larger and improved instruments as well as briefly discussing both theoretical challenges (*e.g.*, dark matter, dark energy, inflation) and sociological aspects related to the fact that much of astronomy is now 'big science'. This is followed by an appendix on electromagnetic radiation, magnitudes, filters, colours, *etc.*, and one on the properties of stars (at just a few pages, obviously highly compressed). A note on units and constants is followed by a list of recommended literature, grouped by topic, with a bit of discussion. The reader is also pointed to series of review articles and various internet resources. A list of acronyms, solutions to problems, and an index — all rather detailed — complete the book. Fortunately, notes to the text are proper footnotes, so no flipping back and forth between the main text and endnotes is necessary. As is usual in textbooks, the text is essentially free of citations (though, usefully, these occur in the captions). As mentioned above, the book is large and heavy. A few portions of the text are set in a smaller font (the same size as that used for captions and footnotes), though these are too few to reduce substantially the physical size of the book. Setting the main text in this size as well would have enabled a substantial reduction, though of course at the cost of making it somewhat more difficult to read.

Despite the minor quibbles mentioned above, I recommend the book both to students and to those who work in fields other than those covered by the book but need a detailed introduction. It is up to date, quite detailed for an introduction, and the numerous figures with references are particularly useful as jumping-off points to the original literature. — PHILLIP HELBIG.

References

(1) V. Trimble, *Class. Quant. Grav.*, **24**, 2443, 2007
(2) J. Fried, *Sterne und Weltraum*, **2**, 99, 2007.
(3) P. Helbig, *The Observatory*, **135**, 234, 2015.

OTHER BOOKS RECEIVED

Numerical Modeling of Space Plasma Flows ASTRONUM–2014 (ASP Conference Series, Vol. 498), edited by N. V. Pogorelov, E. Audit & G. P. Zank (Astronomical Society of the Pacific, San Francisco), 2015. Pp. 252, 23·5 × 15·5 cm. Price $88 (about £58) (hardbound; ISBN 978 1 58381 880 0).

The most recent volume in the ASTRONUM conference series contains 36 brief reports on numerical modelling of space-plasma flows presented at Long Beach, California, in 2014 June. The contributions cover a diverse range of astrophysical topics from turbulence in the interstellar medium and in accretion discs to neutrino transport in supernovae, together with Solar System applications principally concerned with the Sun and the solar wind, and concluding with advances in numerical methods and visualization techniques.

THESIS ABSTRACTS

AGN Feedback in Local X-Ray Galaxy Groups and Clusters

By Electra K. Panagoulia

Galaxy clusters are the largest gravitationally bound objects in the Universe, containing a hot, X-ray-emitting intracluster medium (ICM), while galaxy groups are smaller versions of clusters. Both contain many galaxies in a relatively small volume, so they are ideal locations to study galaxy evolution and, by extension, large-scale-structure formation. Although gravity is the dominant mechanism governing their evolution, active galactic nucleus (AGN) feedback has a significant impact on these objects, yet the details of its *modus operandi* are still not fully understood. In this thesis, the nature of AGN feedback in local X-ray-galaxy groups and clusters is explored. The main question addressed is: what is the impact of AGN feedback in the innermost core regions of these clusters? This leads to further questions: can AGN feedback offset the cooling of the ICM gas in these core regions, and can it transport matter as well as energy outwards? Finally, do data quality and the applied analysis methods affect the derived results?

First of all, a statistically complete, volume-limited sample of nearby groups and clusters of galaxies is compiled, and forms the basis for all subsequent work in this thesis. Then, the overall entropy profile and X-ray-cavity dynamics of this sample are examined, which demonstrate that AGN feedback is a relatively gentle and self-regulated process rather than episodic and erratically powerful. In addition, it is found that these cavities, generated in AGN outbursts, can offset cooling in the cores of their host sources, and exist in sources in which the cooling of the ICM is strongest.

An observation of the core of the Centaurus cluster is then analyzed, and a central drop in its iron abundance is confirmed. It is proposed that the iron generated in the core of the cluster is transported outwards by AGN feedback-generated radio bubbles. Similar central iron-abundance drops are then searched for in the rest of the sample sources, and found in nearly half the sources with X-ray cavities. Therefore, AGN feedback can transport matter as well as energy outwards to large distances from group and cluster cores. Finally, it is shown that poor data quality and different spectral-analysis methods can have a major impact on the conclusions derived regarding the effect and nature of AGN feedback. As such, care must be taken when data from the innermost core regions of groups and clusters are analyzed, due to the complex ICM structure in those areas. — *University of Cambridge; accepted 2015 May.*

A full copy of this thesis can be accessed at:
https://www.dropbox.com/s/3jftu39258qx9sh/thesis.pdf?dl=0

The Interaction Between Quasars and Their Cosmic Environment

By Tiago André F. G. da Costa

There is now good observational evidence that active galactic nucleus (AGN) activity powered by accretion onto supermassive black holes can launch powerful gas outflows from galaxies out to $z \gtrsim 6$. AGN-driven ejection of gas has long been invoked in ΛCDM models of structure formation in order to explain how star formation is terminated in massive galaxies and, hence, why they appear 'red and dead' in the present-day Universe. The aim of this thesis is to constrain the physical mechanisms governing the interaction between AGN and their host galaxies by means of cosmological hydrodynamic simulations, focussing on models in which the energy released by the AGN couples to the ambient medium through the thermalization of a fast inner accretion wind.

We start by characterizing the cosmic sites hosting early quasar growth. We find that $z \gtrsim 6$ quasars are able to form only in very rare dark-matter haloes with mass $\approx 3 \times 10^{12}\ M_{\odot}$ located in the most over-dense regions of the Universe. We show that the number of bright galaxies surrounding the quasar is very sensitive to the efficiency of galactic outflows, and can place important constraints on feedback processes operating already at $z \approx 6$.

We then devise numerical prescriptions for hydrodynamically-driven AGN feedback and calibrate them against existing analytical models. As in the analytical models, we find that an AGN momentum input rate of L_{Edd}/c, as achieved by momentum-driven outflows, can result in efficient feedback and in an $M_{\mathrm{BH}} - \sigma$ relation in line with that observed. Once that is incorporated into more realistic cosmological simulations, we find that a substantially higher momentum flux of 5–10 L_{Edd}/c is needed, since the outflow is now required to reverse the gas inflows that continuously replenish the AGN host galaxy. We therefore argue that observed AGN-driven outflows are likely to be energy-driven (rather than momentum-driven) already at scales <100 pc.

Observed AGN-driven outflows contain a substantial cold-gas component. We show that radiative cooling in the forward shock of energy-driven outflows can give rise to large amounts ($>10^9\ M_{\odot}$) of entrained cold gas. We find that the cold component is spatially extended over tens of kpc and leads to velocity widths of $\approx$ 2500 km s^{-1}, in very good agreement with current observational constraints of cold AGN-driven outflows. — *University of Cambridge; accepted 2015 September.*

A full copy of this thesis can be requested from: costa@strw.leidenuniv.nl

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OBITUARY

Paul S. Wesson (1949–2015)

Paul S. Wesson, a Fellow of the Royal Astronomical Society, who died on 2015 September 16 at the age of 66, was a prolific and influential astronomer and physicist whose contributions will leave a lasting impact, particularly in the fields of cosmology and unified-field theory.

Paul's first papers, published while he was an undergraduate student at the University of London, were on geophysics, and he participated in a Cambridge-led geological expedition to the Kush mountains of Afghanistan in 1972. He switched to theoretical astrophysics by the time he began his doctoral studies at Cambridge, but his early interest in geology made itself felt in his first book, *Cosmology and Geophysics*, in 1978. His doctoral advisor at Cambridge was Martin Rees, but he also fell under the spell of Fred Hoyle, whose influence can be discerned in Paul's science-fiction novels and short stories, and scientifically in his contributions to the on-going Search for Extra-Terrestrial Intelligence (SETI), notably his rehabilitation of the idea (known as panspermia) that life — at least in a limited form — could have propagated through the vast reaches of interstellar space.

Paul worked on various problems in theoretical astrophysics and cosmology as a postdoctoral research fellow with Richard Henriksen in Canada and Rolf Stabell in Norway, and took an initial faculty position at the University of Edmonton in 1980, where he published a second book, *Gravity, Particles and Astrophysics*. His innovative re-calculation of the intensity of the optical extragalactic background light or EBL (with Stabell) received wide notice, dispelling lingering myths about the importance of cosmic expansion in resolving Olbers' paradox, and replacing them with a renewed awareness of the profound link between the darkness of the night sky and the age of the Universe. Related calculations enabled Paul (with the present author) to set robust limits on any possible contributions to the EBL from various species of dark matter and energy, results that were eventually summed up in two more books, *Dark Sky, Dark Matter* (2003) and *The Light/Dark Universe* (2008).

In 1984, Paul took up a permanent position at the University of Waterloo in Canada. It was there, and during the course of several visits abroad (mainly to Berkeley and Stanford) that he carried out what will probably remain his most lasting work, on the unification of gravitation and particle physics. It has been known since the 1920s that General Relativity (GR) with one additional compact space dimension reduces in four dimensions to Einstein's theory plus Maxwell's theory, thus 'geometrizing' the electromagnetic field. String theorists and others have since shown that the other gauge fields of the standard model can be similarly incorporated into GR with additional space dimensions. But unification in this approach is no longer geometrization. Explicit higher-dimensional matter fields must be introduced in order to compact the extra dimensions and explain why they are not observed. Steven Weinberg has aptly likened this compromise to the fable of 'stone soup', in which a miraculous stew supposedly made only out of rocks and water turns out to have been surreptitiously flavoured by various kinds of meats, vegetables, and spices. What Paul discovered in about 1990 is that it may be possible to achieve unification without sacrificing geometrization, if one is willing to relax the requirement of compactification. All forms of matter and energy in the four-dimensional world can then be seen as manifestations of pure geometry in higher dimensions, a realization that forms the core of what has been known since 1996 as Space–Time–Matter theory. Paul's ideas anticipated the boom in research on 'large extra dimensions' beginning in 1998. Their theoretical foundations and implications for cosmology, astrophysics, and particle physics occupied 160 of Paul's lifetime output of almost 300 publications with 20 collaborators, accounting for nearly 5000 of his more than 6500 career citations. Paul summed up this work over the course of five more books including *Space–Time–Matter* (1999), *Five-Dimensional Physics* (2006), and *Brave New Universe* (with Paul Halpern, 2006).

Paul's scientific outlook was influenced, not only by Einstein and Hoyle, but also by theorists such as Paul Dirac and Arthur Eddington. He remained unconvinced that the last word on physical reality belonged to quantum mechanics, hoping instead for a deeper underlying theory to emerge, one that would likely be based on higher-dimensional geometry. His last book, *Weaving the Universe* (2010), was an exploration of the ways in which his discoveries had led him toward the Eddingtonian view that "the stuff of the Universe is mind-stuff". These attitudes were in no way reflexive, but rather the products of long and hard thought, as attested to by the copious margin notes in many of the books he owned on quantum and particle physics as well as relativity and cosmology. Although interested in philosophical implications, he was also instinctively uncomfortable with unfettered speculation. One inscription in a book on the string landscape reads: "After reading all of the wobble in this book, I feel redirected towards concrete, equation-based physics." To those who raised metaphysical issues with extra dimensions, he was most likely to emphasize the need for more exact mathematical solutions with acceptable physical properties. And though he was a theorist first and foremost, he took great pains to remain personally involved with experiment and observation, particularly at Berkeley's Space Sciences Laboratory, Stanford's Hansen Experimental Physics Laboratory, and Canada's Herzberg Institute of Astrophysics in Victoria, BC, where he spent extended periods as a visiting scientist. He passed this attitude on to his students as well, urging them to look up at the stars, but always to keep one foot on the ground. In this, and in much else, Paul Wesson will be sorely missed by many, as a scientist, teacher, colleague, and friend. — JAMES OVERDUIN.

Here and There

IRREGULAR DEFINITION

Deep inside this starry cloud is a mysterious object called BL Lacertae. This is a faint star which blazes forth massively at very regular intervals. — *Daily Telegraph*, 2015 October 5, Night Sky in October.

A DISCOVERY OF SOME POTENTIAL

The study, at the Jet Propulsion Laboratory in California, demonstrates that four connected alkali chimneys, made of iron sulphide and iron hydroxide, could produce a current of almost 1V. — *Astronomy & Geophysics*, **56**, 5.7, 2015.